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Structure and Evaluation of the Process for Origin Determination in Compartment Fires

Gregory E. Gorbett, Brian J. Meacham, Christopher B. Wood and Nicholas A. Dembsey, Department of Fire Protection Engineering, Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609, USA*

Gregory E. Gorbett, Department of Fire Protection and Paramedicine Sciences, Fire, Arson, and Explosion Investigation Program, Eastern Kentucky University, 521 Lancaster Avenue, Richmond, KY 40475, USA

Christopher B. Wood, FireLink, LLC, 1501 Main Street, Suite 17, Tewksbury, MA 01876, USA

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Abstract. The science behind the formation of fire patterns and their ensuing use in the forensic analysis of fire scenes has been questioned since their introduction in the 1940s. This paper provides an overview of a prototype method for determining the area of origin based on fire patterns analysis, named the process for origin determination (POD). The POD is a seven step reasoning process for evaluating fire damage, which starts by identifying the value in further analysis of each surface and compartment of a structure and then procedurally evaluates each surface for use within the overall determination. This paper outlines the application of the POD with test subjects and presents an analysis of the outcomes showing its benefits. To facilitate testing the POD, numerical simulations and physical experiments were employed. The numerical simulations were completed through the use of fire dynamics simulator simulating a single compartment measuring 3.66 m × 3.66 m × 2.44 m with a single ventilation opening. The physical experiments were tests conducted specifically for fire patterns where accuracy rates had been previously identified in the literature. Sixty test subjects participated in the evaluation of thirty-two different origin scenarios. A decrease in variability, which indicates an increase in reliability, was noted in 21 of the 32 scenarios (66%) when participants used the POD. Three accuracy measurements were employed, all three of which illustrated an increase in accuracy when participants used the POD. The accuracy was shown to increase between 50% and 94% when participants used the POD.

Keywords: Fire patterns, Fire effects, Origin determination, Fire investigation

* Correspondence should be addressed to: Gregory E. Gorbett, E-mail: greg.gorbett@eku.edu

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1. Introduction

Since the beginning of organized fire investigation in the late 1940s, fire investigators have relied on burn patterns as a basis for determining the fire origin [1]. Presently, fire patterns are defined as the "visible or measurable physical changes, or identifiable shapes, formed by a fire effect or group of fire effects" [2]. A recent examination has identified seven steps within the overall reasoning process for evaluating fire damage for determining an area of origin, consisting of [3]:

1. Identifying the value in further analysis of a surface or compartment;
2. Identification of the varying degrees of fire damage (DOFD) along the surfaces of the compartment and contents;
3. Identifying clusters and trends of damage (fire patterns);
4. Interpreting the causal factors for the generation of the fire patterns;
5. Developing area(s) of origin hypotheses;
6. Testing the hypothetical area(s) of origin; and,
7. Selecting a final area of origin hypothesis.

The scientific method serves as the foundation for these seven steps. However, each of these steps describes an internal process or series of questions that must be resolved to allow the decision maker to effectively move through the overall process for determining an area of origin. A systematic process for determining the area of origin through the use of fire damage has not been formally developed. The National Academy of Science (NAS) issued a report critical of forensic sciences, including fire investigations, which are dependent on qualitative analyses that require expert interpretation of observed patterns [4]. Many of the NAS recommendations to assist these forensic sciences revolved around the use of the scientific method and the development of new processes that are shown and tested to be reliable and valid, as well as conducting tests to evaluate whether users employing the method were reliable and valid.

In accordance with these recommendations, a prototype, named the process for origin determination (POD), was developed through the decomposition of the fundamental questions identified within the overall reasoning process [3]. This paper presents a brief overview of the POD, outlines its application with test subjects, and presents an analysis of the outcomes showing its benefits.

2. Process for Origin Determination (POD)

The decision framework is presented here as a sequential process where each answer forwards the decision maker to the next step within the POD. The POD is a seven step process described in the introduction where a more detailed explanation of the POD, please refer to previous work on this subject [2, 3, 5, 6].

2.1. Step 1: Value

The first step when evaluating fire damage is to determine if there is any value in analyzing the evidence further. The value question serves as a 'go' or 'no go' type of decision for further analyzing a surface or compartment. This question is equivalent to the 'defining the problem' step of the scientific method.

The value question is posed to every lining surface (e.g. walls, partitions, floors, ceilings) and content surfaces (e.g. furniture, appliances) within the compartment, as well as to the compartment as a whole. The first decision to be made in evaluating the value is to ask the simple question "is there thermal damage?". A surface exhibits thermal damage when visible or measurable physical or chemical changes occur due to the exposure to the byproducts of combustion. If the answer to the damage question is 'no' for a given surface, then that surface should not be considered near the area of origin. The phrase 'area of origin' is used many times throughout this paper despite the fact that the origin should be considered a volume within the compartment. As such, throughout this paper damage to a surface is referred to as being considered the area of origin or not, when in fact it is actually only evidence of the area of origin. If the answer to the thermal damage question is 'yes' for a given surface, then that surface is further evaluated through step 2.

2.2. Step 2: Identifying Varying DOFD

The location, magnitude, and boundaries of damaged areas are identified in this step. There are several ways to perform this both visually and measurably depending upon the surface affected [3]. For example, several recent studies for gypsum wallboard have provided processes to assist in the objective identification of the varying degrees of damage, including a DOFD scale for visible damage [6], a standardized depth measurement system [7–9], and the use of digital image analysis [10–12]. In relation to the scientific method, this step corresponds to the 'collect data' step.

2.3. Step 3: Identifying Fire Patterns

The third step requires a comparative analysis of the data collected from step 2. The purpose of this step is to objectively identify the trends with those areas of damage within the compartment. Ultimately each surface that exhibits a cluster of damage will be ascribed as a single pattern or grouped with other damage that has been shown to extend along other surfaces as a pattern. Thus, providing the decision maker with a discrete number of patterns that must be analyzed through step four of the process. When a trend is identified along a surface, then the line(s) of demarcation that bounds this area of damage should be clearly identified, the cluster of damage identified as a fire pattern, and a number, described below, assigned to this fire pattern. In the event that the damaged surface does not have a trend or identifiable pattern, then the surface as a whole is identified as a fire pattern and a number assigned. In relation to the scientific method, this step corresponds to the 'analyze data' step.

2.4. Step 4: Fire Pattern Generation

The fire patterns identified in step 3 are then evaluated and classified as to the likelihood of the causal link to the fire dynamic variables or other background factors that generated the damage [3]. Currently the *standard of care* for the fire investigation profession refers to this as fire pattern generation and provides a list of them including plume-generated (PG), upper layer-generated (ULG), ventilation-generated (VG), and suppression-generated (SG) [2, 3].

Probabilistic inferences were developed between characteristics of the locations and trends of fire damage in relation to the predominant factors associated with compartment fire dynamics [5]. Bayesian theory, specifically the use of Bayesian networks (BN), has been put forward as a coherent model for interpreting forensic evidence [13]. BNs in this work were developed for determining fire pattern generation by establishing prior probabilities from both the predictive aspect of fire pattern causes (i.e. fire dynamics) and the evidence that remains after the fire (i.e. damage) [3, 14–16]. Each fire pattern identified in step 3 is processed through the relevant BN to determine the likelihood that the pattern is PG, ULG, VG, or UKG. If the fire pattern generation cannot be conclusively determined, then the fire pattern generation is noted as undetermined. In relation to the scientific method, this step corresponds to the 'analyze data' step.

2.5. Step 5: Development of Hypothetical Area(s) of Origin

The fire patterns that are classified as being generated from step 4 as plume-generated or undetermined in generation are considered as hypothetical area(s) of origin. In relationship to the scientific method, this step corresponds to the 'develop hypotheses' step.

2.6. Step 6: Tests of Hypothetical Area(s) of Origin

The hypothetical area(s) of origin are established for their likelihood as being the area of origin through a series of tests to evaluate whether a fire could have originated at this location. Each hypothetical area of origin should be evaluated in light of logical considerations, witness statements, fire dynamics, and arc mapping. In relationship to the scientific method, this step corresponds to the 'testing the hypotheses' step.

