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Automatic Water-Based Fire Suppression System Experiments

– Literature Summary for Model Validation Purposes

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Preface

This is one in a series of reports produced as part of an overarching project to consider the structural building safety aspects of fire safety.

Acknowledgments

This work was funded by BRANZ from the Building Research Levy.

Note

Any direct or indirect indication or reference to commercial entities, products, materials or systems in this document is only included here to assist in the description of the state of the experiments and associated data in available literature. No recommendations, endorsement or implication of adequacy or in adequacy of the entities, products, materials or systems identified in this document is made by BRANZ.

This report is intended for regulating authorities, policy advisers, researchers and fire engineers.

Automatic Water-Based Fire Suppression System Experiments – Literature Summary for Model Validation Purposes

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Reference

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Abstract

A BRANZ project was conducted that aimed to identify the current state of the data available for validation of fire models incorporating suppression algorithms for suppression and post-suppression conditions in buildings, which are largely ignored in current performance-based design practices. The appropriateness of model assumptions is also not well understood. This report contains a summary of collated water-based fire suppression test data and guidance on the important parameters, and variables for consideration when performing validation evaluations of models incorporating suppression algorithms.

The intended validation approach taken here is *a posteriori*, since the experimental data sets are published in literature. A limited discussion of the results of each set of experiments is included in this summary document, in order to assist by limiting the influence of the experiment results on the user of the model of interest, while they implement the model based on an estimate the initial conditions of the selected fire experiment. Therefore a general description of the test setup, varied parameters and the amount and location of the instrumentation used and reported on are included here.

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Acronyms and abbreviations

AFPE	Aon Fire Protection Engineering
BRANZ	BRANZ Ltd
BS	British Standards
BSI	British Standards Institute
ESFR	Early Suppression Fast Response
FDS	Fire Dynamics Simulator
HRR	Heat Release Rate
IMO	International Maritime Organization
ISO	International Organization for Standardization
NFPA	National Fire Protection Association (USA)
NIST	National Institute of Standards and Technology (USA)
RTI	Response Time Index
SEC	Schimer Engineering Corporation
SFPE	Society of Fire Protection Engineers
SP	Swedish National Testing and Research Institute
UL	Underwriters Laboratories Inc.

Units

All units are reported in Standard International units, unless otherwise noted.

1. INTRODUCTION

It was hypothesised that sufficient data is available from published and new sprinkler-related experiments for future development of suppression algorithms and models, in terms of validation.

A BRANZ project was conducted that aimed to identify the current state of the data available for validation of suppression algorithms for suppression and post-suppression conditions, which are largely ignored in current performance-based design practices. The appropriateness of model assumptions is also not well understood. This report contains a summary of collated data and guidance on the important parameters and variables for validation of models incorporating suppression algorithms.

According to ASTM E1355 *Standard guide for evaluating the predictive capability of deterministic fire models*, 'verification' is defined as:

> … the process of determining that the implementation of a calculation method accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method …

and 'validation' is defined as:

> the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method.

Validation typically involves:

1. Comparison of model predictions and results from experiments.
2. Quantification of the differences of model output and test results, considering uncertainties in both the measurements and the model inputs.
3. Deciding whether the model is appropriate for the given application.

It has been previously recommended that combinations of experimental and computational modelling studies with validation by fire tests will make the development of fire suppression systems, such as sprinkler and water-mist systems, much more efficient and effective (Liu and Kim, 2000; Bwalya, 2008; Wade et al., 2007; Bergeron, 2008; McGrattan et al., 2010; Ryder et al., 2006; McGrattan and Forney; 1999).

The intended validation approach taken here is *a posteriori*, since the experimental data sets are published in the literature. To assist limiting the influence of the experiment results on the modeller, limited discussion of the results are included in this summary document. Instead a general description of the test setup, varied parameters and amount and location of instrumentation used and reported on are included here.

1.1 Objectives

The intent of this document is to:

- provide a scoping document that contributes as a resource to the New Zealand building industry in the field of performance-based fire engineering
- outline the available data for comparison with modelling results for fire suppression
- recommend the direction of future work in this area.

The objective of this report is to summarise the relevant experimental data for fire suppression that was identified as being potentially useful for comparisons with modelling results of both suppression and post-suppression conditions. This is in order to evaluate the level of validation that can be achieved for models incorporating suppression algorithms.

1.2 Scope

Automatic suppression systems for buildings are the focus of this literature review. Manual fire suppression and Fire Service suppression technologies and efficacy are outside the current scope of this study.

Fire protection systems with components no longer deemed environmentally acceptable, such as halons, are also not included in this summary as they have been becoming less relevant. For example, since the early 1990s systems utilising halons have been phased out and replaced with alternative systems. Therefore halon-based fire protection systems are currently rare, and thus less relevant to future modelling capabilities.

The most common automatic suppression systems used in New Zealand buildings are water-based systems e.g. sprinklers and water mist systems. Therefore these systems feature as the focus of the efforts for this project, proportional to the usage throughout the current New Zealand building stock.

Parameters that may be useful when attempting to model fire suppression systems are listed, and an indication is given as to whether or not values are available from experimental studies. No assessment of the types of automatic suppression system is presented here. Although each system has a unique list of advantages and disadvantages, and the level of efficacy associated with various categories of fire challenges, these are outside the scope of this study.

Building fire protection was the focus of this study. Ship-board, tunnel and other types of applications for fire suppression experiments are briefly included in discussion in a compartment fire context if they have usefulness in the area of building fire protection.

1.3 Approach

The research project aimed to be able to consider the implications of using currently available experimental data for validation of models incorporating suppression algorithms for both suppression and post-suppression conditions. This project was aimed at identifying the voids in currently available experimental data, so that this information can be used to develop future research plans.

In the research, experimental and model parameters and variables that have been used to describe fire suppression and post-suppression conditions were compared to evaluate availability and the experimental data that is needed to support research development in this area.

To support the scoping document, the main effort of this project was focused on a literature search that was undertaken to establish what research had been conducted internationally that was relevant to this study. Then descriptions of the experimental data sets on suppression and post-suppression conditions were collated. The collated data was then evaluated in terms of important parameters and variables and the suitability or relevance for validation of models incorporating suppression algorithms. The results of this evaluation provide indications of where experimental data is currently lacking and the most useful directions for future research in this area.

2. LITERATURE REVIEW

The following section is a summary of the literature that may be relevant in validation assessments of various models and applications of water-based automatic fire suppression.

2.1 Types of automatic fire suppression system technology

In general, fire control or extinguishment may be achieved by one or a combination of the mechanisms of (Mawhinney, 1993b; Mawhinney et al., 1994; Rasbash et al., 1960; Wighus, 1991; Linteris, 2011):

- removal of heat e.g. by cooling of the:
  - flame zone e.g. thermal agents (Pitts et al., 2006)
  - fuel source, and/or
  - surroundings etc
- removal of oxygen e.g. by:
  - displacement
  - scavenging etc
- removal of ignition sources e.g. by:
  - radiation blocking
  - de-energising of original ignition source etc.

2.1.1 Water systems

Water has properties that can be favourable for fire suppression purposes (Pitts et al., 2006). A high heat capacity (4.2 J/g.K) and high latent heat of vaporisation (2.4 kJ/g) can absorb a significant quantity of heat from flames and fuels. Expanding when it evaporates to steam (1,700 times) results in the dilution of the surrounding air and fuel vapours. Formation of fine drops increases the surface area-to-volume ratio. This increases the potential rate of heat absorption and evaporation, and subsequently the potential fire suppression capabilities (Liu and Kim, 2001; Mawhinney, 2008; Tatem et al., 1994).

Therefore water-based systems form the majority of automatic fire suppression systems used. Sprinkler systems and water mist systems are considered separately in the following sections. One type of system cannot be directly substituted for the other, so they are treated separately. Beyond technology differences, the primary difference between the systems is the water drop size, which is one of the factors that has been reported to influence suppression mechanisms (Liu and Kim, 2000; Mawhinney, 2008; Drysdale, 1985; Rasbash, 1986).

2.1.1.1 Sprinkler systems

Automatic sprinkler systems are considered to be a highly reliable fire protection and suppression system. These systems may consist of a sprinkler head for activation on fire detection (typically between 57°C and 260°C), a water flow alarm for giving a signal, and water for controlling or extinguishing the fire (Hadjisophocleous and Benichou, 2010).

2.1.1.2 Water mist

Water mist suppression systems utilise fine water sprays as the extinguishing medium and are sometimes approached as a hybrid of automatic sprinklers and gaseous suppression systems (Hadjisophocleous and Benichou, 2010). Water mist refers to fine water sprays in which 99% of the volume of the spray is in drops with diameters less than 1000 microns (Mawhinney, 2008).

Water mist can be produced using nozzles, relying on the nozzle geometry and water flow, or by flashing super-heated water to produce a mist. Flashing of super-heated water has been used for fire suppression purposes. Experiment results indicated that extinguishment was dependent on the same factors as for a conventional spray (Mawhinney et al., 1995).

Extinguishment of a fire by a water mist system is suggested to be related to the mechanisms of (Liu and Kim, 2000; Mawhinney, 2008; Rasbash et al., 1960; Mawhinney, 2003; Liu et al., 2005a, 2005c):

- heat extraction via cooling of the fire plume and wetting of surfaces
- oxygen displacement via the evaporating drops
- radiant heat attenuation of the mist surrounding the burning fuel
- kinetic effects of water mist on flames.

2.1.2 Dry chemical systems

Dry chemical extinguishing systems typically apply fine particles of dry chemical through a distribution system into a fire. Chemicals used include sodium bicarbonate-based, potassium bicarbonate-based and ammonium bicarbonate-based powders (Hadjisophocleous and Benichou, 2010).

