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Case Study Example using SFPE Guidelines for Substantiating a Fire Model for a Given Application

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INTRODUCTION

The use of computer fire models in fire hazard and fire protection analyses has gained an increasing level of acceptance in recent years, with predictive capabilities spanning a wide variety of applications. Additionally, individual fire models have been continually developed and refined to provide more sophisticated tools with impressive visual graphics and output. In broad terms, fire modeling and fire simulation can include basic simple algebraic correlations, lumped-parameter models (zone models) and computational fluid dynamics models (field models), which are used to predict, or replicate, various fire phenomena within an established set of boundary conditions.

In order to be an effective tool for a fire related analysis, the model user and involved stakeholders must have confidence in the model results. There has been significant work in recent years to verify and validate individual fire models; however, there has been limited guidance for both the model user and the reviewer/authority having jurisdiction/consumer to assess whether the selected model was appropriate for the particular application. The range of fire models encompass a varying degree of detail and complexity and it is the responsibility of the model user to assess the capabilities of the specific fire model and determine whether the model is appropriate for a proposed application. For a simple algebraic equation, it can be a relatively straightforward process as the correlation often requires limited input data, and was likely developed from simple testing for a single fire phenomena. However, as the fire model increases in complexity, the review and understanding of the model algorithms, inherent or background assumptions, verification and validation, impact of multiple fire phenomena, etc., can be a much more daunting task. Therefore, the Society of Fire Protection Engineers (SFPE) established a Task Group to develop a framework with which one can determine and document substantiation of a fire model application. The resulting document, Guidelines for Substantiating a Fire Model for a Given Application[1] (Engineering Guide) was published in early 2011.

This paper will discuss the process and methodology of the SFPE Engineering Guide for a case study example application, including a review of each of the steps within the methodology and a brief discussion of the options and reasoning for the methodology steps for the particular application. The case study involves a relatively typical atrium smoke control analysis in which fire modeling was used to determine the basic smoke control system design criteria for an atrium within a three level performing arts center.

BACKGROUND

The subject performing arts center contains tiered seating with a main level and two balcony levels. In order to provide access and circulation to the seating levels, the facility lobby is open to all three levels, outside of the seating areas, and thus forms an atrium in accordance with the applicable building code. The atrium includes open lobby circulation and waiting areas on the Ground Floor and open circulation areas on the Balcony and Upper Balcony Levels, with unenclosed stairs and elevators connecting the levels. The building configuration, function, and aesthetic elements create an irregular shaped atrium which wraps around the enclosed seating areas in order to provide access to the tiered seating levels. The following images illustrate the facility and atrium configuration.

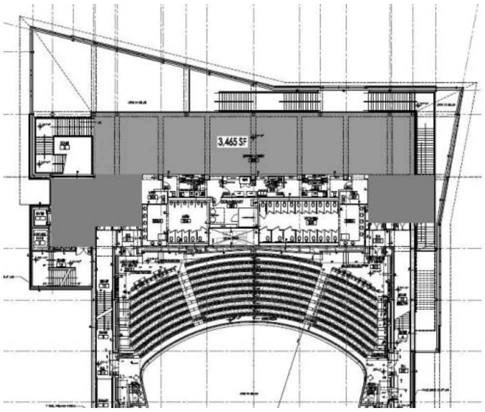

Figure 1 - Upper Level Atrium Footprint

Figure 2 - Atrium Elevation
(image courtesy of Szostak Design)

Figure 1 shows the basic floorplan for an upper level circulation lobby area with the atrium floor area shaded. In general, the floor to floor openings include a large area at the front of the building and the open circulation stairs. Figure 2 shows an elevation of the as-built atrium lobby area. The atrium space is used primarily for circulation and queuing during stage shows although the Ground Floor may also be utilized for small parties and gatherings. Therefore, the smoke control system analysis design fire scenarios needed to encompass a variety of decorations, small displays, and small temporary seating/table groups. The atrium space is utilized as part of the egress path from the seating areas on all levels and therefore, the "theoretical" smoke layer is required to be maintained above the Upper Balcony Level (Level 3) in accordance with the applicable building and fire code requirements. During the initial stages of facility design, it became apparent that the unique shape of the atrium and the obstructed floor openings (limited "stacked" openings for free smoke movement) may warrant a more detailed fire modeling analysis. The fire model Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST), was utilized for the analysis. The SFPE Engineering Guide was not originally utilized to review the specific applicability of the FDS model as the Engineering Guide was not yet substantially developed; however, this case study paper will review the methodology and steps presented in the Engineering Guide to re-assess the use of the fire model options for the specific atrium smoke control application. It should be noted that the review presented herein is the author's interpretation of the general steps, detail, and process outlined in the Engineering Guide.

