SCIENTIFIC METHOD-USE, APPLICATION, AND GAP ANALYSIS FOR ORIGIN DETERMINATION

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ABSTRACT

The fire investigation industry is considered to be lagging behind the rest of the forensic science fields in its assessment of the performance of methodological approaches and conclusions drawn by practitioners within the field. Despite the best efforts of certifying bodies and industry members, there are still many unknowns within the profession. This paper will present practical uses of the scientific method as it relates to Origin Determination. Several recommended practices have been identified and formatted to reflect the scientific method as utilized in NFPA 921. In addition, where practical, a gap analysis has been conducted on these processes with recommendations provided.

INTRODUCTION

Both NFPA 921 *Guide for Fire and Explosion Investigations* and NFPA 1033 *Standard for Professional Qualifications for Fire Investigator* clearly identify the scientific method (SM) as *the* methodology for investigating fire and explosion incidents. In a recent survey of approximately 600 professional fire investigators, it was shown that 74% and 77% of participants believe that NFPA 921 and 1033, respectively, are considered as authoritative for the fire investigation profession.[1] Most fire investigators identify that they are aware that the scientific method is to be used when analyzing fire and explosion incidents.[1] However, a quick review of work product, case studies, and sworn testimony illustrates that many fire investigators may state that they use the scientific method when in fact they do not.[2] The work product should reflect the SM used for each of the processes.

Despite most of the profession agreeing that the SM is the appropriate methodology for fire investigations, some have argued that fire investigators do not or should not use the SM. This argument states that fire investigations should use abductive inference instead.[3] These same individuals argue that abductive inference is a separate and distinct methodology than the SM. In support of this, some fire investigation textbooks have identified abductive reasoning as an alternative to the SM.[4] Performing a literature review of abductive inference and comparing this reasoning style to fire investigations, it appears that these researchers may be accurate in that the fire investigation profession, similar to the medical diagnosis professions, has a strong foundation on abductive reasoning.[5,6,7,8] However, the literature review also demonstrates that abduction is an inherent and necessary part of the SM.[9] The literature on scientific reasoning argues that the theory generation phase of the SM is a necessary element for all sciences outside of the hard sciences and abductive inference is needed.[10]

Table 1: Modes of Reasoning[11]

Deductive reasoning	Reasoning begins with a general rule and proceeds to a specific conclusion.
Inductive reasoning	Reasoning that begins with observations that are specific and limited in scope and proceeds to a generalized conclusion that is likely regarding the accumulated evidence.
Abductive reasoning	Reasoning begins with an incomplete set of observations and proceeds to the likeliest possible explanation for the set

A recent study argues that abductive inference works best only if regulative constraints enable us to view "abduction as a pattern of inference, not just to any explanations, *but to the most plausible explanations. Constraints that regulate the abductive generation of scientific theories will comprise a host of heuristics, rules, and principles having to do with the explanation of the phenomena*".[12] Fire investigation textbooks and authoritative treatises are greatly lacking in the area of how to infer accurately with the provided data. Some published work argues that fire investigators must become good 'critical thinkers' to solve this problem of applying the SM accurately.[13,14] However, these studies do not provide methods on how to employ critical thinking skills to improve conclusions drawn by the fire investigator.

It is clear that the scientific method is much more involved than the 7 steps listed in the process. A question then becomes who or what is guiding the process of inference. Fire investigators need processes in place that assist in collecting data, analyzing the data, developing hypotheses, testing these hypotheses, and selecting a final hypothesis. As established above, the proper use of the SM requires the development of processes, heuristics, or decision tools that assist an investigator through their determination and to establish bounds where specific conclusions can be reached based on explicit processes identified. While NFPA 921 designates that the SM is the general methodology for fire investigations, it does not outline processes that can be used to guide fire investigators through the use of theSM and those critical thinking components. NFPA 921 and other fire investigation textbooks provide a few examples, but fail to identify individual processes.

Developing explicit processes to apply within the SM brings about a whole series of issues that also need to be addressed. First, the profession will need to develop these processes. Once developed, these processes will need to be tested for their reliability, validity, and thresholds for application. Finally, the user of these processes will then need to be evaluated to determine if that person is capable of using the method to arrive at the accurate conclusion (e.g. proficiency testing).

This paper will first identify those processes currently available within the context of how to apply them within the SM. Next, each process will be evaluated for whether or not the process is reliable, valid, and whether it has been shown or can be evaluated for proficiency testing. A gap assessment will be conducted from this analysis and provided. Finally, recommendations are provided and conclusions are given.