2.7. Step 7: Selection of the Final Area of Origin Hypothesis

The task of the fire investigator is to narrow the area of origin in order to focus the process of searching for potential ignition sources. The elimination of area(s) within a structure is an important part of this process, however, if there is damage that cannot be explained or eliminated then those areas must be included within the overall area of origin conclusion. Therefore, all the areas of damage that are identified to be consistent as a hypothetical area of origin in step 6 and any clusters of damage that cannot be explained are to be combined into a single, larger area that becomes the final area of origin determination. In relationship to the scientific method, this step corresponds to the 'select a final hypothesis' step.

3. POD Test Methodology

This section outlines the research methodology used to test the POD for determining the area of origin. To test the reliability and validity of this prototype, a convenience sample of novices was used to apply the POD to study-provided scenarios with various areas of origin, heat release rates, and duration. A total of thirty-two scenarios were provided to the participants. The participants included 60 undergraduate fire protection engineering technology students with no formal training or practical experience in fire investigations. These participants had taken basic classes in fire behavior and fire prevention, but had not taken any chemistry or physics classes. As such, the participants were reasonably representative of typical novices.

A 2 × 2 factorial design was utilized; the two factors were using the POD and having information about damage to contents of the room (Table 1). Participants were randomly assigned to each of the four treatment groups. A paired study design was not utilized in this case due to concern that examining the damage contours a second time could lead to artificially increased accuracy, resulting in accuracy rates biased in favor of the POD. The participants were provided damage contours from each scenario and asked to identify the center of their area of origin determination (also known as Point of Origin). Next, the participants were asked to select the smallest area on a diagram that encompassed the total area of origin determination for each scenario.

To conduct a study of the reliability and validity of the POD, the final area of origin determination would need to be evaluated, not the ability of the users to correctly interpret and conclude intermediate steps. Therefore, it was important that the participant was provided all of the intermediate conclusions that were needed to be drawn in order to conclude an area of origin. As such, when the participants were using the POD, they were provided with the conclusions for the first four steps. The participants were then asked to identify an area of origin in accordance with the guidelines from the POD.

Table 1
2 × 2 Factorial Design

Process for origin determination (POD)	
No POD	With POD
Contents	
Without contents	
Random assignment of 15 participants (no POD, w/out contents)	Radom assignment of 15 participants (POD w/out contents)
With contents	
Random assignment of 15 participants (no POD, w/contents)	Random assignment of 15 participants (POD, w/contents)

The following sections of the research methodology briefly describe the preparation of information provided to the participants, development and deployment of the data collection tool, and statistical analysis procedures.

3.1. Preparation of Scenarios and Survey Information

A group of scenarios were developed from known variables (i.e. origin, fuels, duration). Thirty of the scenarios were based on data collected from numerical experiments, while the remaining two scenarios were based on data from physical experiments. The location and magnitude of damage for thirty-two scenarios were provided to the participants. The two physical fire tests were included for comparison purposes to reported accuracy rates of professional fire investigators.

Numerical experiments were conducted using fire dynamics simulator (FDS), v. 6.1, and its accompanying animation software Smokeview, v. 6.1, to develop an array of scenarios for fire pattern development. The numerical experiments enabled the production of predicted damage profiles based on a variety of origin scenarios with varying burning durations and heat release rates. The damage location and magnitude predictions were then provided to novices as damage contours from an unknown origin. For more details regarding the numerical experiments please see other published work [5].

Thirty FDS/SMOKEVIEW simulations of varying scenarios were completed to evaluate what variables had the greatest influence on the location and magnitude of heat flux within a prescribed compartment fire. The intent of these numerical experiments was to develop varying locations and magnitude of predicted damage for use in testing the prototype process.

The compartment evaluated was a single compartment (3.66 m $\times$ 3.66 m $\times$ 2.44 m) with one doorway that served as the ventilation opening. The fire position (origin) was varied throughout the simulations between against the wall (fire positions 1–3, 5–6) and center of the room (fire position 4) (Figure 1). The time integral heat flux for every surface within each simulation was recorded because it has been shown to be a useful and simple approximate metric for damage [7–9].

Contour plots were created from the time integral heat fluxes throughout the compartment, which illustrated the location and magnitude of heating within each simulation at various time steps. The contour plots were then utilized as the degree of fire damage for testing the POD. The numerical experiments were not intended to provide exact location and magnitude of damage, but more of a relative degree of damage throughout the compartment that would serve as a good test of the POD.

The numerical experiments provided a set of scenarios that would serve as a means to assess the POD when utilized by novices. The simulations provided contour plots for each fire position, with five peak heat release rates at 17 time step intervals (every 60 s up to 1000 s). A total of thirty numerical experiments were used for this study. These included five of the six fire positions at two different peak heat release rates at three different time step intervals (Table 2). Fire position five was not evaluated due to the lack of any discernable difference between the peak heat release rates and time step intervals, most likely due to the majority

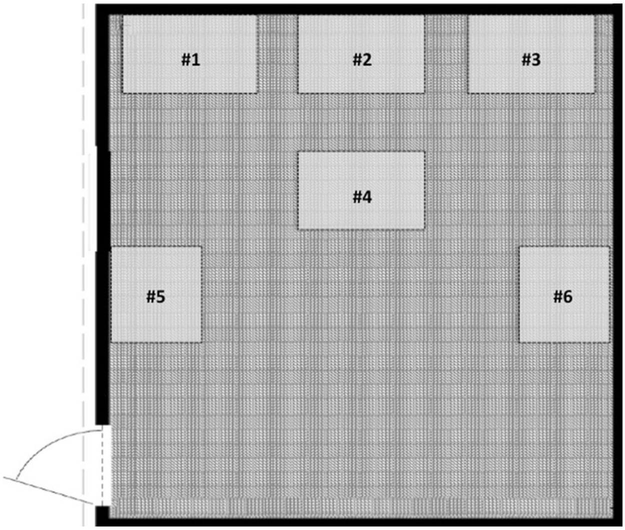


Figure 1. Simulation compartment layout—floor plan with fire positions identified.

of the heat exiting the ventilation opening. Two peak heat release rates, 1.5 MW and 4 MW, were chosen to reflect the more challenging conditions to test the POD. Three time step intervals for each peak heat release rate were chosen to best represent varying conditions within the compartment, which include 120 s, 360 s, and 900 s. The 120 s time step interval will clearly reflect fuel-controlled conditions, while the 360 s and 900 s time step intervals will represent a short and long duration ventilation-controlled condition.

Table 2
Scenarios Provided to Each Participant

	Fire position						
Peak HRR	1	2	3	4	5	6	
Numerical experiments							
1500 kW	120 s	120 s	120 s	120 s	N/A	120 s	Time steps
	360 s	360 s	360 s	360 s	N/A	360 s	
	900 s	900 s	900 s	900 s	N/A	900 s	
4000 kW	120 s	120 s	120 s	120 s	N/A	120 s	
	360 s	360 s	360 s	360 s	N/A	360 s	
	900 s	900 s	900 s	900 s	N/A	900 s	
Physical experiments							
ATF study		Carman & Oulette [17]					Reported accuracy 5.7%
FIODS study		Tinsley & Gorbett [19]					Reported accuracy 74%

The location and magnitude of damage for two additional physical experiments was included with the array of numerical scenarios provided to the participants. These two specific physical fire tests were included due to reported accuracy rates of professional fire investigators [17–19]. The first physical experiment provided was one conducted in 2008, in which a 5.7% accuracy rate was identified in area of origin determination based on professional fire investigators determining the quadrant of the room [17, 18]. This study will be referenced as the ATF study throughout this work. The second physical experiment included was performed in 2012, in which a 74% accuracy rate was identified in area origin determination. This study will be referenced as the FIODS study throughout this paper [19].