Automatic dry chemical suppression systems were deemed to be outside the scope of this study, because of their rare use in buildings both in New Zealand and internationally.

2.1.3 Gaseous systems

Gaseous systems typically flood the space with a gas (e.g. halons, carbon dioxide, etc.) to displace the air in the space and therefore reduce the local oxygen concentration (Linteris, 2011; Liu, 1997).

Similarly, automatic gaseous suppression systems were deemed to be outside the scope of this study because of their limited use in buildings both in New Zealand and internationally.

2.2 Fire scenarios, variables and parameters for experiments

Considering various parameters used in experiments involving water-based automatic fire suppression systems, the structure chosen to present the summary of published relevant data is based:

- First on the occupancy or general description of the intended use of the space e.g. accommodation, office, buildings with historical or cultural significance etc.
- Secondly on parameters used to describe the scenario such as compartment geometry, ventilation, fire type, size and shielding, suppression system interaction with the fire, and suppression system characteristics and operation.
- Thirdly, repeatability was also considered.

For example, considering water mist systems, fire suppression effectiveness is suggested to be dependent on (Liu and Kim, 2000; Mawhinney, 2008; Drysdale, 1985):

- spray characteristics such as (Rasbash, 1986; Mawhinney, 1993a):
    - distribution of drop sizes
    - flux density.
- spray dynamics such as (Mawhinney and Hadjisophocleous, 1996):
    - enclosure effect
    - dynamic mixing caused by the discharge of water
    - discharge modes (e.g. flooding vs cycling operation)
    - suppression system configurations, e.g. (Mawhinney and Richardson, 1996):
        - individually thermally actuated nozzles
        - zoned systems
        - full compartment systems
        - local application systems
    - suppression additives (Finnerty, 1996; McCormick et al., 2000; Edwards et al., 1999).
- in conjunction with the fire scenario, including the factors:
    - compartment size and geometry
    - nozzle orientation/configuration
    - shielding of the fuel
    - fire size
    - ventilation conditions.

In application of a set of experiment results for comparison with model output for the same initial conditions and setup, typically a fire scenario is of interest. Therefore the approach that has been used here is based on fire scenario descriptions first, and then secondly on the aspect of the testing that was the focus for the experimental program. In practical terms, the experiments are collated first in terms of the type of space the experiments were conducted in, and then secondly the test parameter that was varied during the test series.

2.2.1 Space/compartment types

The types of spaces considered (in the order that they are summarised in the following sections) are:

- accommodation spaces (excluding cooking-related fires)
- kitchen and cooking-related spaces
- office spaces
- heritage and library spaces
- electronic equipment spaces
- entertainment space
- factory or machinery spaces
- generic compartments.

2.2.1.1 Accommodation spaces

The section considering accommodation spaces includes fires started in living and sleeping spaces etc. Cooking-related fires are not included in this section, but instead are summarised in the following section.

2.2.1.2 Kitchen and cooking-related spaces

Cooking oil or fat fires in cooking areas are the most difficult fires to be extinguished, because they burn at a high temperature and re-ignite easily.

Water thermal properties are advantageous for removing heat from fires and fuels and surroundings. However, due to rapid vaporisation and superheating of water, undesirable results may occur on interaction with a hot liquid fuel. A vapour explosion may occur when water is introduced with a hot liquid. Boil-over can also occur when water is introduced into the hot liquid (Liu et al., 2008; Manzello et al., 2003).

2.2.1.3 Office spaces

Office spaces may include single offices or open plan arrangements.

2.2.1.4 Heritage and library spaces

Water-mist fire suppression systems have been investigated for potential applications in heritage buildings and libraries.

2.2.1.5 Electronic equipment spaces

The types of fire scenarios considered here are similar to those that may occur in computer rooms, electrical switch-gear cabinets, cables and main telephone exchange distribution frames. Full-scale water mist fire tests have been conducted to evaluate the feasibility of using water mist systems for the protection of electrical and electronic equipment.

Fire tests involving only cabinets or stand-alone equipment, where the fire suppression was internal to the cabinet or equipment casing, were not included in this review.

2.2.1.6 Entertainment space

Entertainment space is used in this document to describe public entertainment spaces, such as night-clubs and bars etc.

2.2.1.7 Factory or machinery spaces

The types of spaces considered in this section include:

- machinery spaces in industrial settings or on board ships
- gas turbine enclosures
- flammable liquid storage rooms
- combat vehicles, etc.

The fire scenarios typically associated with these types of spaces involve the fuels and lubricating and hydraulic oils ignited by hot engine parts, overheated bearings or electrical arcing. Liquid fuels may be in pressure lines, producing spray fires or pool fires.

Tests have been performed to evaluate the capabilities of water mist systems for use in machinery spaces have varied with:

- compartment size (e.g. small-scale of 24 m^3 to full-scale IMO Class III engine rooms)
- compartment ventilation
- fire type (e.g. wood crib, spray, pool, cascade fires, etc.):
    - fuel type for spray and pool fires (e.g. high viscosity heavy oils to diesel and Heptane fires)
- fire sizes (up to 30 MW)
- fire location relative to fire protection systems (shielded and unshielded)
- water-mist system characteristics
- fire protection configuration (e.g. nozzle spacing and drop distance from the ceiling).

A selection of experimental investigations of these influencing parameters is summarised in Section 2.2.9.

2.2.1.8 Generic compartments

This section summarises tests that were performed in generic compartments, e.g. a test compartment with a burner, a test compartment with a single chair, etc.

2.2.2 Categories of interest

The main parameter that was the focus of each investigation of the influence on the suppression performance was the next category. These categories included:

- compartment size and configuration
- ventilation
- fire type and size
- shielding of fire
- interaction with other fire protection systems
- suppression system characteristics
- fire-fighting additives
- nozzle/head configuration
- flooding vs localised application
- continuous vs cycling application
- repeatability.

Not all of these categories are associated with summarised experiments relevant to validation assessment of models incorporating suppression.

2.2.2.1 Compartment size and configuration

It has been shown that an increase in the compartment volumes and ceiling heights reduces the effectiveness of water mist in fire suppression (Pepi, 1995). This is because it is difficult to deliver a sufficient concentration of fine spray to the fire location (Pepi, 1995; Bill et al., 1997).

2.2.2.2 Ventilation

Ventilation may influence the activation, operation or both of a suppression system. The impact of ventilation on water mist performance has been demonstrated to vary with the ventilation of the compartment. For example, full-scale tests in a compartment with open doors were carried out by the U.S. Navy for various fire sizes (Williams et al., 1999). The results showed that for the same amount of ventilation (three open doors), there was a slight increase in time taken to extinguish small fires compared to no open doors, but there was no change reported for large fires.

2.2.2.3 Fire type and size

The location relative to a sprinkler/nozzle etc., type (e.g. pool or spray fire) and size of a fire influence the performance of a fire suppression system.

2.2.2.4 Shielding of fire

Whether a fire is unshielded or shielded influences the potential extent of success of a fire protection system. With increasing degrees of obstruction, the amount of water mist reaching the fire is reduced and the control of the obstructed fire is more difficult.

2.2.2.5 Interaction with other fire protection systems

There are a range of fire protection systems that may or can have an influence on the activation and performance of a fire suppression system, depending on the specific design of the building (Beyler and Cooper, 2001).

2.2.2.6 Suppression system characteristics

For example, the water mist system type has been shown to impact the performance for various types of fires. That is, low-pressure single-fluid or twin-fluid, and high-pressure single-fluid systems. The difference between the high-pressure and low-pressure systems is the spray characteristics, including the drop size, number of drops produced and the momentum of the drops. High-pressure system experiments have been conducted in a range of fire scenarios (Back et al., 1996a, 1996b; Edwards and Watkins, 1997; Pepi, 1998; Bill et al., 1997; Williams et al., 1999; Darwin and Williams, 1999) and have been shown to have generally better extinguishing capabilities than low-pressure systems.

2.2.2.7 Fire fighting additives

Fire fighting additives also affect the suppression performance of both sprinkler and water mist systems (Liu and Kim, 2001). For example, five types of additives were investigated as to their impact of suppression effectiveness by Edwards et al. (1999) for ship-board applications. The results of the tests indicated an 18% to 60% reduction in time to extinguishment for the sprinkler system tested and a reduction of 74% to 90% for the water mist systems tested. The largest improvements were reported for the low-pressure water mist system tested, with reductions of 85% to 99% in the time to extinguishment and reductions in water usage when compared to the use of sea water only (Edwards et al., 1999).

2.2.2.8 Nozzle/head configuration

Configuration of the nozzles, including such parameters as the spacing and distance below the ceiling of the nozzles, has been demonstrated to impact the performance of a water mist system. For example, tests carried out in a 960 m³ compartment (Back et al., 1996b) showed a difference in the time to extinguish unventilated fires for different configurations of system nozzles (at the same or two elevations within the compartment).

2.2.2.9 Flooding vs localised application

Flooding and localised application of water mist systems has been shown to have different results for the same test scenarios. For example, water mist systems using the flooding method and localised application methods, separately and combined, were compared by Dyer (1997) for fire scenarios involving lubrication oil (~1.5 MW) or aviation jet spray fires, or (~1.5 MW) pool fires located under the engine. The total flooding method was reported to consistently have shorter times to extinguishment than the localised application method for the challenging fire scenarios tested. The test results for the combination of flooding and localised application of the water mist system were reported to show a large decrease in the time to extinguishment compared to the flooding method for the same fire scenario (Dyer, 1997).

2.2.2.10 Continuous vs cycling application

Cycling the discharge of a water mist system can influence the suppression performance compared to a continuous discharge.