BACKGROUND

The National Academy of Science issued a report where they critically reviewed the forensic sciences within the United States and made recommendations to help move the profession forward.[15] Many of these recommendations revolved around the use of the SM 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. The following excerpt from the NAS report further verifies NFPA 921's stance that the SM is the appropriate methodology:

> Adherence to scientific principles is important because they enable the reliable inference of knowledge from uncertain information – exactly the challenge faced by forensic scientists. Thus, the reliability of forensic science methods is greatly enhanced when those principles are followed...the law's admission of and reliance on forensic evidence depends critically on (1) the extent to which a forensic science discipline is founded on a reliable *scientific methodology*, leading to accurate analyses of evidence and proper reports of findings and (2) the extent to which practitioners in those forensic science disciplines that rely on human interpretation *adopt procedures and performance standards* that guard against bias and error.[16]

The NAS report also calls for the development of processes for those forensic science disciplines where practitioners rely heavily on human interpretation, and that those processes should be tested for reliability and validity. This section defines reliability, validity, and proficiency testing, as well as discusses what testing has been published in the fire investigation literature regarding these concerns.

The terms reliability and validity are defined in a variety of ways within the literature. For purposes of this paper, 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".[17] For example, if a process is developed to identify arc sites then that process should be evaluated through a series of tests. First, the process should be evaluated for its reliability, or consistency, at arriving at a similar conclusion given the same data. This reliability testing should be performed for a single user when tested multiple times and between multiple users when given the same test (test-retest reliability and inter-rater reliability). Using the arc site identification example, the first test would be to see if a user was able to consistently identify the sites as arcs and distinguish the damage that is not an arc site (i.e. melting, alloying). Next, the process would be given to multiple users to see if the users were consistent in identifying similar sites as arcs. Out of this testing, bounds or thresholds associated with when and what conditions increased or decreased the reliability should be identified (i.e. burning conditions).

Next, the process should be tested to ensure its validity. This would evaluate as to whether or not the identified arc sites were actually arc sites. Again, bounds or thresholds should be established from this testing as to what conditions influenced the accuracy in arc site identification.

Finally, users should demonstrate their ability to employ this process in a scenario through proficiency testing. Technical professions use proficiency testing as an approach to enhance the quality of performance and as a measure to identify where improvement may be needed. Typically proficiency testing within the forensic sciences is tied to accreditation of laboratories.[18] However, many have identified proficiency testing as a requirement for crime scene examiners as well, "crime scene examination is pivotal to all forensic examination. Many criminal cases have demonstrated that the examination and analyses that follow any crime scene examination cannot be corrected in the laboratory if inadequate, incorrect or poorly performed procedures are adopted at the scene".[19,20] The use of proficiency testing in combination with training programs has been shown to be effective for crime scene examiners when used within a complimentary system (figure 1). Doctors and nurses employ proficiency testing within the laboratory and in the processes of obtaining medical diagnoses.[21]
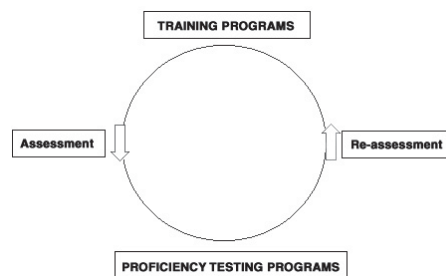
Figure 1: Diagram showing a complimentary system of training and proficiency testing[22]

The first attempt at proficiency testing for fire investigations was from three exercises (performed in 2005 and 2008) completed in conjunction with a training seminar to analyze burn pattern development in post-flashover fires.[23,24] These exercises focused on the impact of ventilation on fire patterns and the ability of fire investigators to use fire patterns to determine the area of origin. The room was divided into four quadrants and the participants were asked to identify the quadrant in which they believed the fire

originated based on visual identification alone. The study reports a 5.7% accuracy rate in attendees determining the correct quadrant of origin. Neither exercise provided the demographics of the attendees, nor does the author imply that the exercise can stand up to any statistical rigor. Nevertheless, Carman attributed the failure to the lack of understanding by the investigation profession of the differences between pre- and post-flashover fire behavior.

Another attempt at proficiency testing was performed in 2012. A survey was published where researchers collected demographics of approximately 600 professional fire investigators and compared these demographics to data regarding area of origin determination both with and without measurable data (depth of char, calcination) to evaluate its effectiveness when applied without an on-site scene examination.[25] This permitted the comparison of the demographics and accuracy in determining the area of origin. It was shown that 73.8% of the participants without measurable data and 77.7% with measurable data accurately determined the area of origin. Thus, the total percentage of participants choosing the correct area increased 3.9% with the inclusion of measurable data as part of the given. No link could be identified between any set of demographic data and accuracy with the origin determination. The failure to identify any set of demographics that would permit an investigator to be more accurate is a very strong finding that the methodology is the most important aspect with the origin determination and not necessarily the years of experience or degree held by the person.