Varying degrees and location of damage were provided to the participants. To enable this, contour plots of damage were developed from the numerical and physical experiments.

The numerical experiments collected the total imposed heat flux for the duration of the simulation. This time integral gauge heat flux boundary file was evaluated using Smokeview. The grid of devices for each wall and ceiling surfaces were evaluated as contour plots. A normalized damage scale was provided based on the total heat fluxes identified within the compartment. This scale was normalized to the greatest total heat flux identified from all of the simulations (Figure 3). Participants in each of the four treatment groups used these contour plots of damage.

A degree of fire damage assessment was conducted on the physical experiments to develop contour plots of damage. The ATF study was prepared using the DOFD method [6]. The FIODS study was prepared based on measurements of the depth of calcination. The contour plots of damage were then prepared using the same MATLAB code as the numerical experiments. A similar damage scale as identified for the simulations was also used (Figure 3).

3.2. Development and Deployment of Data Collection Tool

To test the reliability and validity of the POD, participants (novices) were asked to complete an origin determination exercise using the data from thirty of the numerical experiments and two physical experiments. Participants were randomly assigned to each of the four treatment groups. A total of thirty-two scenarios were provided to the study participants.

A convenience sample of novices was used to assess the reliability and validity of the POD. The participants included 60 undergraduate fire protection engineering technology students with no formal training or practical experience in fire investigations. Although this was not a random sample, the participants were reasonably representative of typical novices. Participants were randomly assigned into the four treatment groups (POD with contents, POD without contents, no POD with contents, no POD without contents; 15 novices per group) and provided damage contours from each scenario. The participants were asked to first identify the center of their area of origin determination and then select the smallest area on a diagram that encompassed the total area of origin determination for each scenario.

Responses from participants were collected electronically using Qualtrics survey software [20]. This platform provided the participants with a simple method to record the center of their area of origin determination and the regions that encompassed their total area of origin determination. The participants were not able to return to a scenario once submitted. The participants were not permitted to talk to each other as they performed the study.

The participants accessed the data collection tool through a website link provided via email. The tool was designed to randomize the scenarios for each participant. This randomization of the scenarios was done to reduce the effects of sequencing from simple to more complex cases, as well as reduce any effects due to fatigue.

Participants were not aware that the data they were evaluating was from numerical simulations or physical fire tests, only that the data they were reviewing was contour plots of damage. A color-coded generic damage scale was provided with the plots representing white as less damage and black as more damage (Figure 3).

Participants in all four treatment groups were provided similar damage contour plots for the walls and ceiling; however, the damage contour plots of the contents were provided only to participants in the treatment groups with information about contents. Including availability of information about contents as a factor allows for the evaluation of a relationship between having content information and not having content information.

Instructions were provided to each participant. The instructions for participants in the treatment groups not utilizing the POD were simply that there are a total of 32-sets of images that you will be shown, please select the center of your area of origin and then select the smallest area that encompasses your area of origin determination.

The instructions for participants in the treatment groups utilizing the POD were similar, except a sentence was added to indicate that the participants were to follow the specific instructions throughout.

For all treatment groups, these instructions were followed by an image of an exploded view diagram to prepare participants for the orientation of the provided images (Figure 2). A description of an exploded view diagram was also provided with the image in order to better explain the exploded view diagram.

After reading these initial instructions and viewing the orientation of the exploded view diagram, the participants would then simply click on a forward button at the bottom of the screen and begin to evaluate each of the 32 scenarios. Sixteen of the scenarios were randomly presented to the participants. After half of the scenarios were completed, an attention-verification question was asked to ensure that participants were actively reviewing instructions and making conscious decisions rather than simply haphazardly identifying the origin center and origin regions. The attention verification question used in this study was selected as one that has been shown to ensure valid responses for online surveys [21]. Following the attention-verification question, the final sixteen scenarios were randomly presented to the participants.

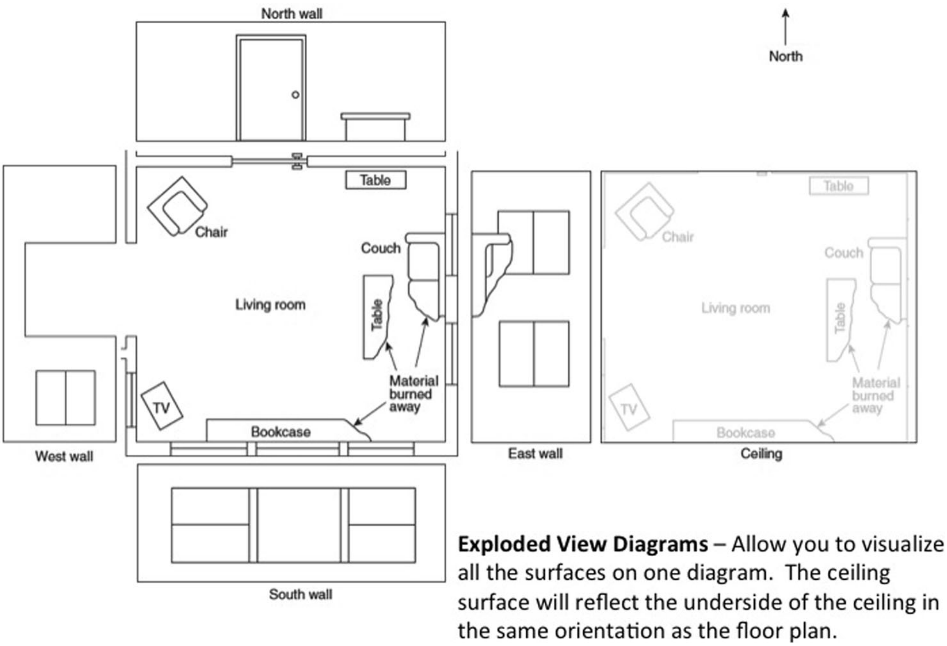


Figure 2. Exploded view diagram image and instructions provided to participants.

Two of the treatment groups were to assess the accuracy and variability of the participant responses without any process provided. This section briefly outlines the sequencing of questions provided to the participants. The complete data collection tool has been provided in previously published work [5]. One of the treatment groups was provided contour plots reflecting location and magnitude of damage to the walls and ceiling (no POD without contents) (Figure 3). The other treatment group was provided the same contour plots of the walls and ceiling with the addition of contour plots of damage to the contents of the room (no POD with contents) (Figure 4).

Participants were provided an exploded view diagram of a single compartment for each scenario (Figure 3). All participants were provided the following wall and ceiling contour plots of damage with a description that contour lines and changes in color are used to illustrate the varying degrees of damage on each ceiling and wall surfaces, and that the rectangular shapes in the diagram are combustible contents.

The participants were asked to then make two conclusions related to their area of origin determination. First, they were asked to select the center of the area of origin by clicking the mouse in that location (Figure 5). The software recorded the X- and Y-position of the click. Secondly, the participants were asked to select all the regions that encompass the smallest area of origin. The regions were rectangular grid spaces approximately the size of the combustible items within the compartment (Figure 6). The participant could select multiple regions. The software would record the region as ‘on’ or ‘off’ depending on whether the region was selected by the participant.

Participants in the treatment groups utilizing the POD were used to assess the accuracy and variability with a provided process (POD). The sequencing and layout of the questions provided to the participants using the POD will be described here. One of the treatment groups was provided contour plots reflecting location and magnitude of damage to the walls and ceiling, numbered and labeled fire patterns, a table identifying the generation for each fire pattern, and contour plots of damage to the contents (POD with contents). The other treatment group was provided the same contour plots of the walls and ceiling, labeled and numbered fire patterns, and table listing the fire pattern generation, however, this group was not provided contour plots of damage to the contents of the room (POD without contents).