2.2.2.11 Repeatability

Full-scale testing is an arduous task that can be costly in terms of time, materials, space and equipment. Such limitations can limit the number of tests conducted for any one fire scenario. However results from multiple tests for the same fire scenario are needed to assess the repeatability of the results of the experiment. Therefore having a number of the same or similar tests estimate the repeatability and associated range of possible results is useful for the comparison with model output in the context of evaluating the model validation (Bukowski et al., 2002; Yung and Benichou, 2000).

2.2.3 Accommodation spaces

2.2.3.1 Compartment size and configuration

2.2.3.1.1 Test A.1

As part of the ship-board accommodation test program (Turner, 1993), a set of tests were performed in an open space test setup, utilising the SP fire hall and a 10 x 10 m suspended ceiling. There were no walls in the test setup, therefore ventilation was not restricted in any way. Two different ceiling heights, of 2.5 m and 5.0 m, were tested. Furniture was placed in the open space under the suspended ceiling (Turner, 1993).

The test comprised of a compartment that represented a sleeping cabin that was connected to a corridor, as shown in Figure 1 (Turner, 1993).

Thermocouples were located throughout the compartment and the attached corridor, adjacent to each of the nozzles, and as thermocouple trees located along the centreline of the corridor (Figure 1). Heat release rates (HRRs) during the tests were also reported (Turner, 1993).

The full test report is: Arvidson M & Ryderman A. 1992. *Cabin and Public Space Fire Tests with Marioff's Hi-fog Fire Protection System.* Swedish National Testing and Research Institute, 91 R30141, Borås, Sweden (Turner, 1993).

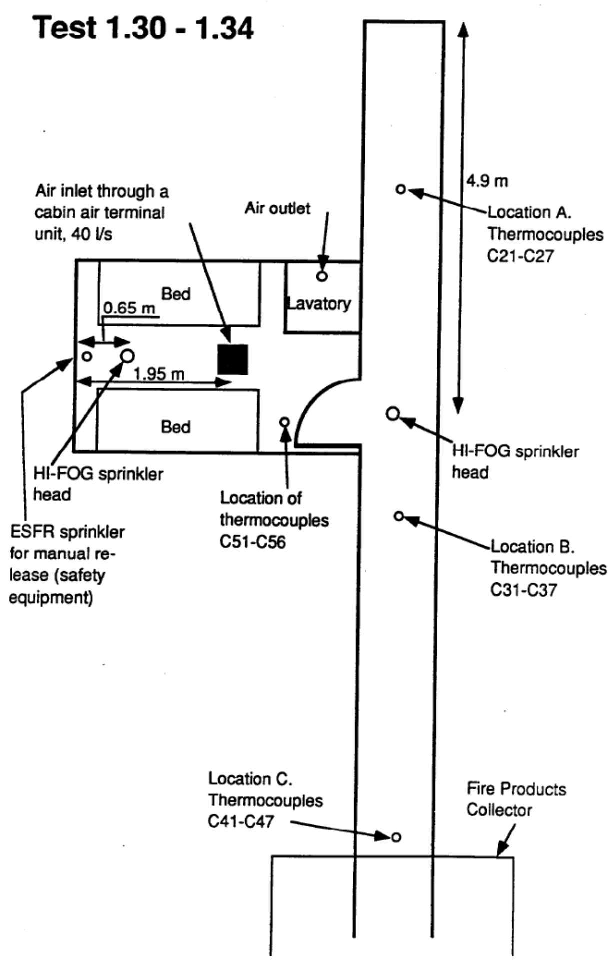


Figure 1: Schematic of an example cabin/corridor test conducted at the Swedish National Testing and Research Institute (Turner, 1993)

2.2.3.1.2 Test A.2

A two-level (approximately 93 m² per level) wood-framed house in Kemano Village was used for fire suppression experiments. An 11-head quick response (68.3°C) sprinkler system was installed, as designed to NFPA 13D (1999). The sprinkler system covered the entire ground floor and a 5.9 x 3.8 m wide by 2.3 m high recreation room in the basement (Su et al., 2002).

Four sprinklered tests were conducted: two experiments where the ignition source was located in the basement room (Figure 2 and Figure 3); one experiment with the ignition source located in a 3.9 x 3.2 m wide by 2.44 m high bedroom on the ground level (Figure 4); and one experiment with the ignition source located in the 7.2 x 3.7 m wide by 2.44 m high living room on the ground level (Figure 5) (Su et al., 2002).

The fuel load consisted of typical residential contents (Su et al., 2002).

For Test 1, the ignition source was lit newspaper in a wastepaper basket. This basket was behind a wooden end table in a corner between the ends of a sofa and a chair with a long curtain on the wall behind, and it was filled with newspaper that touched the curtain. Then 100 ml of diesel was dripped onto the sofa arm for ease of ignition. The recreation room door was left open during the experiment. The layout of the test is shown in Figure 2 (Su et al., 2002).

Test 2 used the same room as Test 1, but with a different layout of contents as shown in Figure 3. The arm of the upholstered chair was located equidistant from the two sprinklers in the basement recreation room. The fire was started by igniting a cloth that was draped over the arm of the chair, and the end was located in a metal pan on the floor beside the chair. Diesel (150 ml) had been dripped over the arm of the chair and the cloth and the pan. The recreation room door was left open during the experiment (Su et al., 2002).

Test 3 was performed in the bedroom on the ground level. A queen-sized bed was located in the corner of the room, 0.15 m from a wall. Diesel (150 ml) in a metal pan located under the bed was lit to start the test. The bedroom door was left open during the experiment. One sprinkler head was located centrally in the room. A second sprinkler head was located outside the bedroom doorway in the hall. The layout of the test is shown in Figure 4 (Su et al., 2002).

Test 4 was performed on the ground level in the living room that was connected to the dining room (4.0 x 3.1 m) in an open plan arrangement. The furniture in the living room included a leather armchair, wooden end table, sofa with a curtain behind it, and a television set. A metal pan was located on the floor between the sofa and armchair.

Cloths were draped over the arm of the sofa into the pan and over the adjacent armchair into the pan. Diesel (125 ml) was dripped onto the cloths into the pan. The diesel in the pan was lit to start the test. Two sprinklers were installed in the living room. A schematic of the test is shown in Figure 5 (Su et al., 2002).

Temperature measurements from locations in the room of fire origin and the corridor outside this room were reported for each test. Carbon monoxide and carbon dioxide concentrations, sprinkler activation times and visual observations were also reported. Smoke detectors, carbon monoxide detectors and heat detectors were also installed through the house and the detection times were reported (Su et al., 2002; Crampton et al., 2002).

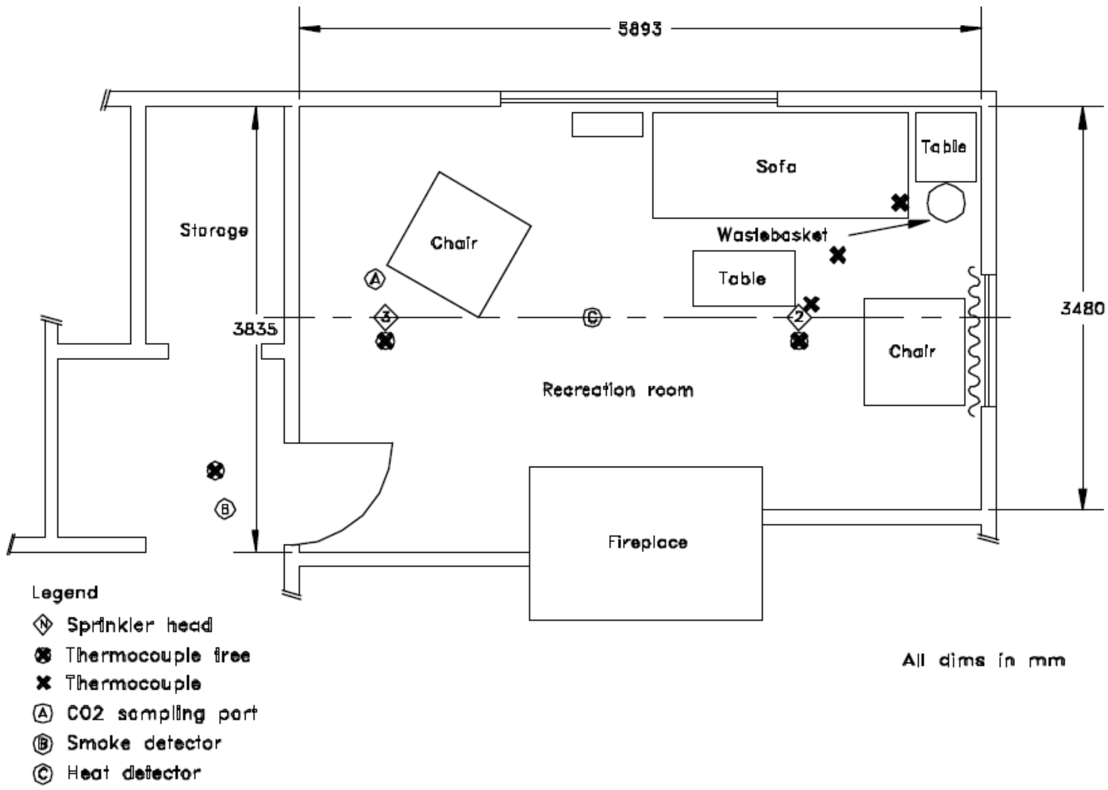


Figure 2: Schematic of the recreation room on the basement level for the test layout for Test 1 of the Kemano Village two-level house tests (Su et al., 2002)