METHODOLOGY
Current processes regarding origin determination listed in NFPA 921 will be arranged using the SM. These sub-processes will be outlined within the overall process of origin determination.

The literature was reviewed for each of these processes to determine whether there was peer-reviewed publications available that demonstrated reliability, validity, or proficiency testing within the process identified. A gap analysis is provided that identifies areas of needed research for each identified process.

RESULTS AND DISCUSSION
Origin determination is considered by many as the most important hypothesis in fire investigation and has been noted as such in NFPA 921 "generally, if the origin cannot be determined, the cause cannot be determined".[26] Origin determination is the focus of this paper, and as such the area of origin determination process will be evaluated as the overall process with sub-processes identified that are intended to serve as hypotheses and ways to test hypotheses within the overall process. Fire investigators routinely rely on several methods to determine the origin of a fire. NFPA 921 provides advice and recommended practices to determine the origin of a fire starting in chapter 4 under basic methodology and then more specifically in chapter 18, the origin determination chapter.

NFPA 921 section 18.1.2, provides direction to the fire investigator for determining the origin of a fire from the coordination of information derived from one or more of the following:
   (1) Witness information-the analysis of observations reported by persons who witnessed the fire or were aware of conditions present at the time of the fire
   (2) Fire Patterns-the analysis of effects and patterns left by the fire
   (3) Arc Mapping-the analysis of the locations where electrical arcing has caused damage and the documentation of the involved electrical circuits
   (4) Fire Dynamics-the analysis of the fire dynamics, that is the physics and chemistry of fire initiation and growth, and the interaction between the fire and the buildings systems"[27]

Even though these four items of information are listed as the information needed to determine the area of origin, the chapter alters this description of the process in the very next section and at various other points throughout the chapter. In 18.2.5, the recommended methodology is outlined as follows with a goal of determining the fire spread analysis:

(1) Initial scene assessment,
(2) Development of a preliminary fire spread hypothesis,
(3) In-depth examination of the fire scene and reconstruction,
(4) Development of a final fire spread hypothesis, and
(5) Identification of the fire's origin

And then again within the same chapter, a flowchart is provided as an example of applying the SM to origin determination. This flowchart increases the type and number of information to be used or needed to determine the area of origin that was not included in previous processes outlined (Figure 2).
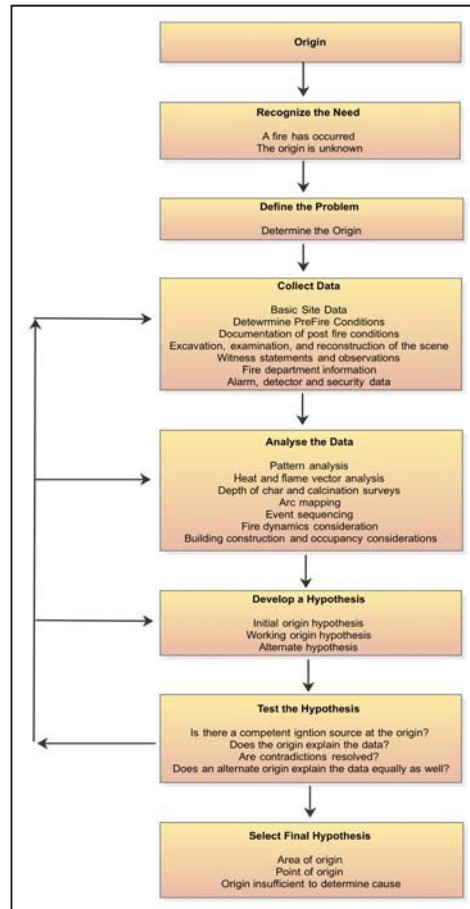
Figure 2: Example of Applying the Scientific Method to Origin Determination
(adapted from NFPA 921, Figure 18.2)