Each participant was instructed to follow the provided guidelines in order to determine the area of origin. Again participants were provided with exploded view diagrams with contour plots depicting damage to the walls and ceiling; however, the participants utilizing the POD were provided with dashed lines outlining areas along the contour plots that were labeled and sequentially numbered as fire patterns. A table was also provided within this diagram that identified the most likely

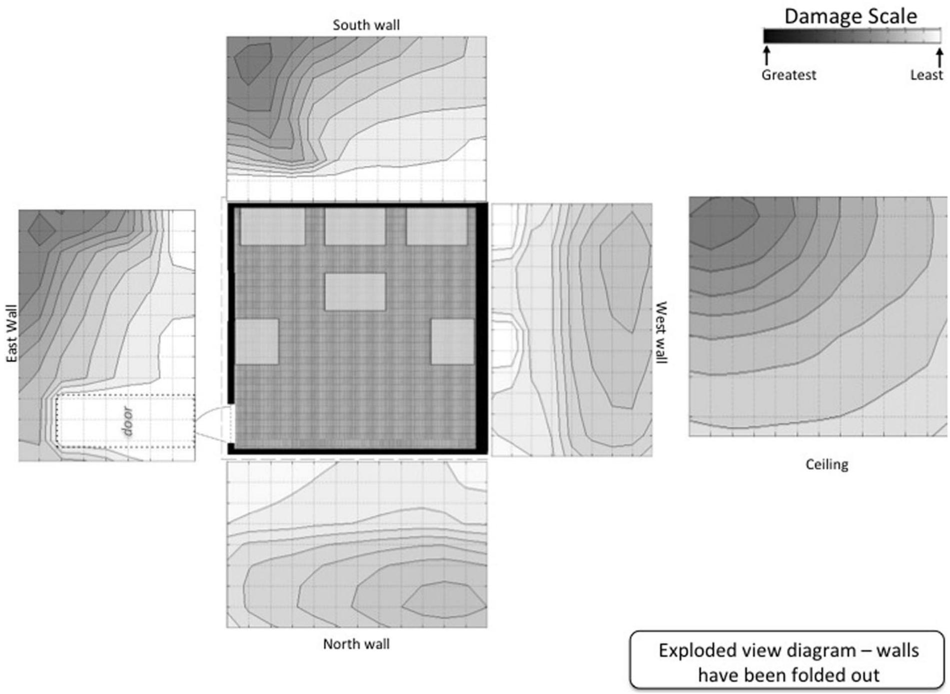


Figure 3. Exploded view diagram with contour plots of damage to walls and ceiling with damage scale.

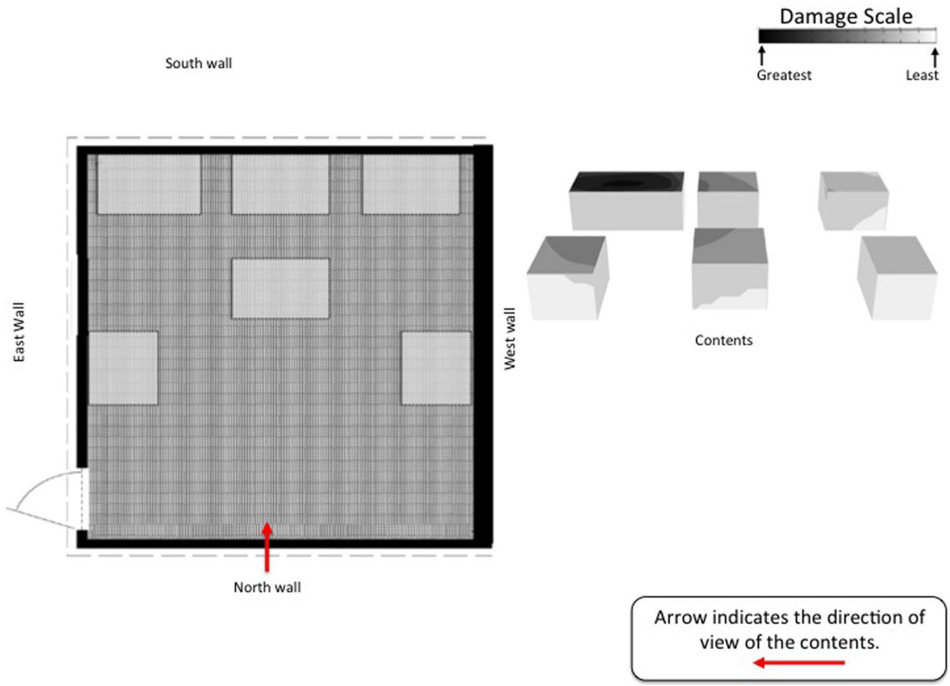


Figure 4. Contour plots of damage to contents.

generation or cause for the fire pattern (Figure 7). The options for fire pattern generation included upper layer generated, ventilation generated, plume generated, or undetermined. The instructions provided to the participant for this step were as follows:

> Fire Patterns Numbered & Their Identified Cause
> Below are exploded view diagrams of a single compartment. The boundary of each fire pattern has been noted on the diagram by a dashed-line. Each fire pattern identified within this scenario has already been identified and provided a number (FP#1 = Fire Pattern #1). In the bottom-right corner of the image each fire pattern is assigned a cause for that pattern (fire pattern generation). The options for generation include upper layer generated, plume generated, ventilation generated, or undetermined. Particular attention should be given to those patterns identified as PLUME or UNDETERMINED generation, as these will assist in determining the area of origin. The rectangular shapes in the diagram are combustible contents.

Each participant was then instructed to identify the center of their area of origin determination by clicking on a diagram (Figure 5). However, the instructions for participants in the treatment groups using the POD explicitly instructed that

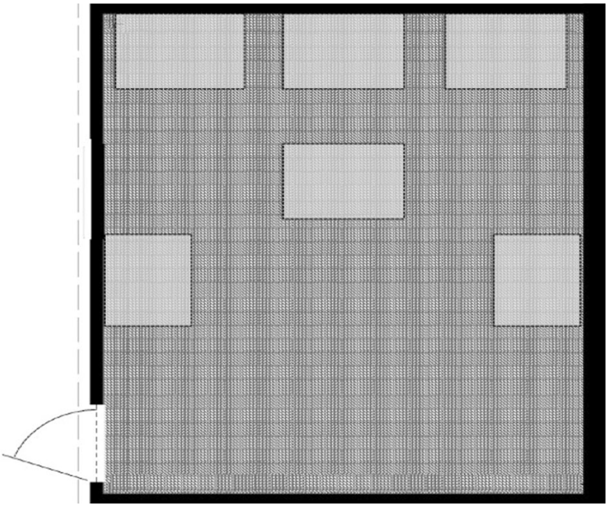


Figure 5. Diagram for center of area of origin determination.

only identified plume generated and undetermined fire patterns were to be considered as the area of origin.

The participants were then instructed to identify all the regions that encompass the smallest area of origin (Figure 6); however, participants were instructed that the fire patterns that were classified as undetermined and plume generated would be considered as the area of origin and that the participant would have to select all the regions that included these fire patterns.

3.3. *Statistical Analysis*

The two measures used to assess the POD were validity and reliability. For the purposes of this dissertation, reliability is defined as "the same results are obtained in each instance the test procedure is being performed—its consistency" and validity is defined as "the ability of a test procedure to measure what it is supposed to measure—its accuracy" [22].

Reliability was evaluated by examining the consistency of participants arriving at the same determination for location of the true origin. The distances between the X- and Y-coordinate selected by the participants as location of origin and the true origin was calculated for each of the 32 scenarios. While this measure does not incorporate directionality, we can conclude that the POD group is more consistent in their selection of origin if the variability of the distances is smaller for the participants utilizing the POD compared to those using no process. Further, the POD was a more reliable method of determining the origin.