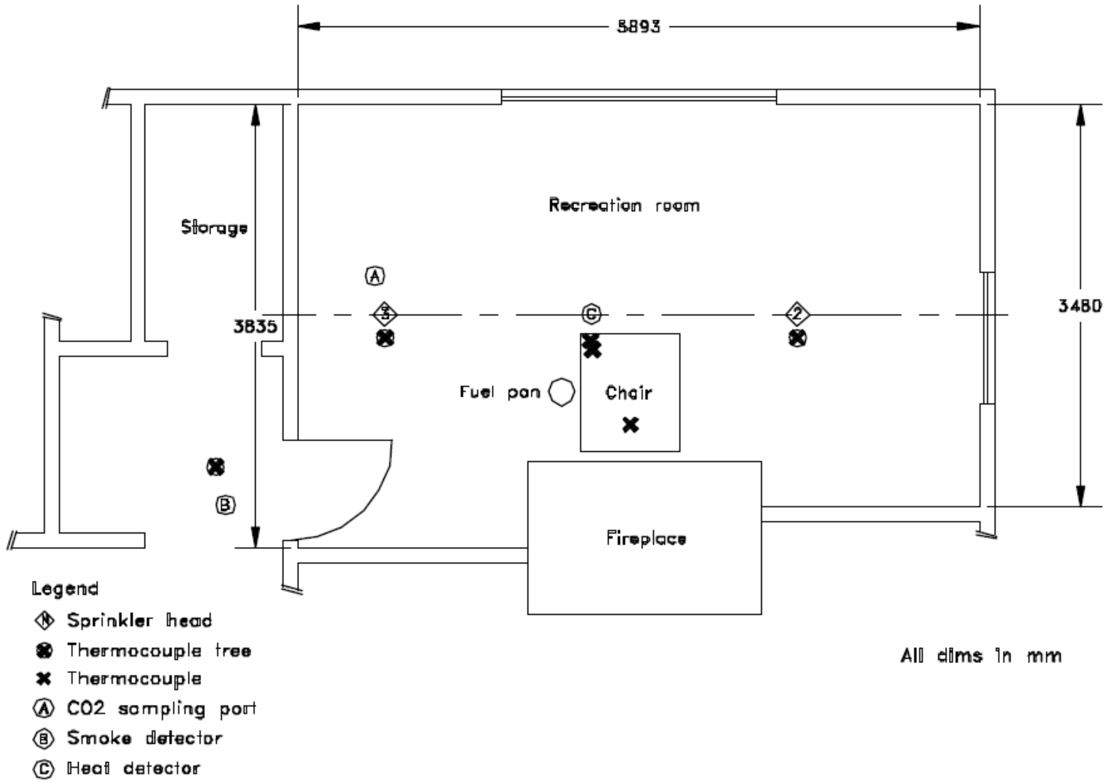


Figure 3: Schematic of the recreation room on the basement level for the test layout for Test 2 of the Kemano Village two-level house tests (Su et al., 2002)

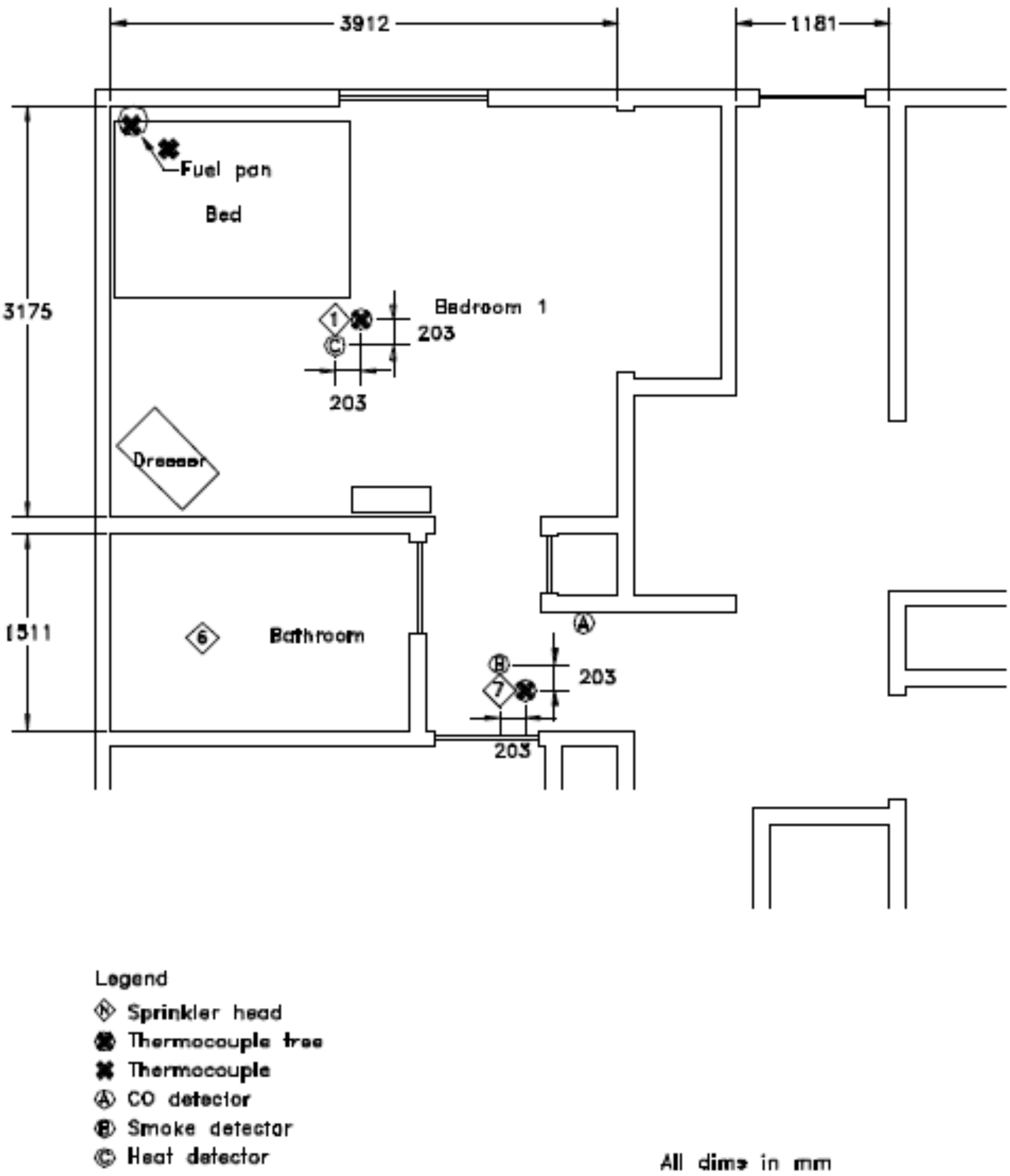


Figure 4: Schematic of the bedroom on the ground level for the test layout for Test 3 of the Kemano Village two-level house tests (Su et al., 2002)

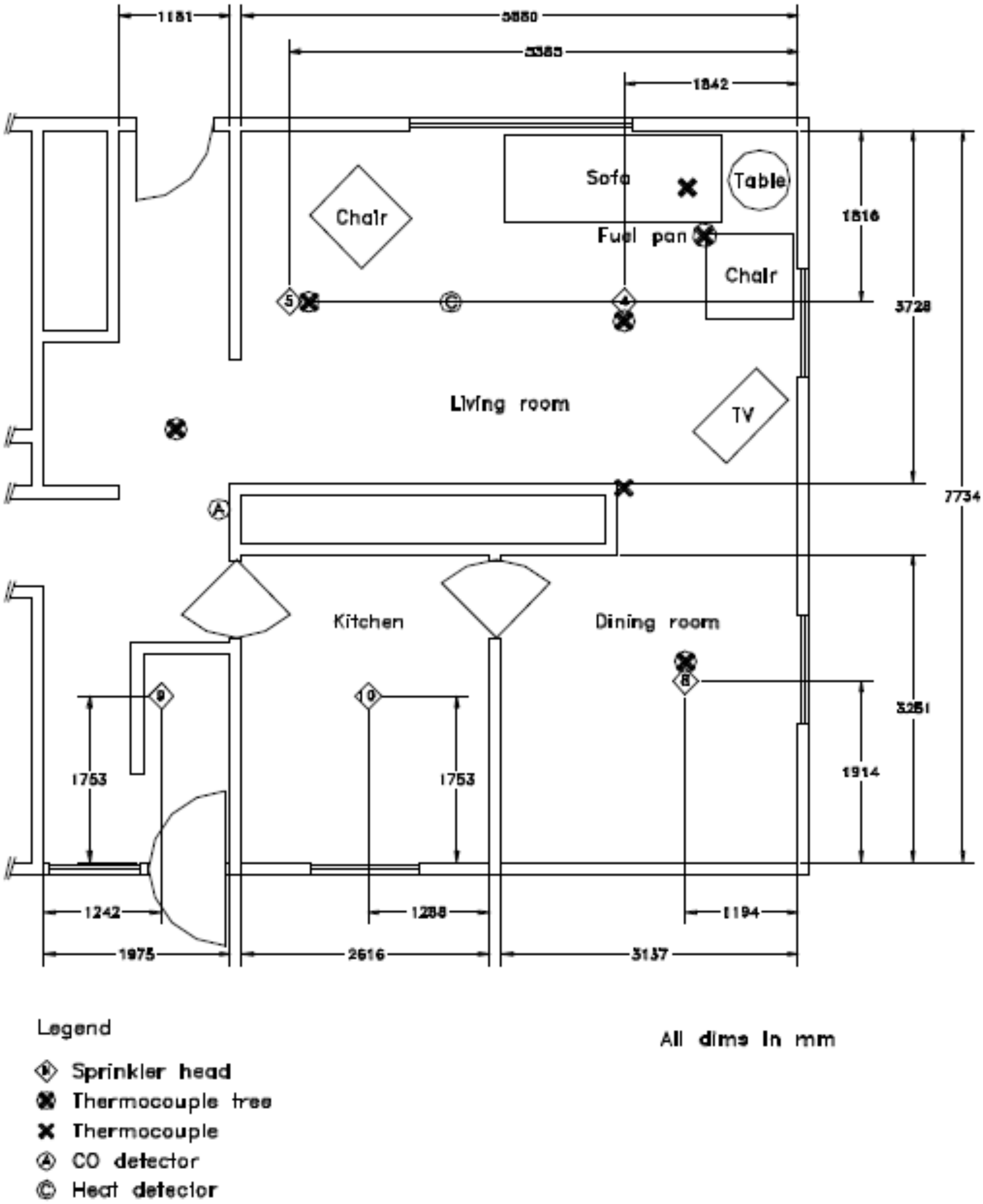


Figure 5: Schematic of the living room on the ground level for the test layout for Test 4 of the Kemano Village two-level house tests (Su et al., 2002)