ENGINEERING GUIDE METHODOLOGY

The Engineering Guide establishes a methodology with specific steps to review the suitability of a fire model for a specific application including;

1. Define the Problem of Interest
2. Select a Candidate Model
3. Verification and Validation
4. User Effects
5. Documentation.

The methodology is summarized in the following figure taken from the Engineering Guide[1]. The figure outlines the process in flow chart form.

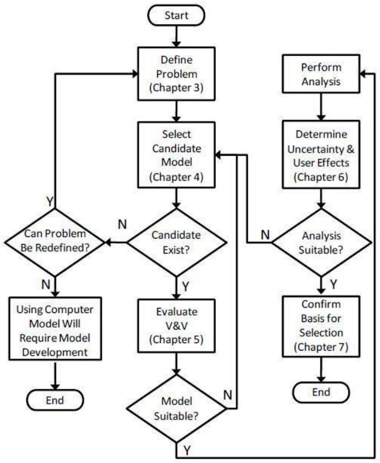

Figure 3 - Engineering Guide Fire Model Selection Flow Chart

The following sections review and discuss the Engineering Guide steps for the case study example.

Define the Problem of Interest

The initial step in reviewing a fire modeling application is to fully understand the scope of the problem, the factors that may influence the calculation or model, and if considered necessary, a review and/or literature search of previous work in the subject area. In the case study example, the generalized problem is the review of smoke and heat development and movement in the specific atrium space for selected design fire scenarios. Atrium smoke control is a well documented and reviewed subject in fire protection engineering and most often the analysis methodology is prescribed by the applicable building and fire codes. In this case, the applicable building code required an atrium smoke control system and specifically prescribed the algebraic equations to be used in the analysis. The code also referenced NFPA 92B, *Standard for Smoke Management Systems in Malls, Atria, and Large Spaces*[2], for additional information on how to conduct an analysis to determine the smoke control system design criteria. An atrium smoke control analysis is a bit unique in reference to the use of the Engineering Guide as the applicable building and fire codes often require the use of a fire modeling analysis and sometimes prescribe the basic analysis parameters in the form of algebraic equations. While a detailed literature review is likely not warranted given the subject area, a review of the specific available information, parameters, relevant phenomena, and key physics associated with the analysis is certainly necessary.

The intent of an atrium smoke control system is to provide a tenable environment for the evacuation or relocation of occupants both within the atrium and within any open adjacent spaces. Therefore, the key physics involved in an atrium smoke control system analysis include smoke movement, smoke temperature, smoke concentration, smoke layer location and depth (if applicable), compartment pressure, compartment ventilation, visibility, and flame height. The analysis may also include an evaluation of heat release rate, heat flux, ceiling jet temperature and velocity and sprinkler/detector response as part of an initial design fire analysis; however, for the purpose of this case study, the design fire(s) analysis will assumed to be a separate review. Due to the non-standard configuration of the subject performing arts center atrium, including the presence of multiple floor openings, it can be assumed that a uniform smoke layer may not form for various design fire locations, and the analysis should account for the impact of smoke movement around the many obstructions. Therefore, the smoke control analysis (problem of interest) should focus on tenability conditions within the atrium which necessitates the fire model analysis to adequately address smoke movement, smoke temperature, and visibility, and accommodate the impact of mechanical and natural ventilation within the space.

Several other parameters need to be considered based upon the available information, including the geometry of the space, the timeline of the analysis, time based events, impact of materials and initial and boundary conditions. The following summarizes an initial review of the parameters for the performing arts center atrium.

Geometry - The geometry of the space is well defined and recognized to be substantially different than the configuration of the atrium historically used in atrium fire testing.

Timeline - The timeline of the analysis could be either steady-state or transient dependent upon the type of fire model used. Given the configuration of the atrium space, and the likely necessity to further review additional factors such as timed egress and time-based fire growth, smoke production, and smoke exhaust, the overall analysis will likely need to accommodate a transient review.