Validity was evaluated by assessing accuracy of origin among the participants. Accuracy was defined as both true accuracy and accuracy according to the POD. Accuracy was measured using the X- and Y-coordinates of the center of origin and using the origin regions. In some of the scenarios, use of the POD could lead

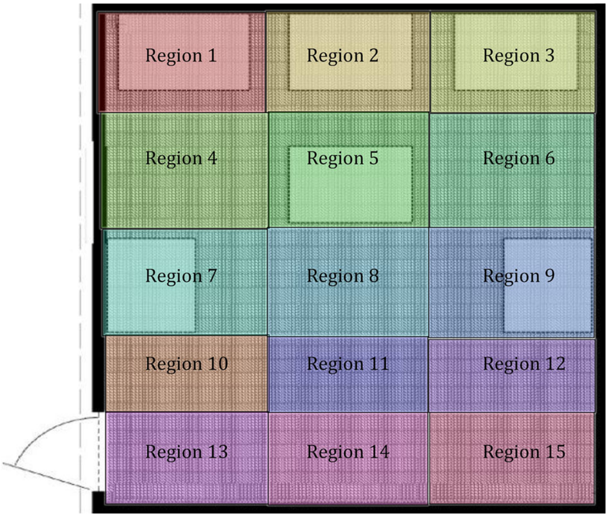
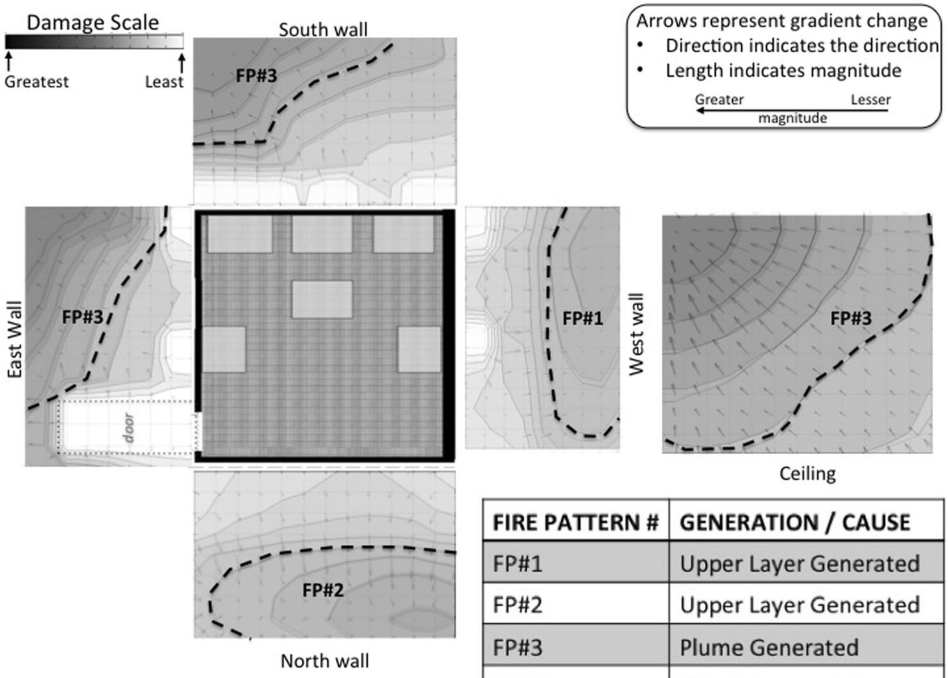


Figure 6. Regions to be selected for area of origin determination.



FIRE PATTERN #	GENERATION / CAUSE
FP#1	Upper Layer Generated
FP#2	Upper Layer Generated
FP#3	Plume Generated
FP#4	Plume Generated

Figure 7. Contour plots with identified fire patterns and fire pattern generation (fire position #1).

Table 3
Reliability Measures: Overall Variability Change and Test for Equality of Variances

	Number of scenarios	Total scenarios	%
Overall variability change			
Decreasing variability w/POD	21	32	66
Increasing variability w/POD	11	32	34

	Without POD	With POD
Test for equality of variances		
Mean (μ) distance from true origin	105.46	86.93
Standard deviation (σ)	10.81	10.58
Median distance from true origin	105.79	88.98

to the origin being defined as the whole room; in that case, the center of the room would be the center of origin and all regions would be selected as origin regions. It is of note that in some cases, true region accuracy (the region that encompassed the origin) is easier to achieve than method region accuracy. For true region accuracy, a participant would only need to select the correct origin region (e.g., Region 1), while for method accuracy they would need to select all of the correct origin regions (e.g., all regions if the POD led to origin center at the center of the room).

The true origin was considered as the combustible item. Therefore, the center point for each combustible item was selected as the true origin center. In the case that the method led to the origin at the center of the room, the coordinates for the center of the room were selected as the method origin center. For each scenario, the participant's identified center of origin was considered accurate if it was contained in a circle with radius 45 pixels (diameter of 90) around the true origin center. A bivariate analysis was performed to compare accuracy between those utilizing the POD and those using no process. The Chi Square Test of Independence was not appropriate in this study as the small sample size could lead to contingency table expected cell counts of less than five. Appropriateness of sample size was confirmed through using Fisher's Exact Test of Independence [23]. Fisher's Exact Test of Independence is more accurate than the Chi Square Test when expected values are small and it is the appropriate bivariate analysis method when both variables are nominal (accurate vs. not accurate, POD vs. no process). Fisher's Exact Test will be used for comparison of accuracy between groups with a significance level of $\alpha = 0.05$ throughout. A higher proportion of participants utilizing the POD accurately identifying origin center compared to those using no process indicates the validity of the POD. Additionally, the sample distribution was evaluated for normal distribution. In the event that the distribution does not follow a normal distribution, a nonparametric test was used [24].

The true region of origin contains the combustible item. For each scenario, a participant's region of origin was considered accurate if they selected the region containing the combustible item. Both true region accuracy and method region accuracy were compared between those utilizing the POD and those using no process with Fisher's Exact Test. Similar to center of origin, a higher proportion of participants utilizing the POD accurately identifying origin region compared to those using no process indicates the validity of the POD.

3.4. Limitations

Due to the large frequency of images the participants were asked to assess, participant fatigue was a potential limitation. However, the time to completion was estimated to be no more than thirty minutes and the order in which scenarios were presented was randomized.

In practice, the information required for each step would have to be collected by the investigator. While a significant component of the POD, most of that information was provided to participants utilizing the process in this study. If accuracy rates are higher for those participants compared to participants using no method, this is most likely a result of following the steps outlined in the process rather than differences in ability to collect the information required for each step. This aspect of the study design allowed for a direct evaluation of the POD.

This process did not evaluate the third dimension to the origin determination; elevation of fire base was not asked of the participants. Additionally, participants were not permitted to select multiple origins.

4. Results and Discussion

This section has been organized into reliability results and validation results. The results for each measure will be described below with a focus on the change related to the use of the POD.

4.1. Reliability Results

The reliability measure examined the consistency of participants arriving at the same determination for location of the true origin. The distances between the X- and Y-coordinate selected by the participants as location of origin and the true coordinate for origin was calculated for each of the 32 scenarios. While this measure does not incorporate directionality, we can conclude that the POD group is more consistent in their selection of origin if the variability of the distances is smaller for the participants utilizing the POD compared to those using no POD.

The variance (σ^2) provides a good measure for comparing the reliability of the POD in comparison to those that did not use the POD. The variance of the given answers by the participants without the POD was compared to the variance with the participants using the POD. The variability in distances was compared from the participants' selected center of origin and the true center of origin to determine if those using the POD are answering "closer together." A decrease in variability was seen at the individual scenarios level in 21 of the 32 scenarios (66%), the variability in those distances was smaller for those using the POD than those not using the POD (Table 3). There were 19 of 30 simulation scenarios (63%) that demonstrated less variability when using the POD and both physical experiments had a decrease in variability when the POD was used [5].