2.2.3.1.3 Test A.3

Eighteen room tests were conducted in a 7.3 x 6.7 m compartment with a 45º slope and six up slope beams in one of the test cells in the large-scale fire testing facility at Underwriters Laboratories. The peak of the room was along the centreline of the room (Figure 6). The (152 x 356 mm) beams were present in all tests. The locations of the beams were varied. A channel beam and a box beam configuration were tested (Figure 7). The loft opening was opened or closed for various tests (Figure 6) (Golinveaux et al., 2007).

The fuel package was an upholstered sofa and chair, wooden coffee table and a wooden end table with a wastepaper basket beneath it. The wastepaper basket was filled with shredded paper. The fuel package was tested under a furniture calorimeter to characterise the HRR of the fuel package. The peak total HRR exceeded 4.5 MW and the convective HRR exceeded 2.5 MW. The fuel package was located either in the corner (with a 76 mm clearance between the back of the furniture and the wall) or in the centre of the room, as shown in Figure 8 (Golinveaux et al., 2007).

The room was installed with 6-25 sprinkler heads for various tests. Each sprinkler head discharged 49.2 Lpm and water flow to the sprinklers was not limited. Various sprinkler locations were tested (Golinveaux et al., 2007).

Type K, 1.5 mm diameter, Inconel sheathed thermocouples were located adjacent to each sprinkler to record ceiling temperatures. A thermocouple tree was suspended from the centre of the ceiling at the ridgeline. Eleven beaded Type K thermocouples were located every 305 mm of the 3.05 m length of the tree. Oxygen, carbon monoxide and carbon dioxide concentrations were measured by a gas probe located 1.5 m above the floor of the compartment and at a second probe located at the level of the loft opening. A schematic of the instrumentation layout is shown in Figure 9. Video and infrared cameras were used to record each test. Visual observations were also reported. (Golinveaux et al., 2007)

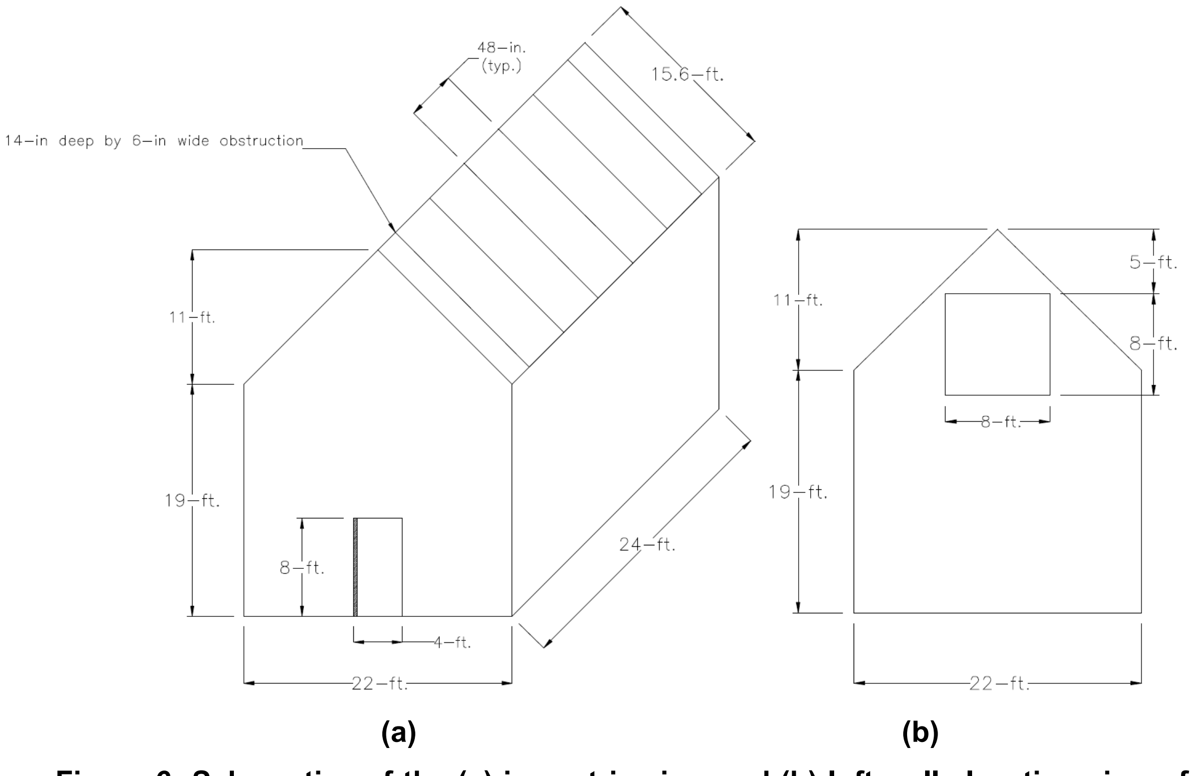
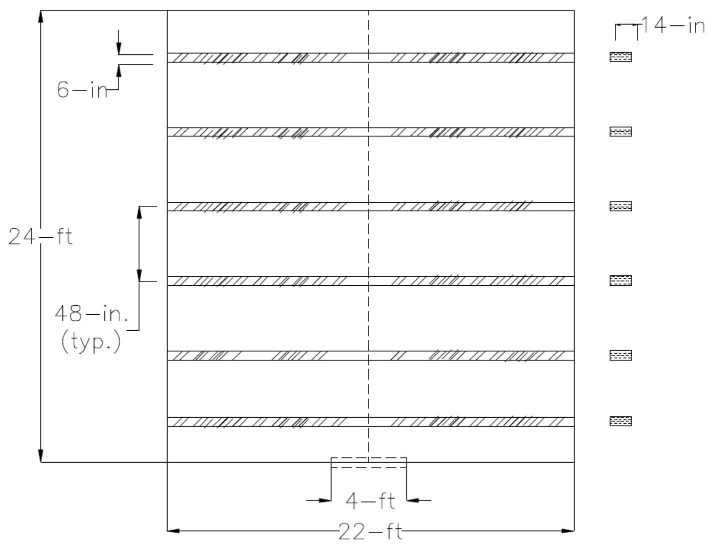
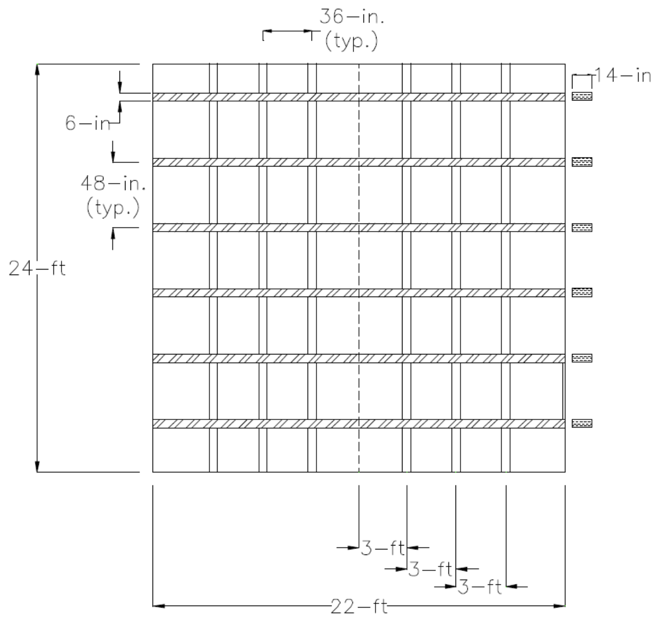


Figure 6: Schematics of the (a) isometric view and (b) loft wall elevation view of the test compartment for 45º slope ceiling tests. (Golinveaux et al., 2007)

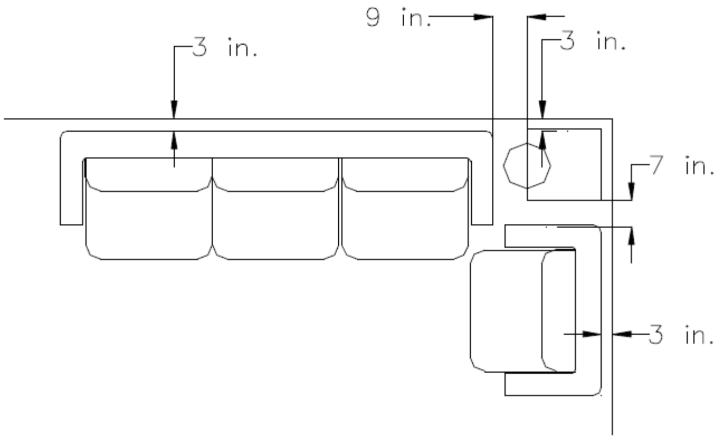


(a)