Events - The analysis will likely need to accommodate specific events including fire growth and fire control, smoke/fire detection, smoke exhaust fan startup, and make-up air fan startup and/or passive make-up air door/window/vent opening.

Materials - The materials within an atrium for a design case are often difficult to predict for several reasons. The potential contents of the atrium are often not well defined in the design phases of the project and also may change over the lifetime of the building. The review of atrium contents are more directly related to a design fires analysis which would develop user defined encompassing fire scenarios to input into the smoke control analysis model. The building materials and interior finish within the atrium space can impact the atrium smoke control model results and should be reviewed during model development. However, the specific materials are again oftentimes not well defined in the early stages of design and conservative assumptions such as inert or adiabatic material properties may need to be defined for model development.

Initial and Boundary Conditions – The initial and boundary conditions relevant to the subject atrium case study include interior and exterior temperature, exhaust fan and make-up air fan/vent status, interior and exterior door status, normal HVAC system status, and exterior wind conditions. It is often necessary to make assumptions for the initial and boundary conditions and assess the impact of the assumptions during the model analysis.

The final piece to fully define the problem of interest is to clearly define the objectives and quantifiable output of the fire model analysis. In this case, the objective of the analysis is to evaluate smoke layer and/or tenability conditions throughout the modeled space and therefore, the key parameters include smoke temperature, specie concentration, and smoke concentration (visibility) for comparison with defined tenability limits. The tenability conditions will likely need to be evaluated in several locations throughout the modeled space and for the duration of the model analysis timeline.

Select a Candidate Model

The baseline intent for substantiating a fire model for an application is to ensure that a model with the required capabilities (governing equations and assumptions) and level of accuracy are appropriate for the problem of interest. Many models and model types are available, often with overlapping capabilities. In order to adequately review a candidate model, the user must establish the available model input data and the desired outputs.

For the subject case study the input data, including geometry, fire scenarios, timeline, events, materials, and initial and boundary conditions are all well defined or can be defined with bounding assumptions as discussed previously. Similarly, the desired outputs are based upon the location of a theoretical smoke layer and/or tenability conditions within the atrium space. Based upon the applicable code requirements and the configuration of the performing arts center atrium, the smoke layer and/or tenable conditions must be maintained at least 6-feet above the walking surface of the Upper Balcony lobby area, which is the highest exit access level within the atrium space. However, as mentioned previously, due to the multiple floor openings and the lack of a clear unobstructed smoke path to the roof level for several potential design fire locations, a clear smoke layer may not form within the space and it is prudent to assess tenability conditions throughout the egress paths within the space and not just at the highest floor level.

The general options for choosing a fire model include algebraic equations/correlations, zone models (lumped parameter), or field models (computational fluid dynamics). For the subject atrium case study example, the use of algebraic equations is the simplest option, especially given the fact that the equations are directly referenced by the applicable building code. However, the atrium configuration does not match well with the experimental data from which the equations were developed and the subject atrium geometry is at the bounds of the inherent cross-sectional area versus height (A/H^2) and length versus width (L/W) ratios for the correlations. Additionally the desired level of output information is more detailed than can be obtained from the available equations. Therefore, the algebraic equations are likely not sufficient for the specific performing arts center atrium analysis. It should be noted that the equations may be appropriate to obtain initial smoke production and exhaust data to input into a more detailed fire model for refinement.

A zone model can provide more detailed output information for a smoke movement analysis in comparison with the simpler algebraic equations; however, the zone model still assumes uniform upper and lower layers within the modeled space. Similar to the algebraic equations, a zone model could be used to develop initial information for the subject performing arts center atrium; however, a zone model could not account for the complicated geometry and provide the level of output detail deemed necessary for the final analysis.

A field model can allow for much more detailed input information and in turn, provide much more detailed output information in comparison with the simpler algebraic equations and zone models. A more complicated solution is not always a better solution, but for the case of the performing arts center atrium, the additional flexibility and detail is likely necessary. Therefore, a field model is deemed appropriate for the performing arts center atrium to assess the impact of the complicated geometry on smoke and heat movement, to allow the incorporation of time-based events such as smoke exhaust and make-up air initiation, and to allow the evaluation of tenability conditions throughout the modeled space. The field model, FDS, was therefore confirmed as the initial candidate fire model for the evaluation. The following figure shows an image of the as-built performing arts center and an image of the FDS model, which was built in the FDS graphical interface, Pyrosim. While certainly not a direct technical aspect of a fire model analysis, the ability to realistically mimic a building design and analysis output within the fire model can provide a good communication link with other stakeholders in the process.