Another method to evaluate the reliability of the POD was accomplished through plotting each answer set as a scatter plot, finding the centroid of that answer set, calculating the distance from that centroid to all answers, and then calculating the 95% confidence interval of the answer set. The centroid, or the geometric center of the data, was calculated for the answer sets for each scenario without the POD and with the POD. The distance between each X- and Y-coordinate selected by a participant as the center point of his or her area of origin was then calculated from this centroid coordinate. From this, a 95% confidence interval distance was calculated and used as the diameter of an ellipse that centered on the centroid for the answer set. If the diameter of the ellipse is smaller when using the POD, then it can be concluded that the answers were more consistent and therefore more reliable with the use of the POD [5].

An example of this comparison has been provided for fire position 1 at 4 MW, 900 s (Figure 8). The coordinate for the true origin point was also plotted. The closer the centroid was to the true origin coordinates, the more accurate the answer set was, which indicates validity of the POD. The figures illustrate two data sets (1) without POD and (2) with POD, two ellipses each with a diameter based on the 95% confidence interval for the distances for each data set, centroid for both data sets, and the true center point. Evaluating the diameter of the ellipses can assess reliability. The dashed line ellipse illustrates the 95% confidence interval distance diameter for the answer set without the POD, while the solid line ellipse illustrates the 95% confidence interval distance diameter for the answer set with the POD. The blue dots represent the answers from participants without the POD, green asterisks represent the answers from participants with the POD, the blue square indicates the centroid of the data set without POD, the black square indicates the centroid of the data set with the POD, and the red square indicates the true origin point (Figure 8).

As confirmation to the variance results from above, 21 of 32 (66%) scenarios had a smaller diameter ellipse for the answers using the POD. A total of 24 of the 32 (75%) scenarios had their centroid closer to the true center when using the POD, which is discussed in greater detail in Sect. 4.2 of this paper. Of those 11 scenarios where the POD results were not as consistent (i.e. larger diameter and larger variance), the centroid was closer to the true center with using the POD.

The greatest variability was consistently observed with the higher heat release rate simulations at the longer durations. This was expected based on previous review of the literature. Interestingly, four of the eleven that demonstrated greater variability was found with fire position 4 (center of the room fire).

4.2. Validity Results

The validation studies were purposefully setup to evaluate the question for validity at varying levels. The first level was to evaluate whether the participants accurately identified the region that was the true area of origin. Next, the validation question evaluated whether or not the participants chose the correct region(s) reflected by the POD (method). Finally, the validation question evaluated whether the center point identified by the participants were within the established area of origin and the influence of the POD on distance away from the origin.

The first validation test evaluated which region(s) the participants selected as their area of origin (Figure 6). The participant was classified as accurate if they selected the region that reflected the region identified as the true origin. A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 19 out of 32 scenarios (59%), a decrease in accuracy when using the POD in only 6 out of 32 (19%), and no change in accuracy when using the POD in 7 out of 32 scenarios (22%) (Table 4). None of the six scenarios that decreased in accuracy when using the POD were shown to be statistically signifi-

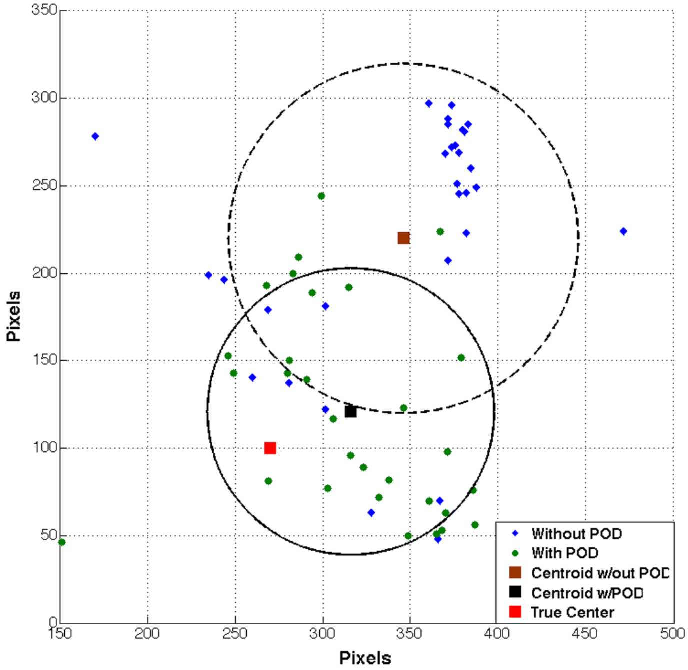


Figure 8. Scatterplot of answer sets with centroids identified (solid line is ellipse for answer set using POD, dashed line is ellipse for answer set without POD)-Fire Position #1 4 MW, 900 s (units are in Pixels).

Table 4
Validation Results: Comparison of Region Accuracy

	Number of scenarios	Total scenarios	%
Overall comparison of region accuracy rates without and with the POD			
Increasing accuracy with the method	19	32	59
No change in accuracy	7	32	22
Decreasing accuracy with method	6	32	19

	# Showing significant increase	Total increasing scenarios	%
Statistical significance evaluation			
Statistically significant increase (alpha = .05)	6	19	32

	Without POD	With POD
Test for overall significance		
Mean (μ) accuracy rate	0.83	0.92
Standard deviation (σ)	0.12	0.14
Median accuracy rates	0.78	0.97
Independent samples t test to compare means	t = 2.74	p = .01
Wilcoxon two-sample test to compare medians	z = 3.48	p = 0.001

cant. It was found that 6 out of the 19 scenarios (32%) that were shown to increase in accuracy when using the POD were statistically significant (Table 4). The nonparametric Wilcoxon test is a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed [24]. Overall there is a statistically significant increase in accuracy rates for the true origin region when the POD was used (z = 3.48, p = 0.001) (Table 4).

The general trend with the simulation data was a decrease in accuracy with the higher heat release rates and longer duration simulations (Figure 9). Fire position 4 (center of the room fire) had the lowest accuracy rates of any of the simulations, however, the most significant increases in accuracy were demonstrated when the POD was used at this fire position. Both of the physical experiments had a statistically significant increase ($p < 0.05$) in accuracy when using the POD (Figure 9).

A potential limitation with these results comes from the imposed definition of accuracy. A participant was classified as accurate when the region identified as the true region was selected, regardless of the number of regions selected by the participant. This potentially allows for an artificially high accuracy rate should the participant select all of the regions for all scenarios. Each scenario was evaluated to identify what percentage of participants selected each region with and without the POD to examine this possibility. It was found that the majority of the scenarios had greater percentage of participants selecting the true region of origin, followed by a slight decrease in percentages of participants selecting 1–2 adjacent regions around the true origin, and then a consistent decrease in percentages and number of regions selected moving away from the true origin. Many of the sce-

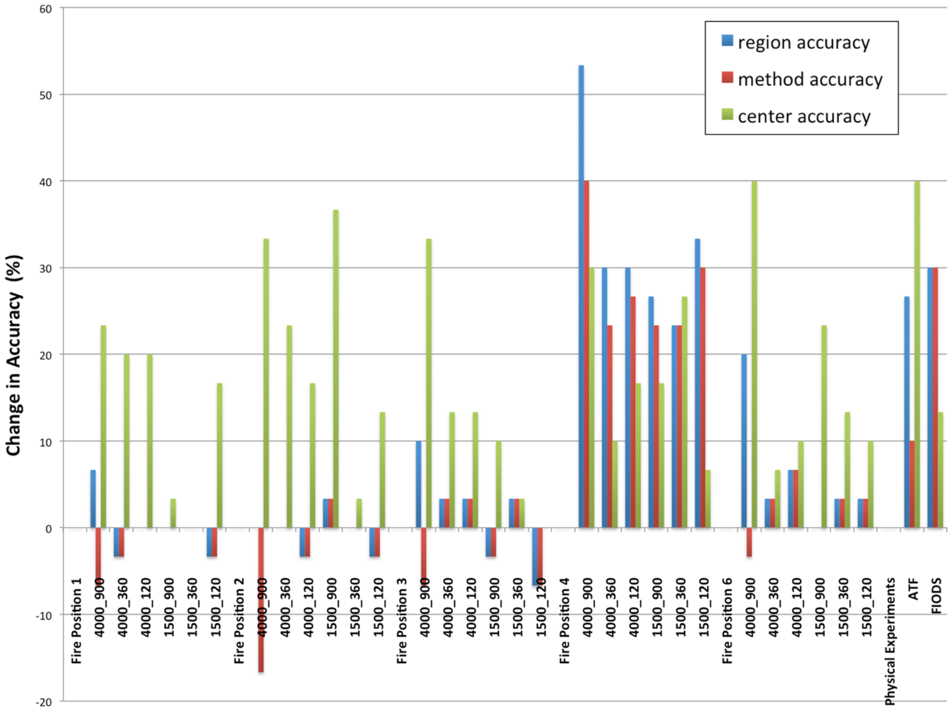


Figure 9. Change in accuracy for all 32 scenarios when using the POD for all validation measures.

narios had several regions not selected by any of the participants, which is evidence that an artificially high accuracy rate was not influenced by random selection of all regions.