Reviewing chapter 18 provides a confusing approach, from a procedural standpoint, to origin determination. Section 18.1.2 will be evaluated as the processes put forward by NFPA 921 to assist in satisfying the area of origin determination conclusion. Figure 3 represents this discussion as influence diagrams on area of origin determination, which rests with the accurate assessment of the hypothetical area of origin and fire spread hypotheses in relationship to the damage caused by the compartment fire dynamics, identification and recognition of the geographical location of arc sites (arc mapping), and the reliability of eyewitness data. This paper will evaluate what processes currently exist for each of these influences.
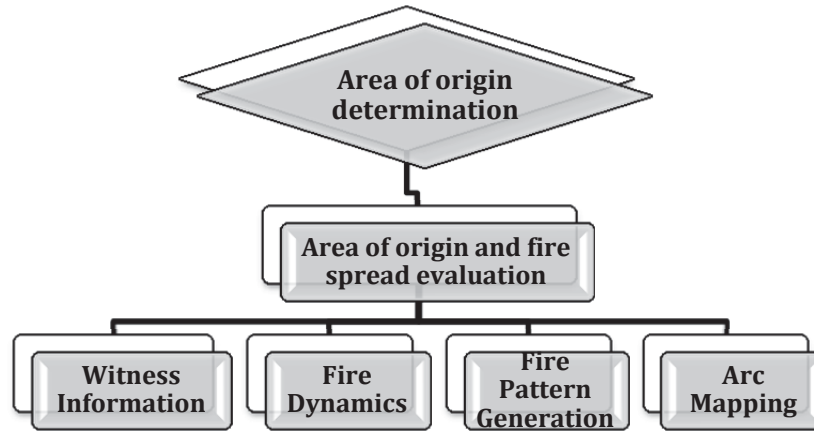
Figure 3: Influences on the Area of Origin Determination

General Methodology

Figure 4 illustrates the three sub-processes within the overall process of origin determination as described by NFPA 921. Each sub-process should then list out specifically within the steps of the SM what processes are to be used to collect data, analyze data, develop and test hypotheses, and how to select the final hypothesis. Figure 4 identifies that the first step (recognize the need) in determining the area of origin (AOO) is that a fire has occurred and the origin is unknown. The second step (define the problem) is to determine the AOO. These two steps are the same regardless of what sub-process is used to assist in this determination.

The next three steps (collect data, analyze data, and develop hypotheses) have been separated out into their respective sub-processes, which include arc mapping, fire patterns, and witness statements. The overall methodology represents that each of the sub-processes should develop hypotheses that are essentially siloed based on the information provided. The hypothetical area(s) of origin developed should begin to overlap in some areas and not in others. We propose that these developed hypothetical area(s) of origin tend to set logical relations between the sub-processes, similar to a Venn diagram.

Next, these hypothetical area(s) of origin should then be compared and evaluated against each other (note the dashed arrows from test hypotheses back into analyze data for each sub-process). Appropriate weighting of data, interpretations of the data, and contradictory data should be analyzed and reconciled at this point. If the data cannot be reconciled then the area of origin should be broadened out to encompass all area(s) consistent with the data. Note that fire dynamics is not a separate sub-process because the process alone cannot develop AOO hypotheses, the understanding of fire dynamics serves to test the hypotheses developed by the other three sub-processes.

A sequence of arrows in a circular formation encompass the collect data, analyze data, develop hypotheses, and test hypotheses steps to represent the feedback loop and to illustrate that the process is not linear. Avato and Cox have articulated a similar concept of the circular nature for the scientific method and was a base for the illustrations here.[28,29] The final step is to select the final origin hypothesis. As noted above this should be the AOO hypothesis that is most consistent with the data, and if not, then all hypothetical area(s) of origin that are still consistent with the data should be incorporated into one area and determined as the AOO.
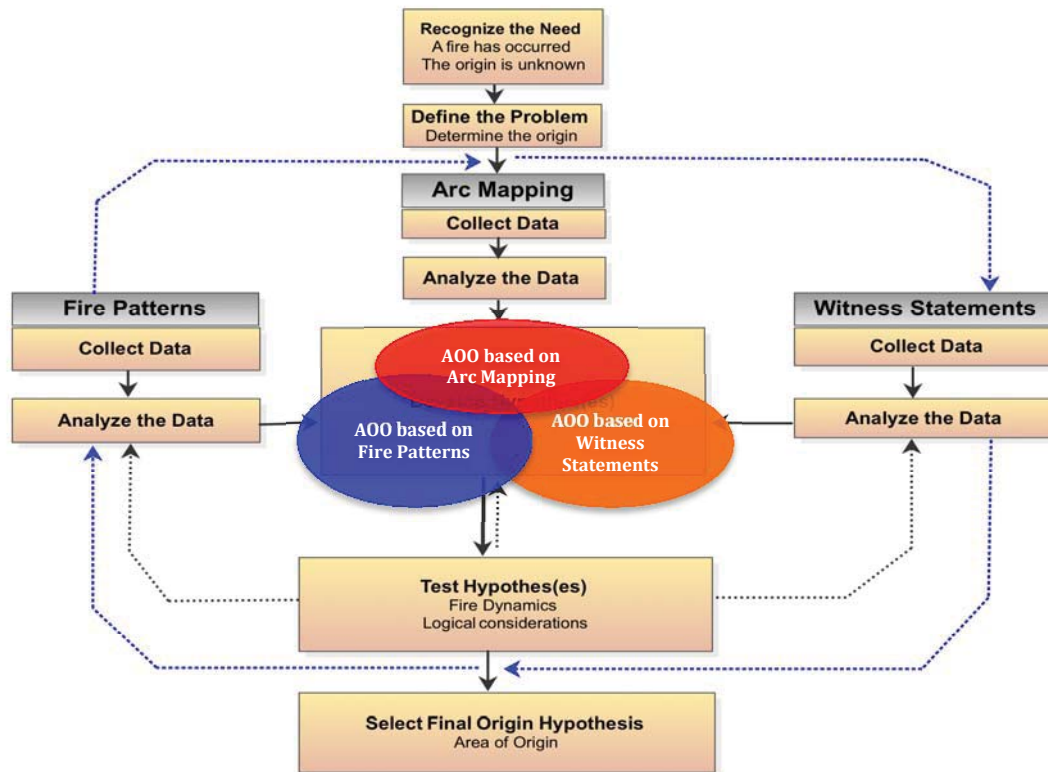
**Figure 4**: Overall Origin Process with Sub-process outlined to follow the SM