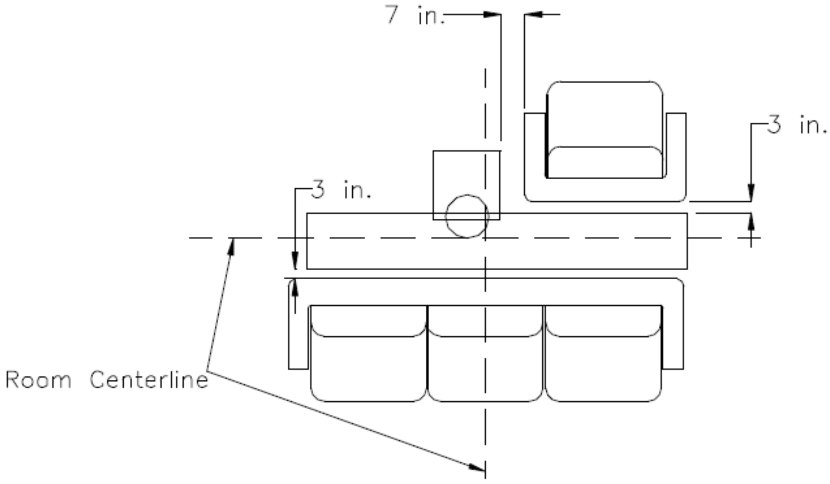


(b)

Figure 7: (a) Channel and (b) box beam configurations tested for 45º slope ceiling tests. (Golinveaux et al., 2007)

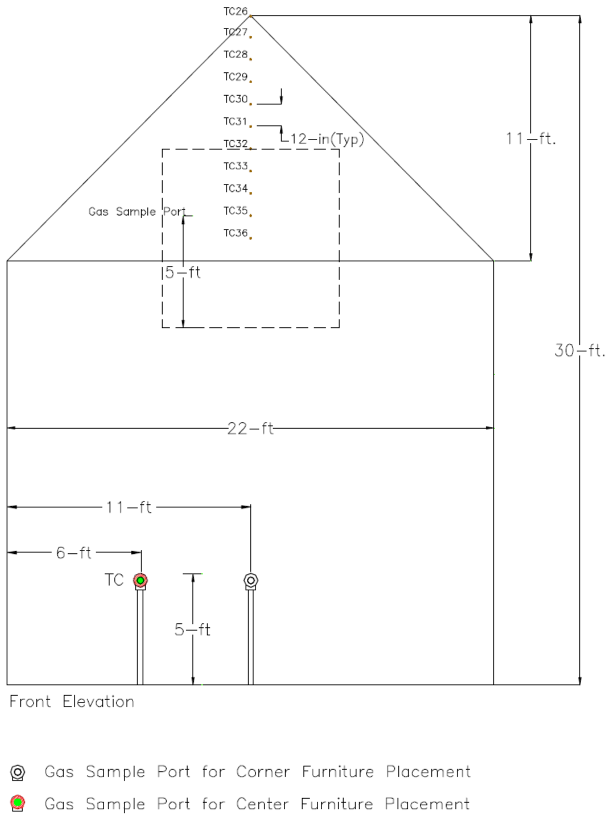


(a)

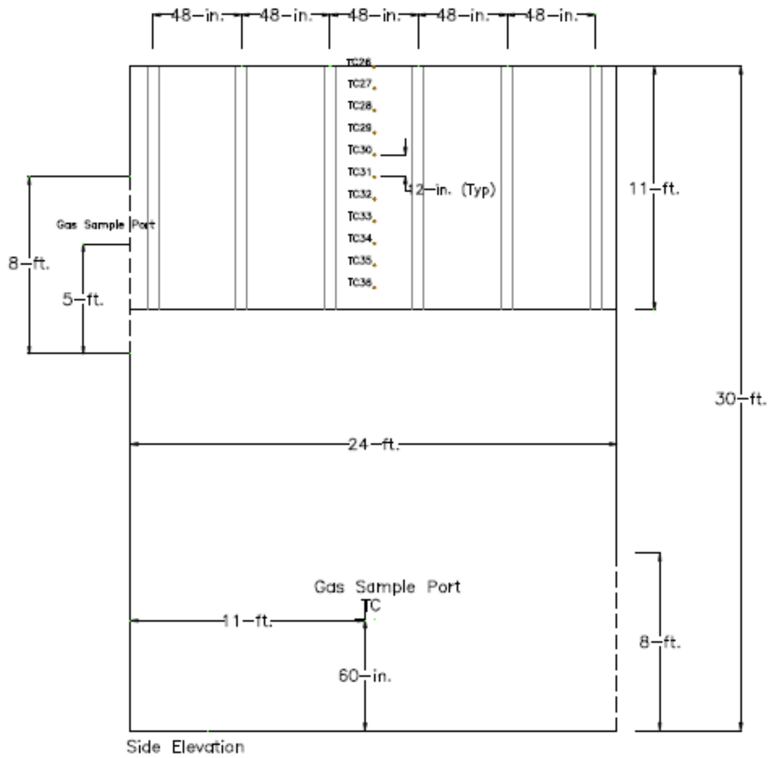


(b)

Figure 8: Schematics of the (a) corner and (b) centre configurations of the fuel package location for the 45º slope ceiling tests (Golinveaux et al., 2007)



(a)



(b)

Figure 9: Schematics of the instrumentation for (a) front view and (b) side view of the 45º slope ceiling tests (Golinveaux et al., 2007)

2.2.3.1.4 Test A.4

Twelve full-scale tests were conducted to investigate the influence of sloped ceilings, and sloped ceilings with beams, on residential sprinkler performance in the large-scale facilities at Underwriters Laboratories (Floyd et al., 2010).

The compartment sizes tested were varied up to 7.3 x 7.3 m. Some of the compartment layouts are shown in the schematics of Figure 10a to 10f (Floyd et al., 2010).

The sprinkler design was intentionally limited to two-head sprinkler design and the associated water supply, as related to applications of NFPA residential sprinkler standards for detached dwellings and residential occupancies up to four storeys (NFPA 13D, 2010a; NFPA 13R, 2010b). The flow supplied to each of the sprinklers was 49.2 L/min or the manufacturer's required flow rate to achieve a delivered density of 0.018 L/min/m². Recessed pendent and side-wall sprinkler types were tested. Two, four or six sprinkler heads were installed in each test (Floyd et al., 2010).

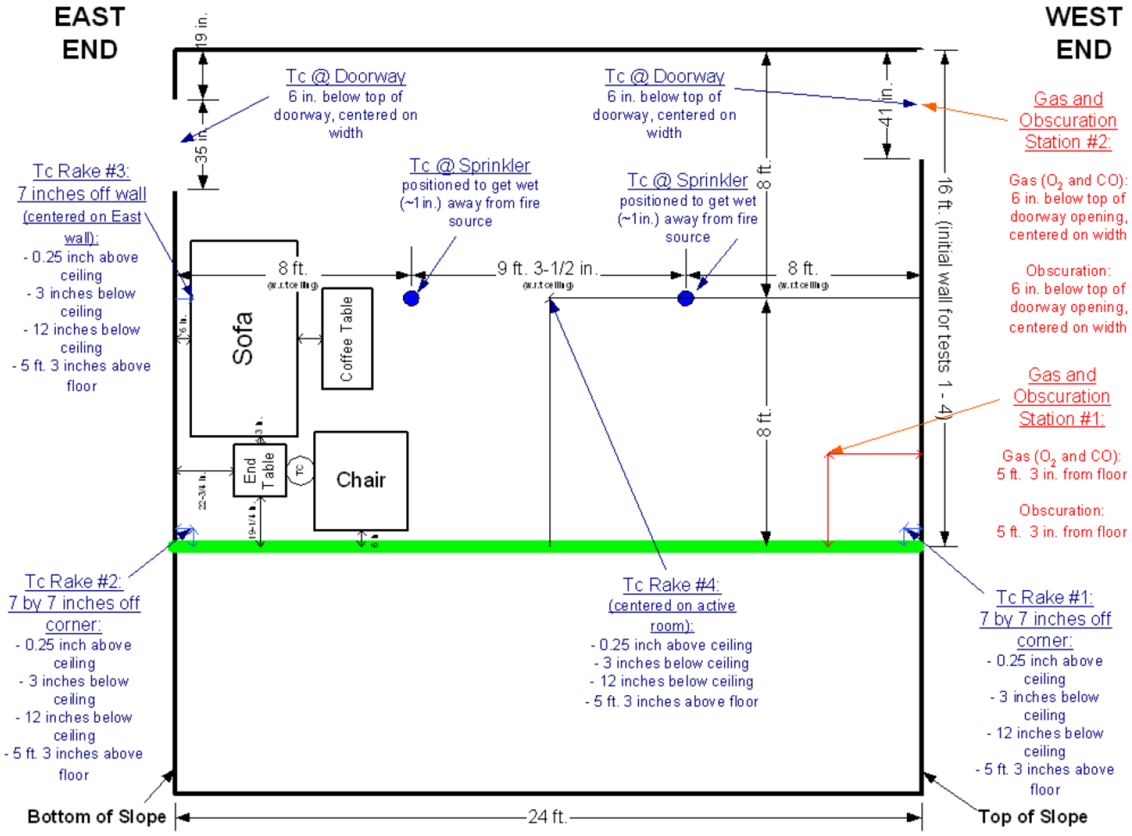
The fuel package consisted of actual resident furniture. A polyurethane foam-on-wooden-frame sofa and armchair, veneered particleboard end table and coffee table, and a metal wastepaper basket filled with shredded paper were used (Floyd et al., 2010). The fuel package was similar to that used by Factory Mutual in Los Angles and in other test programs, e.g. Golinveaux et al. (2007).