The next validation test evaluated which region(s) the participants selected as their area of origin in comparison to what regions should have been selected as identified by accurate use of the POD. This evaluation is referred to as method accuracy. The participant's selection was classified as accurate if they selected the exact region(s) that reflected the region(s) identified as the area of origin from the POD. A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 16 out of 32 scenarios (50%), a decrease in accuracy when using the POD in 10 out of 32 (31%), and no change in accuracy when using the POD in 6 out of 32 scenarios (19%) (Table 5). None of the ten scenarios that decreased in accuracy when using the POD were shown to be statistically significant. It was found that 3 out of the 16 scenarios (19%) that were shown to increase in accuracy when using the POD were statistically significant (Table 5). Again, the nonparametric Wilcoxon test was found to be a more appropriate test for evaluating overall statistical significance, as these accuracy rates were not normally distributed [24]. Overall there is a statistically significant increase in accuracy rates for identifying the method regions when the POD was used (z = 2.11, p = 0.04) (Table 5).

The general trend with this analysis was that the accuracy decreased for those simulations that had higher heat release rates and longer durations. Fire position 4 had the lowest accuracy rates, however, it had the most significant increases in accuracy when the POD was used. Both of the physical experiments increased in accuracy with the use of the POD. The FIODS study had a statistically significant increase ($p < 0.05$) in accuracy when using the POD (Figure 9).

There are two ways to evaluate accuracy using the X- and Y-coordinates of the center of the origin. The first method to evaluate accuracy using the X- and Y-coordinates is to evaluate whether or not the participant coordinates fell within the prescribed area of origin. For each scenario, the participant's identified center of origin was considered accurate if it was contained in a circle with radius 45 pixels (diameter of 90) around the true origin center (Figure 9). A comparison between the accuracy rate without the POD and with the POD was conducted for each scenario. There was an increase in accuracy when participants used the POD in 30 out of 32 scenarios (94%), a decrease in accuracy when using the POD in 0 out of 32 (0%), and no change in accuracy when using the POD in 2 out of 32 scenarios (6%) (Table 6). It was found that 7 out of the 30 scenarios (23%) that were shown to increase in accuracy when using the POD were statistically significant (Table 6). The nonparametric Wilcoxon test was again a more appropriate test for

Table 5
Validation Results: Comparison of Method Accuracy

	Number of scenarios	Total scenarios	%
Overall comparison of method accuracy rates without and with the POD			
Increasing accuracy with the method	16	32	50
No change in accuracy	6	32	19
Decreasing accuracy with method	10	32	31
	# Showing significant increase	Total increasing scenarios	%
Statistical significance evaluation			
Statistically significant increase (alpha = .05)	3	16	19
		Without POD	With POD
Test for overall significance			
Mean (μ) accuracy rate		0.83	0.89
Standard deviation (σ)		0.12	0.14
Median accuracy rates		0.78	0.94
Independent samples t-test to compare means		t = 1.71	p = .1
Wilcoxon two-sample test to compare medians		z = 2.11	p = 0.04

evaluating overall statistical significance, as these accuracy rates were not normally distributed [24]. Overall there is a statistically significant increase in accuracy rates for the center point when the POD was used ($z = 4.74$, $p < 0.0001$) (Table 6).

The accuracy rates for this validity test were lower than those of previous validity studies, most likely due to the definition of accuracy being more difficult to achieve. The general trend was consistent with the other validity studies demonstrating lower accuracy rates for the higher heat release rates and longer duration simulations. Again, fire position 4 had the lowest accuracy rates. Both of the physical experiments increased in accuracy with the use of the POD. The ATF study had a statistically significant increase ($p < 0.001$) in accuracy when using the POD (Figure 9).

The second validation test evaluated the distance between the centroid for the answer sets with the POD and without the POD as compared to the X- and Y-coordinate of the true origin (Figures 10, 11). This test illustrated that 24 out of 32 (75%) of the scenarios where the POD was used resulted in a centroid closer to the true origin (Figures 10, 11). The change of distance towards the true origin point was also plotted to illustrate the actual distance, positive indicating towards the true origin and negative indicating movement away from the true origin. Out of the 32 scenarios, 24 scenarios (75%) indicated movement towards the true origin, while 8 (25%) indicated movement away from the true origin [5].

A threshold of 11 cm was identified as being a significant change in distance moved by the centroid of the answer set. The 11 cm threshold represented the cell

Table 6
Validation Results: Comparison of Center Point Accuracy

	Number of scenarios	Total scenarios	%
Overall comparison of center point accuracy rates without and with POD			
Increasing accuracy with the method	30	32	94
No change in accuracy	2	32	6
Decreasing accuracy with method	0	32	0

	# Showing significant increase	Total increasing scenarios	%
Statistical significance evaluation			
Statistically significant increase (alpha = .05)	7	30	23

	Without POD	With POD
Test for overall significance		
Mean (μ) accuracy rate	0.49	0.66
Standard deviation (σ)	0.11	0.11
Median accuracy rates	0.50	0.66
Independent samples t-test to compare means	$t = 6.00$	$p < 0.0001$
Wilcoxon two-sample test to compare medians	$z = 4.74$	$p < 0.0001$

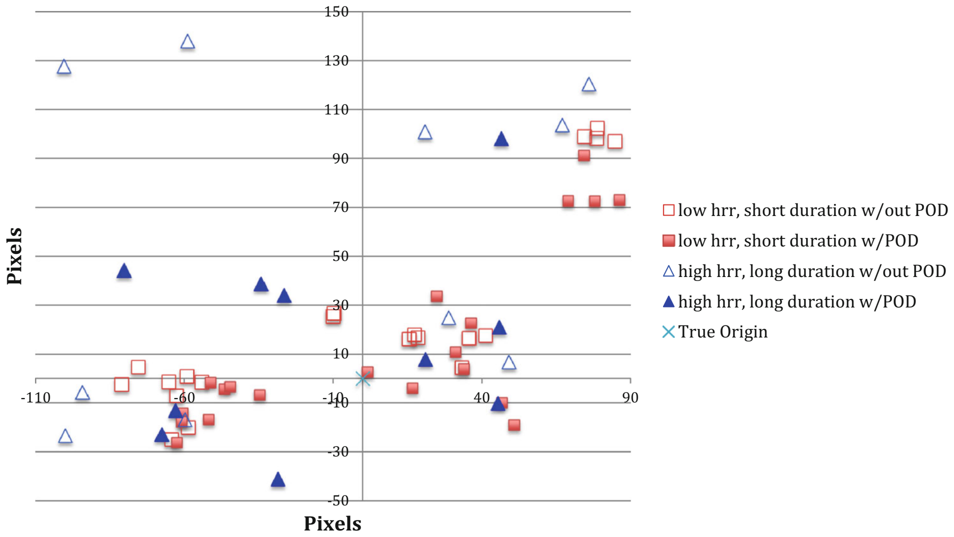


Figure 10. Centroid locations distinguishing between low HRR, shorter duration and high HRR, longer duration scenarios for all fire positions (Note: The plot has been color-coded to easily distinguish between without and with the POD).

size for the FDS simulations. This was chosen, as it is a fraction of D* and essentially represents the resolution of the numerical experiments. Mesh resolution was determined using the non-dimensional expression D*/dx, where D* is a characteristic fire diameter and dx is the nominal size of a mesh cell [25]. D* for the 1.5 MW fires was calculated to be 1.128 with a D*/dx of 10 or approximately 11.28 cm, while the D* for the 4 MW fire was calculated to be 1.67 with a D*/dx of 16 or approximately 10.44 cm. The attempt with the simulations was to maintain the non-dimensional ratio of D*/dx to ensure that the fire resolution of the modeling simulations were similar. Using this threshold for significance, it was found that 21 out of 32 (~66%) scenarios had moved meaningful distances towards the origin, while 6 out of the 32 (18%) scenarios had moved meaningful distances away from the origin.