Arc Mapping

Arc mapping is defined as the "systematic evaluation of the electrical circuit configuration, spatial relationship of the circuit components, and identification of electrical arc sites to assist in the identification of the area of origin and analysis of the fire's spread".[30] NFPA 921, section 18.4.5.1 provides a suggested procedure for arc mapping.

(1) Identify the area that will be surveyed.

(2) Sketch and diagram the area as completely and accurately as possible.

(3) Identify zones within the survey area, such as ceiling, floor, north wall, etc..

(4) Identify all conductors of the electrical circuits passing through the zone, noting, when possible, loads on each circuit, direction of power flow (upstream versus downstream), locations of junction boxes, outlets, switches (or any such control), size of each conductor, and the over-current protection size, type, and status.

(5) Select a zone for examination and begin the process of systematically examining each of the conductors in that zone.

(6) Examine and feel each conductor, for the purpose of identifying surface anomalies or damage, such as beads and notches. When it is necessary to remove conductors from conduits, take care to prevent damage to the conductors.

(7) Determine if the surface anomaly occurred from arcing, environmental heat, or eutectic melting (alloying of metals).

(8) Locate the arc site on the sketch and document its physical characteristics (faulted to another conductor in same cable, faulted to conductor from another cable, completely severed conductor, partially severed conductor, faulted to grounded metallic conduit, or a conductive building element).

(9) Flag the location of the arc site(s) with a suitable marking and document such location(s).

(10) Preserve the items as evidence, when warranted.

Figure 5 illustrates the outlining of arc mapping as a sub-process within the SM.
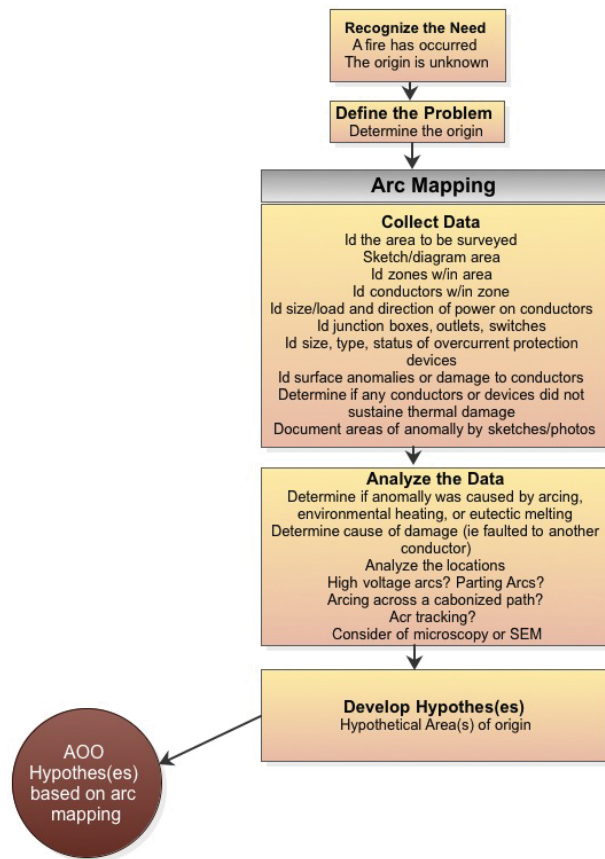
Figure 5: Arc Mapping Sub-process outlined to follow the SM

There has been some research related to if this process accurately depicts origin determination.[31,32,33,34] The literature demonstrates that the reliability and validity of identifying arc sites is questionable. Also, the literature is divided on the question of reliability and validity relating to origin determination. Finally, the literature provides no discussion on proficiency testing.