Approximately 230 g of shredded paper was used in the wastepaper basket. The fuel package, modified to include a cotton wick soaked in gasoline, was used between the wastepaper basket and the armchair to ensure fire spread. The cotton wick was ignited using an electric match. The fuel package used in testing was characterised using the results from four furniture calorimeter tests: two tests with the furniture against a non-combustible wall; one in a corner with non-combustible wall lining; and one in a corner with a combustible wall lining (Floyd et al., 2010).

The fire locations tested were low in the corner, low or high in the room centre, centre of the room, or centre of the room at a beam (Floyd et al., 2010).

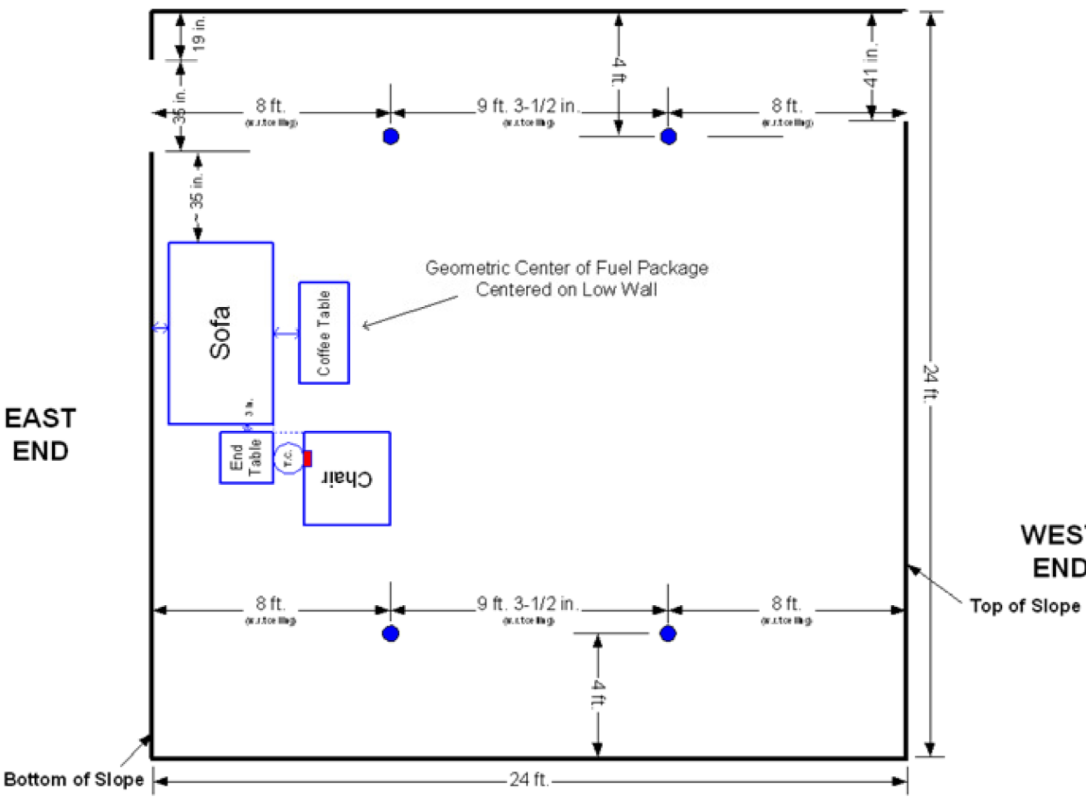
Four thermocouple trees, each with four thermocouples, located 6 mm above the ceiling, 76 and 305 mm below the ceiling and 1.6 m above the floor, were located within the room. Thermocouples were also located adjacent to each sprinkler head, to indicate sprinkler activation. Oxygen, carbon dioxide and carbon monoxide concentrations and smoke obscuration were measured above the doorway and at 1.6 m above the floor (Floyd et al., 2010).

It is noted that the experiments were intentionally designed for comparison with model outputs (Floyd et al., 2010). Therefore the location of the instrumentation and the sampling, and subsequently the data sets from testing, are in a form that is highly usable for model and test comparisons.



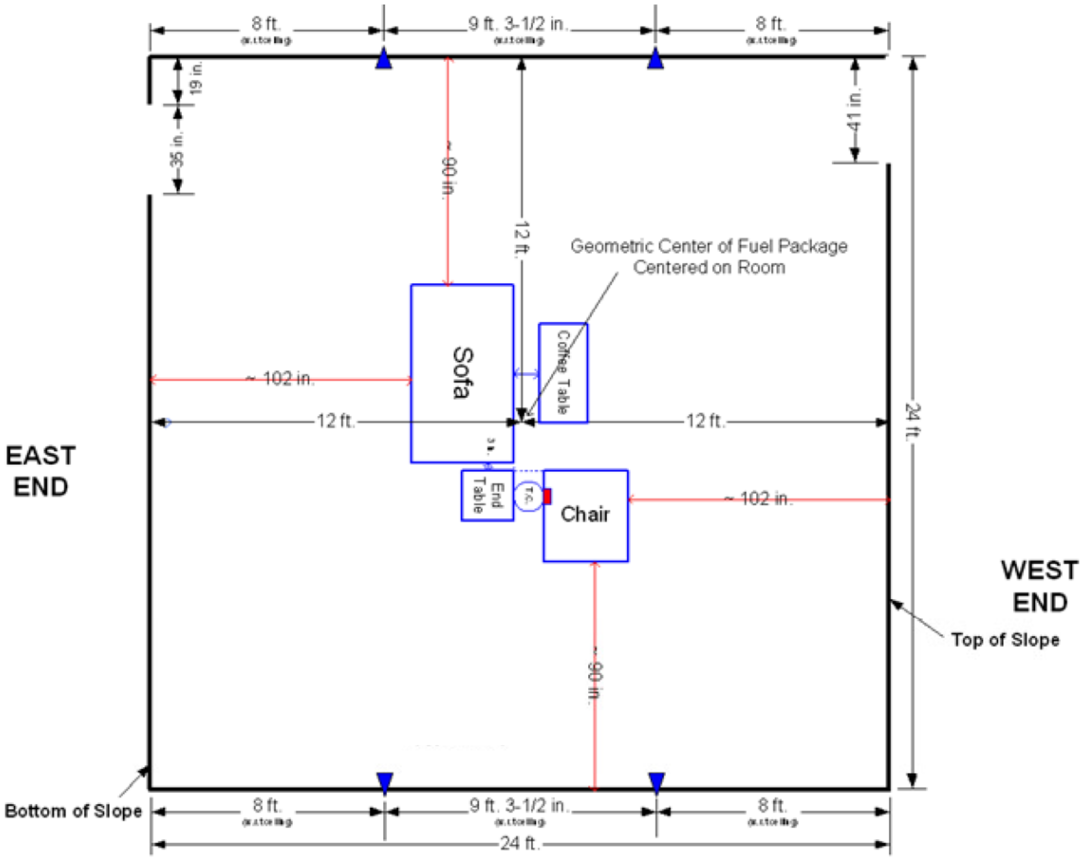
Test 1 - Room Plan View with Instrumentation

(a)



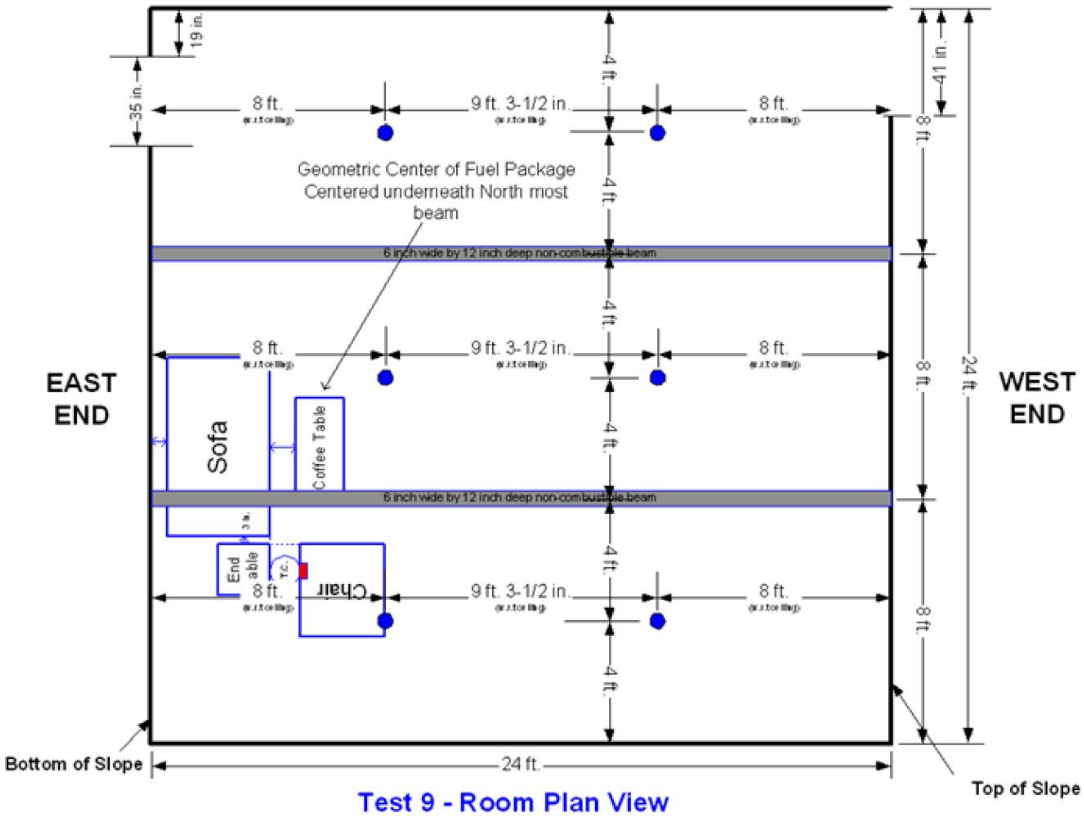
Test 5 - Room Plan View

(b)