All centroid locations have been plotted for all fire positions for the simulations centered on (0,0) as the true origin (Figure 10). The centroid locations for the higher HRR, longer duration simulations can be compared to the lower HRR, shorter duration simulations for each fire position without and with the POD (Figure 10). In comparison, the higher HRR, longer durations were significantly greater in distances away from the true origin and were spread out further, indicating less reliability and validity. Finally, the centroid locations for the physical experiments have been plotted together and illustrate movement towards accuracy with the use of the POD (Figure 11).

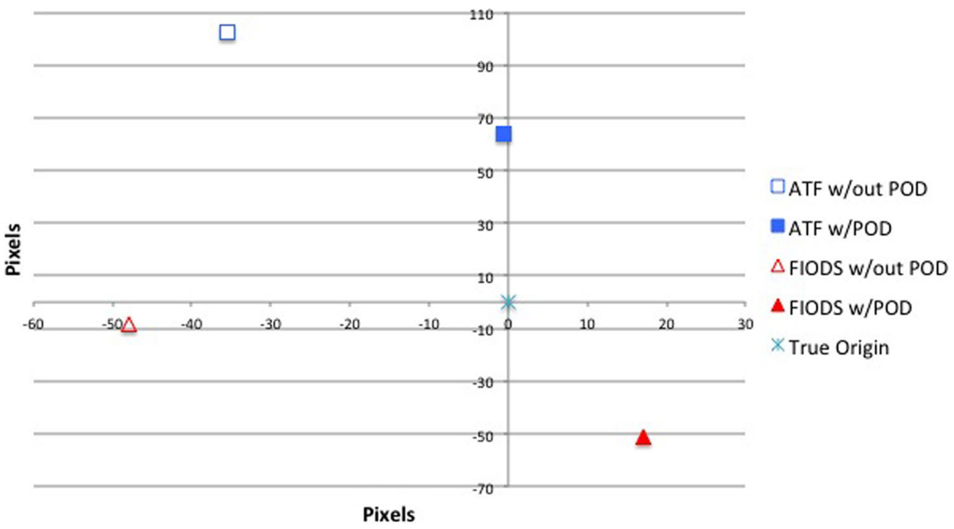


Figure 11. Comparison of centroid locations for physical experiments without and with the POD.

4.3. Evaluation of the Effects of Using Contents

Estimates evaluating the consequences of using content data versus not using content data were found to be unstable. The stratified analysis on contents versus no contents led to small sample sizes ($n = 15$), which could give results more likely to be inconclusive, statistically insignificant, and strongly influenced by outliers. After further review in evaluating this question, it was also determined that the value placed on this analysis would be small if any due to the lack of directions within the proposed process on how to account for the content data. This is an area proposed for future research.

5. Conclusions

It has been shown through the use of reliability and validity tests that the proposed POD assisted decision makers in more consistently and more accurately determining the area of origin for a fire over a variety of scenarios.

5.1. Simulations

It was illustrated that the higher heat release rate, longer duration simulations consistently had lower accuracy rates and greater variability in answers both without and with the POD. This was expected based on a review of the literature. Remarkably, however, the greatest improvement in accuracy with the POD was demonstrated under these higher HRR, longer duration scenarios. This indicates that when participants use a systematic approach, their performance will improve significantly under the more difficult scenarios.

One of the most important aspects in evaluating origin determination is the ability for a decision maker to narrow the area of origin to the smallest area that still encompasses the true origin. This narrowing down to a smaller area, ultimately limits the area that requires in depth analysis for potential ignition sources. Therefore, the most important measures evaluated in this study were the ability of the decision maker to identify an area that encompassed the true region of origin. The POD performed statistically significantly better at identifying the true region of origin and the center point of origin. In addition to this, the POD illustrated lower variability across regions selected by the participants, which indicates that the decision maker was able to narrow their focus more when using the POD. In each of the scenarios where variability stayed approximately the same or increased, a handful of significant outliers were identified. Despite these outliers, the vast majority of the answers were identified as moving closer to the true origin. Some areas that may require further evaluation in these regards are refining the POD instructions and training on the use of the POD. It may also indicate that the decision maker should increase their hypothetical area of origin to encompass the entire compartment when higher HRR, longer duration fires are being investigated due to the increase in uncertainty.

The greatest variability and lowest accuracy rates with the simulations was found to be fire position 4 (center of the room fire). This was also expected due to the lack of any wall surface near the origin to clearly characterize the plume-generated fire pattern associated with a possible origin. Additionally, the region for fire position four was not as clearly delineated as that for the other fire positions, which could have attributed to the greater variability in region selection. The use of the POD for this scenario did show a significant increase in accuracy and decrease in variability with the answers provided, which indicates that the POD assists the decision maker under this more difficult scenario.

5.2. *Physical Experiments*

The FIODS study reports an accuracy rate for approximately 600 professional fire investigators to be around 77% [19]. The variability decreased significantly when the POD was used in the FIODS scenario (Figure 11). The accuracy measures indicated that the participants without the POD were approximately 53%, but was increased to 83% when the participants used the POD.

The ATF study [17–19] reported an accuracy rate for selecting the quadrant of the room for approximately 60 professional fire investigators to be 5.7%. The accuracy measures indicated that the participants without the POD were approximately 6% accurate, but increased to 93% when the POD was used. The variability also decreased when the participants used the POD (Figure 11).

The accuracy and reliability for the participants when applying the POD to physical experiments was consistently demonstrated to increase in accuracy and decrease in variability with the use of the POD. Both physical experiments evaluated indicated similar accuracy rates to the reported literature when the novices did not use the POD. However, when novices used the POD, they achieved higher accuracy rates than the professional fire investigators given the same scenario.

5.3. Practical Implications

Origin determination through the use of fire damage involves a complex reasoning process, which can have significant uncertainty, consisting of a series of sub-processes that need to be coordinated and analyzed during a fire investigation. It is a gross oversimplification to state that the scientific method, by itself, provides the necessary guidelines to assist an investigator in determining the origin of a fire. This is especially true when qualitative analyses and potential biases can potentially influence the decision maker. Specific processes must be developed and tested for reliability and validity as outlined by the NAS recommendations [4]. The POD was developed to serve as a starting point to meet this requirement.

The POD simply identifies a systematic approach where many of the steps use well-accepted knowledge within the profession to illustrate the effectiveness of methodically evaluating damage in the context of the compartment fire dynamics. The POD assists the decision maker by removing much of the potential bias and qualitative interpretation, as well as providing a means of treating the associated uncertainty. Reliability and validity testing of the POD illustrates its effectiveness to bring novices to greater levels of accuracy in comparison to the professional fire investigation community. This research illustrates that anyone can use the POD and apply these seven steps with this knowledge and arrive at a better outcome. Thus, illustrating the effectiveness of the POD to satisfy much of the requirements identified in the NAS report [4].

Frequently, the overall goal of fire identification is to determine the cause of the fire. It is axiomatic that in order to find the actual cause, an accurate area of origin is required. Therefore, improving the area of origin determination should improve the ultimate cause determination.

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