Table 2: Gap Analysis for Arc Mapping Sub-process

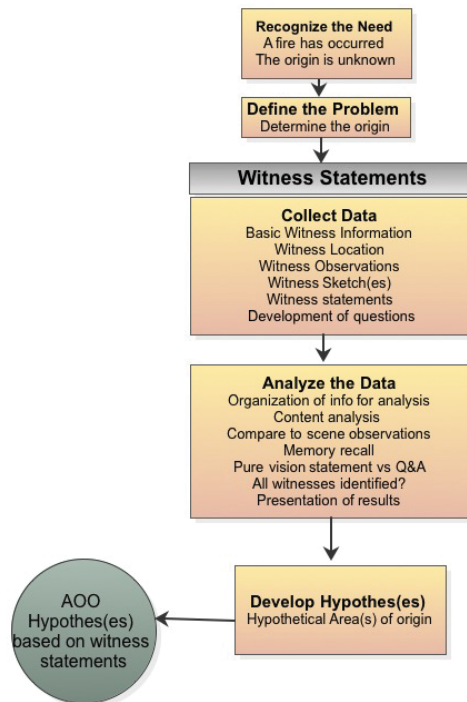|	Process Developed	Reliability Testing	Validity Testing	Proficiency Testing
Collect data	Yes	IP	IP*	No
Analyze data				
-identifying arc sites	Yes	IP	IP*	No
-distinguishing between dmg	Yes	IP**	IP**	No
-on scene id / analysis	Yes	No	No	No
-microscopy / metallurgy	Yes	IP*	IP*	No
-determining cause	Yes	IP*	IP*	No
Develop AOO hypotheses	Yes	IP	No	No
IP indicates work in progress based on literature review and that the literature is split on this issue *indicates literature is indicating positive agreement **indicates literature is indicating negative agreement				

Witness Information
There is no specific process outlined within NFPA 921 for use of eyewitness information, so we turn to a study by Geiman and Lord's work for guidance.[35] The process outlined by these researchers is included here:

1. Interviewing of witnesses to obtain information
2. Organization of witness information in a manner conducive to analysis
3. Content analysis of witness interviews
4. Presentation of results
5. Analysis of witness statements to test fire origin hypotheses

Figure 6 illustrates the outlining of witness statements as a sub-process within the SM.

Figure 6: Witness Statements Sub-process outlined to follow the SM

Table 3: Gap Analysis for Witness Statements Sub-process

	Process Developed	Reliability Testing	Validity Testing	Proficiency Testing
Collect data	Yes	IP	IP*	No
Analyze data				
-identifying witnesses	Yes	IP*	IP*	No
-organization of information	Yes	IP*	IP*	No
-compare to scene data	Yes	IP*	IP*	No
-content analysis	Yes	IP*	IP*	No
-presentation	Yes	IP*	IP*	No
Develop AOO hypotheses	Yes	IP	No	No
IP indicates work in progress based on literature review and that the literature is split on this issue *indicates literature is indicating positive agreement **indicates literature is indicating negative agreement				

Fire Patterns

Fire effects are the visible or measurable observations remaining after the byproducts of combustion have damaged the material. Fire patterns are the clustering of these fire effects into groups of damaged areas that may assist in analyzing the data more efficiently. Next, the investigator analyzes the fire patterns for geometry, direction, and the causal factors (e.g. linking fire dynamics to fire pattern generation). No processes exist for determining the varying degree of fire damage amongst materials, leaving much of this up to the subjective interpretation of the investigator. The only lining material that has received significant evaluation in the literature to develop such a method is gypsum wallboard. A recent study[36] published findings on a process for visible observation of fire effects to gypsum wallboard, while another study[37] focused on the process for measurable data. There exists no process on how to cluster this damage into fire patterns. The only procedural aspect that NFPA 921 provides for fire patterns analysis for origin determination is the heat and flame vector analysis. However, no procedural details are provided on how to implement this analysis.
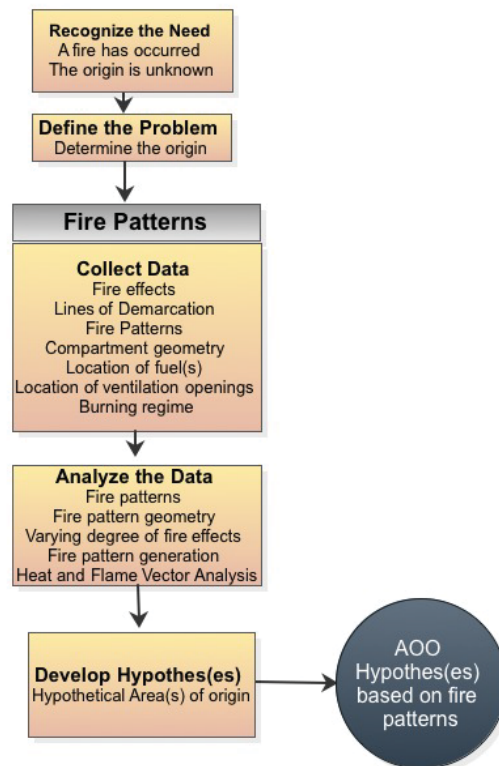
Figure 7: Fire Patterns Sub-process outlined to follow the SM