Figure 4 - Case Study Performing Arts Center FDS Model

Verification and Validation

Regardless of the candidate model selected by the user, the Engineering Guide emphasizes the importance for the user to consider and assess the predictive capability of the model to be sure it is appropriate for its intended use. Only after making such an assessment may the candidate model become the selected model. Toward that end, verification and validation (V&V) must be performed to ensure the application of the model is appropriate. It is the end user's responsibility to determine that the results from a model will provide sufficient accuracy for a particular application. This critical step may prevent the errant use of a model by an uninformed end user and will prompt an educated user to consider the relevance of the model's capabilities with respect to the desired application.

The process of verification is intended to ensure that the mathematics of the model are correct and that the physics will be correctly described by appropriate equations. Because a model is often comprised of equations that are packaged into a program developed by others, the practicality of the user's role in verification is generally limited but must not be overlooked. It is incumbent on the user during the verification process to have a thorough understanding of the underlying assumptions and limitations of the calculations performed by the model.

The intent of the validation process is to require the user to confirm the model's predictive capability to properly describe the physical characteristics of the phenomena of interest. Such a technical justification is necessary in order to have confidence that a model is capable of producing results that are within the experimental uncertainty of applicable fire test data, and therefore valid for the application of interest.

The justification of FDS for use in the performing arts center atrium example is supported by a particular V&V study originally conducted to assess the appropriateness of its use for nuclear power plant applications. The study, documented in a joint NRC / EPRI report (NUREG-1824)[3], compared FDS model predictions to data measured in a series of six sets of large-scale fire experiments. NUREG-1824 characterizes specific fire model predictions in terms of color classifications; green, yellow or red. Predictions are ranked in accordance with the comparison of the calculations to two specific criteria. First, there is a check of whether the physics of the model is appropriately described by the calculation. Next, a comparison of the calculated relative differences to the experimental uncertainty is performed. In other words, do the model predictions differ significantly from the measured data?

NUREG-1824 applies green and yellow classifications to indicate that the modeled physics are appropriate for the calculation, within the calculation's assumptions. A green ranking means that the model satisfies both criteria discussed above. A yellow ranking indicates that the physics are properly described by the calculation but the predictions do not match the experimental data as well, and therefore the model should be used with caution. A red classification indicates that the fire model should not be used for the particular purpose of interest.

For the subject case study, the desired model output parameters of interest have been previously defined as (1) hot gas layer, (2) species concentration, and (3) smoke concentration (visibility). It should be noted that it is common for other atrium analyses to consider tenability criteria based on these same parameters as part of a typical performance based design approach. NUREG-1824 classifies both the hot gas layer temperature and the oxygen and carbon dioxide concentrations as "green" while the smoke concentration is classified as "yellow." Specifically, FDS is deemed suitable for predicting compartment temperatures in both the room of origin and adjacent compartments, with the results generally falling within the experimental uncertainty. Similarly, FDS is shown to be suitable for the prediction of major gas species in well ventilated conditions.

It should be noted that the yellow ranking for smoke concentration does not mean that the prediction is not appropriate for use. In the V&V study documented in NUREG-1824, only one of the six test series included measurements related to soot concentration. While FDS has been proven as capable of predicting the transport of smoke and hot gases throughout compartments, calculations over predicted the measured smoke concentrations by as much as 600 percent. For the purpose of the performing arts center case study, an over prediction in smoke concentration is deemed to yield a conservative prediction of visibility, and therefore is considered a valid prediction for use in this application.

In the event that existing V&V studies are not applicable for the application of interest, it may be necessary to either review additional experimental data or commission specific fire experiments in order to collect measurements against which model predictions may be compared. The blind application of a model must be avoided at the cost of reporting erroneous results. Ultimately, the results obtained from the most basic of calculations to more complex fire models are only as good as their accuracy of the physics that are being described.