Table 4: Gap Analysis for Fire Patterns Sub-process

	Process Developed	Reliability Testing	Validity Testing	Proficiency Testing
Collect data	Yes	IP	IP*	No
Analyze data				
-varying degrees of damage	IP***	IP	IP	No
-fire patterns identification	No	No	No	No
-geometry	Yes	IP	IP	No
-direction of fire travel	Yes	IP*	IP*	No
-heat and flame vectors	Yes	IP*	IP*	No
Develop AOO hypotheses	Yes	IP	No	No
IP indicates work in progress based on literature review and that the literature is split on this issue *indicates literature is indicating positive agreement **indicates literature is indicating negative agreement ***limited data exists				

Fire Dynamics

Fire dynamics is not a separate sub-process because the process alone cannot develop AOO hypotheses, the understanding of fire dynamics serves to test the hypotheses developed by the other three sub-processes. However, the test of hypotheses should follow a set procedure as well. Heat and flame vector analysis and the origin matrix have been put forward as a means to testing.
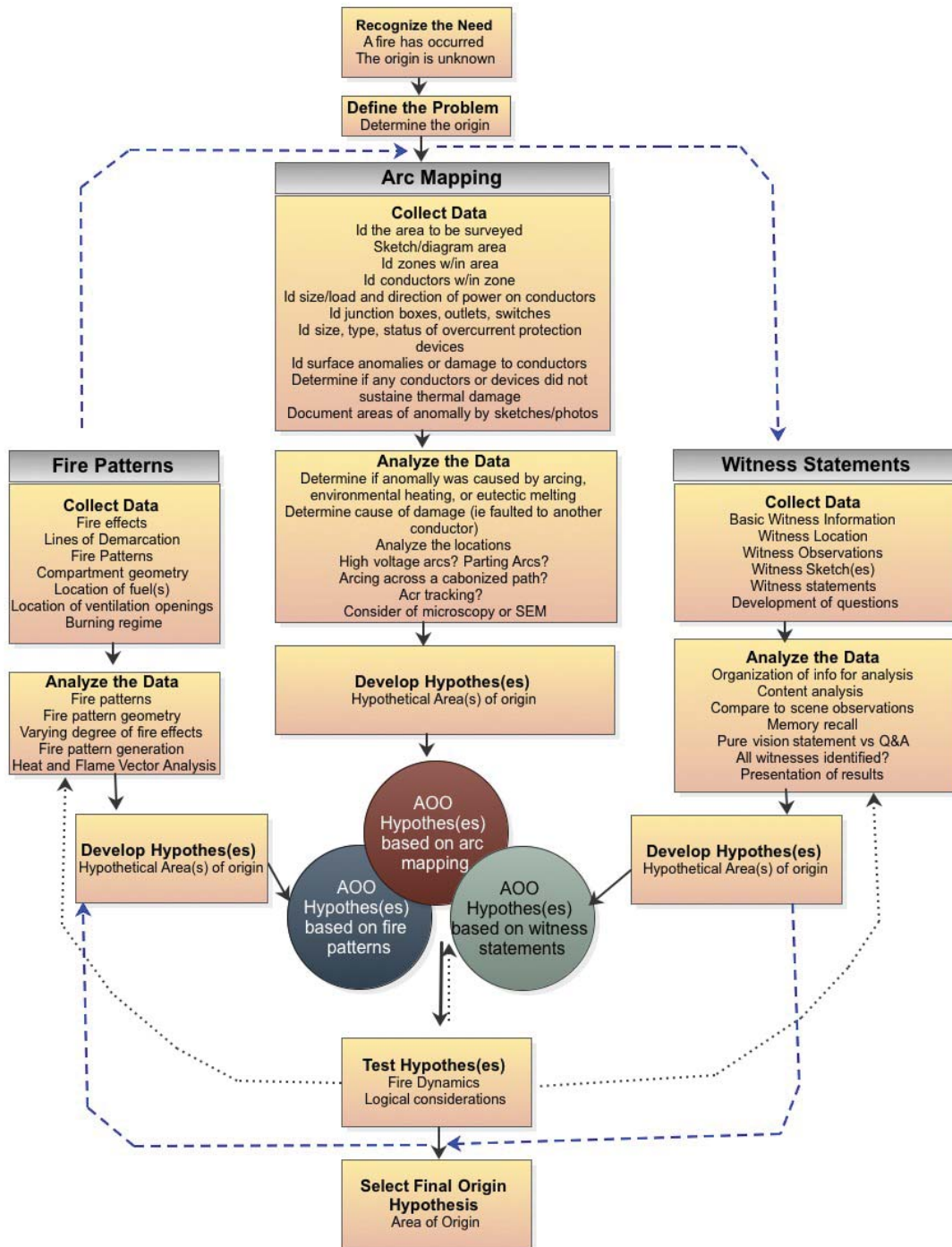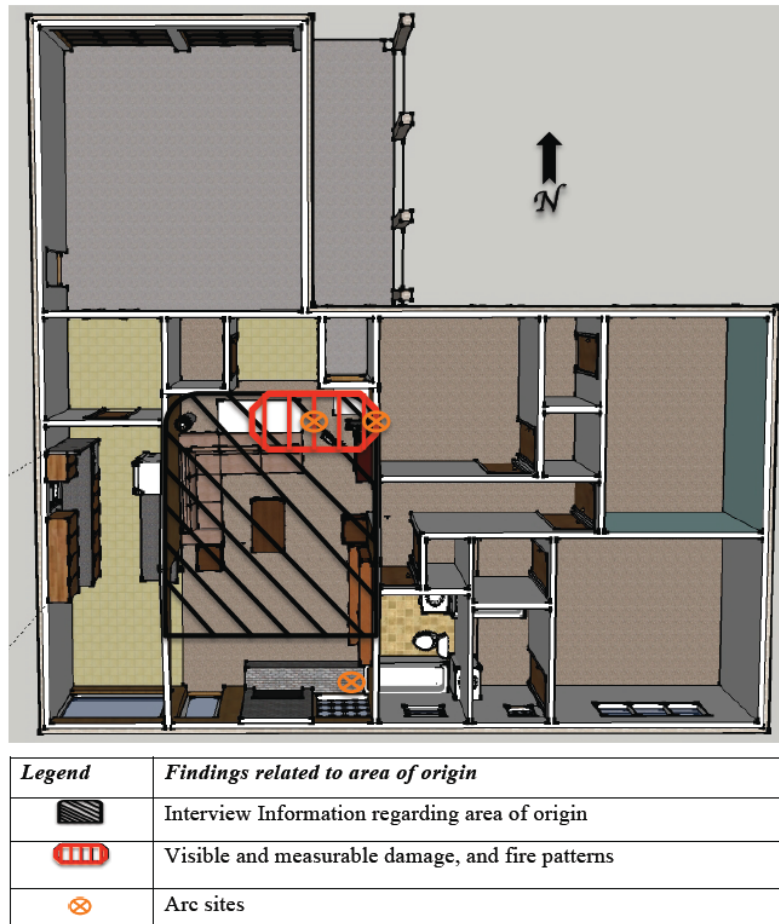
Complex Overall Process

Figure 8: Fire Patterns Sub-process outlined to follow the SM

RECOMMENDATIONS

Research should be directed at filling in the gaps identified within each sub-process. New processes should be developed to assist in filling in the gaps. All processes used for origin determination should undergo reliability and validity testing. Standardized proficiency testing should be developed for each process developed and all users of these processes should be tested for proficiency.

One method that may assist in illustrating the singularity of the hypothetical area(s) of origin developed by each sub-process and their ultimate interrelationship is to consider the overlapping nature of a Venn diagram (Figures 4 & 9).

Legend	Findings related to area of origin
	Interview Information regarding area of origin
	Visible and measurable damage, and fire patterns
⊗	Arc sites

Figure 9: Coordination of Information for Area of Origin Determination

CONCLUSIONS

Origin determination is a complex process consisting of a series of sub-processes that must be identified, coordinated and analyzed during a fire investigation (Figure 8). Failure to identify and adapt the incident specific processes when determining origin may result in an incorrect determination.

Analysis of the data collected from each process and evaluated against the data from the other processes used will assist the investigator in determining the corrects origin(s).

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