User Effects

Additional levels of uncertainty are often integrated into a model by the user in the form of assumptions, input parameters, and the spatial definition of the modeled space. User effects often result in additional error outside the predictive capability of the calculations. As such, a modeler should have a good understanding of the sensitivity of user input parameters and the impact they may have on the model output. In the subject case study, sources of uncertainty arise from grid resolution as well as from other input parameters as described below:

Spatial Domain – The grid resolution for the performing arts center was selected based upon the large size of the computational domain as well as available computer resources due to time constraints. Ultimately, a basic grid of 1.5 ft × 1.5 ft × 1.0 ft (0.45 m × 0.45 m × 0.3 m) was selected and determined to be detailed enough to provide valid results of sufficient accuracy. Basic guidelines for selecting appropriate grid sizes are available and often a good starting point when initially developing a model.[4] However, it is prudent to perform a grid resolution study in order to confirm that the size of the grid is adequate for the prediction of the specific output parameters; in this case temperature, species concentration, and visibility results. In the current example, additional simulations were performed with varying grid size to examine the accuracy of the results. It was concluded that varying the grid size did not have a notable impact on the simulation results.

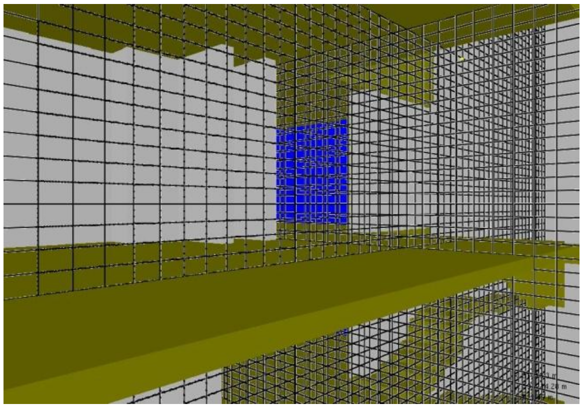

Figure 5 – Computational Grid

Heat Release Rate – The utilized fire scenarios can have a substantial impact on the analysis and for design cases, are most often directly prescribed by the model user. The design fire scenario development can be one of the most difficult tasks for the model user as there is typically limited information regarding the contents, decorations, and other potentials combustibles within the space during the early stages of design. It is often prudent to include a range of fire scenarios in order to account for various uses, furniture plans, etc. The minimum fire size for the performing arts center was prescribed by the applicable code requirements as 5,000 Btu/sec, although the code permits a reduction in the design fire if supported by an engineering analysis. Although the furnishings proposed for use in the performing arts center atrium likely would have an energy release rate on the order of 3,500 Btu/sec (based on a review of the planned individual fuel packages and spacing), the code prescribed value of 5,000 Btu/sec was generally selected for use in the design fire scenario in order to provide a conservative severe-case scenario and to encompass a number of specific potential fuel packages such as limited furnishings, interior finish, decorations, etc.

Design Fire Location – The placement of design fires within the modeled space has a direct impact on the amount of smoke generation within the model. In the case of the performing arts center, both an axisymmetric fire in the open lobby space and a balcony spill plume at the entry level were considered. These scenarios result in severe-case predictions of smoke production and provide a review of the impact of the various smoke path obstructions.

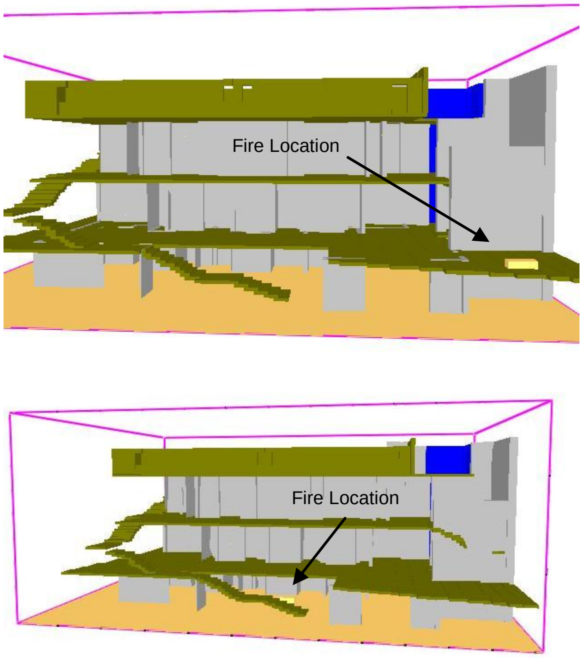

Figure 6 – Design Fire Locations at Orchestra Level (top) and Entry level (bottom)

Suppression effects – The effect of sprinklers is clearly a significant factor in real fire scenarios; however, adequately modeling the direct impact of sprinklers within a fire model for most scenarios is still a future goal for model development. Therefore, assumptions for the impact of sprinklers are most often made outside of the model itself and simply bound and limit the fire scenario growth. For the subject case study, the effect of sprinklers was included in the balcony spill scenario by predicting the time of sprinkler activation using a separate computer model, DETACT[5]. Light hazard sprinkler spacing and quick response sprinklers were used as parameters in the calculation for sprinkler activation time. Although the time of sprinkler activation could have been predicted using the field model, a more conservative approach was taken by utilizing DETACT. Because DETACT predicts detector activation from a ceiling jet flow beneath an unconfined ceiling, sprinkler activation is not influenced by a developing smoke layer which would otherwise be captured in the field model through the constraint imposed by the physical boundaries of the modeled space. The effect of sprinkler activation was incorporated into the model input via definition of the fire growth rate. Instead of reducing the heat release rate at the time of sprinkler activation, the t-squared growth is replaced by a steady fire at the point of activation. This assumption was applied only to the balcony spill plume condition and not to the axisymmetric fire scenario.

Since the effect of sprinkler activation on the fire growth was not a prediction of interest in FDS, this parameter was not included in the V&V assessment of the field model. It should be noted that a separate V&V study should be performed when other models are used to provide input parameters, such as the use of DETACT in this particular example.

Soot production – The soot yield of fuel directly impacts the prediction of smoke concentration, or visibility. In the case of the performing arts center, the soot production was assumed to be based on conservative properties to encompass the potential wide variety of combustibles within the space. The utilized value was based upon combustibles comprised of 50 percent cellulosic materials (wood, paper, cardboard) and 50 percent synthetic materials (plastics, rubber, fabrics, polyurethane foams).

Location and type of measurements - As stated earlier, the values of temperature, carbon monoxide concentration in the smoke, and visibility were evaluated by inspecting the resulting predictions at specific points above the exit access paths within the atrium. FDS' companion software program, Smokeview, is capable of viewing specific quantities of results in several formats. For the purpose of this study, single point measurements, slice files, and iso-surfaces were used to examine the spread of smoke through the atrium and to quantify the exposure amounts at a 10-foot level above various floor levels. Note that the code requirements specify that tenability be maintained at a height of 6 feet above the floor. Therefore, analysis of the conditions at a 10-foot height was deemed to provide more stringent results as the hot gas layer descends from the ceiling of the atrium.

In general, the specific input parameters discussed above were selected and evaluated to ensure that the modeling results yield measured values that are implicitly more stringent and therefore result in a conservative analysis. While the sensitivity of many of the parameters was not specifically quantified, the trend in this particular case study was to ensure that multiple levels of conservatism existed throughout the model. The model results, therefore, are consistent with those of a severe-case condition but still within acceptable limitations defined by the modeler and project stakeholders.

DOCUMENTATION

During the initial stages of any fire modeling application, it is generally considered good practice to document the steps outlined in the Engineering Guide. Such documentation provides one with a template that can be used as thorough justification for qualifying a model as appropriate for the desired applications.

For the subject case study, a report outlining the methodology, postulated fire scenarios, tenability criteria, input parameters, modeling results and conclusions was provided to the client and was presented in a manner sufficient to address the aspects that would be of interest to all project stakeholders. At the time the subject case study was performed, the Engineering Guide had not yet been developed. While the client report did not cover every aspect presented in the Engineering Guide, it did address many of the essential components.

Depending on the project and the requirements of the client, stakeholder or AHJ, it may be necessary to provide varying levels of detail or types of documentation. The benefit of providing a documented methodology is that it will ensure that the steps outlined in the Engineering Guide are followed. Currently, a number of options are available to the user, which may include a simple or detailed checklist, discussing the steps in a report or as an attached appendix, formal presentation to an AHJ or other authority, or something less formal intended to be filed internally for record.

REFERENCES

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