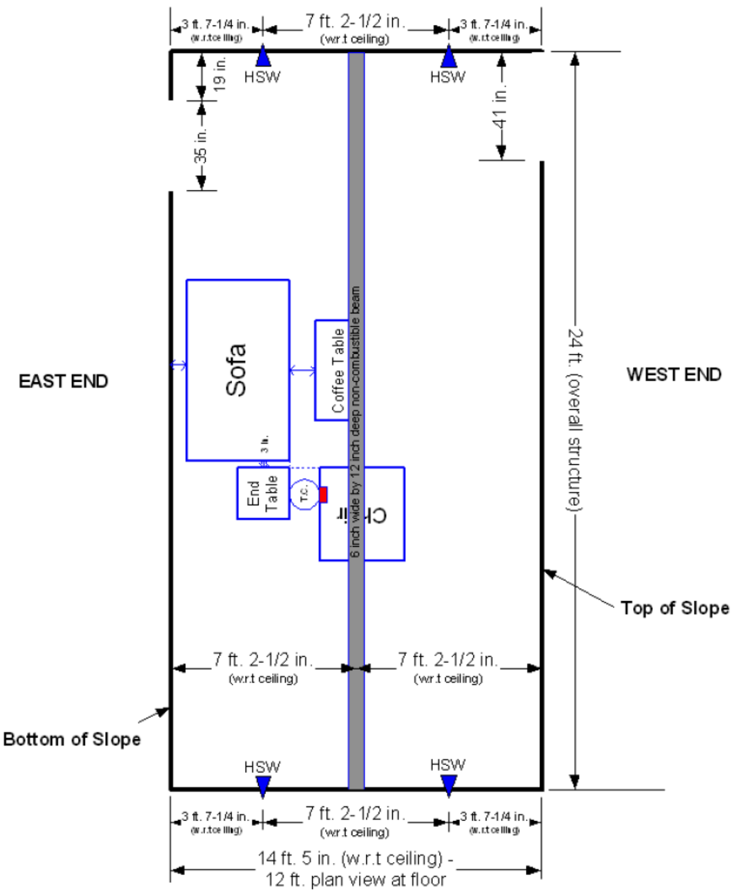
Test 7 - Room Plan View

(c)

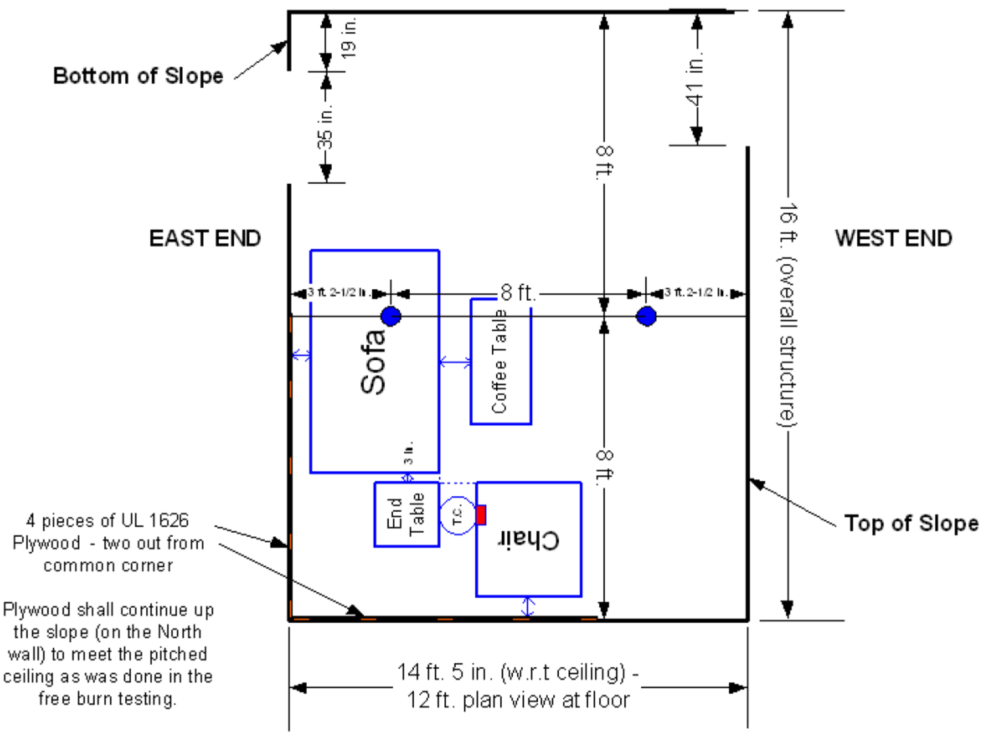


Test 9 - Room Plan View

(d)



(e)



(f)

Figure 10: Schematics of the plan view setup for a range of tests conducted for residential sprinklers tests with sloped ceilings and beams (Floyd et al., 2010)

2.2.3.2 Ventilation

2.2.3.2.1 Test A.5

One set of tests, forming part of the ship-board accommodation test program (Turner, 1993), were performed in a cabin/corridor test setup, as shown in the example schematic of Figure 1. Air supply to the cabin was maintained at 40 L/s through a vent in the ceiling of the cabin. Tests were conducted with the variants of the cabin door left open or closed. Variants of the fire types tested included simulated arsonist fires and fires over 1 MW that went to flashover.

Thermocouple temperatures, rate of smoke production and HRR were recorded for each test. An example of the temperature in the cabin during a test with automatic activation of the water mist system and the door closed is shown in Figure 1. The thermocouple temperatures and HRRs for a flashover fire and manual activation of the water mist system were reported (Turner, 1993).

The full test report is: Arvidson M & Ryderman A. 1992. *Cabin and Public Space Fire Tests with Marioff's Hi-fog Fire Protection System.* Swedish National Testing and Research Institute, 91 R30141, Borås, Sweden (Turner, 1993).

2.2.3.2.2 Test A.6

Room fires in a dormitory with and without sprinklers were investigated. The fire room chosen was a day room (Figure 12) that was open into a dormitory corridor (59.6 m long and 1.35 m wide by 2.08 m high), as shown in Figure 11. The building the tests were conducted in consisted of poured concrete floor and ceiling with concrete block walls. (Madrzykowski et al., 2004)

No floor coverings were installed. The walls and windows of the day room were covered with 12 mm thick gypsum board. A fire-resistant aspen wood drop ceiling was installed in both the day room and the corridor. The drop roof consisted of tiles. At the west end of the corridor was a 1.35 m wide by 0.61 m high vent at floor level. At the east end of the corridor was an open window, with the dimensions 0.8 x 0.3 m of clear area. In Tests 1 and 2, four additional windows (also of 0.8 x 0.3 m clear area) were opened in sleeping rooms with the door to the corridor remaining closed. In Test 3, five sleeping room doors were left open (Madrzykowski et al., 2004).

The day room space was furnished with three sofas, as shown in Figure 12. A bulletin board was located on the wall above one of the sofas. Two pieces of craft paper were draped from the bulletin board onto the sofa (Madrzykowski et al., 2004).

Thermocouple trees with eight thermocouples each (at 0.025, 0.305, 0.610, 0.910, 1.22, 1.52 and 1.83 m below the ceiling) were located along the centreline of the corridor and two in the day room, as shown in Figure 11 and Figure 13. Heat flux gauges were also used throughout the corridor. Smoke alarms were mounted under the suspended ceiling, and the time to activation was also reported (Madrzykowski et al., 2004).

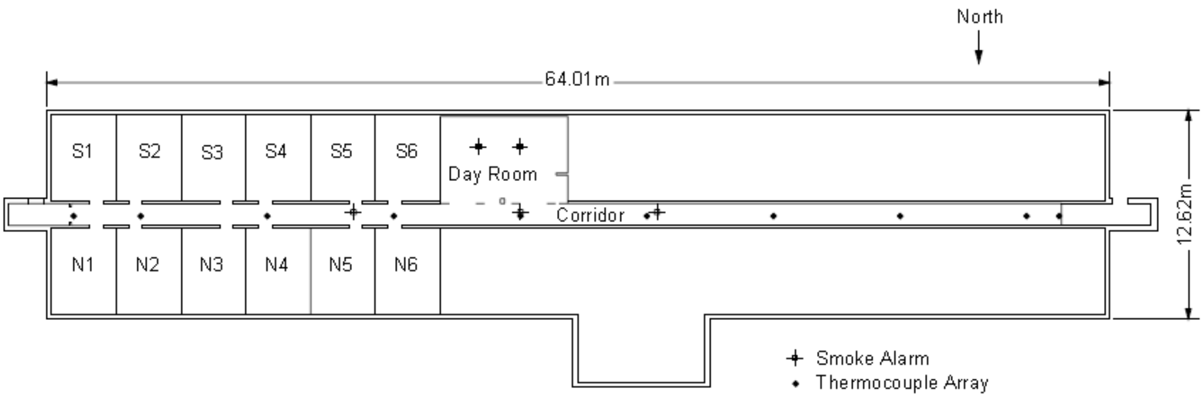


Figure 11: Schematic of the floor plan of the dormitory including thermocouple array and smoke alarm locations (Madrzykowski et al., 2004)

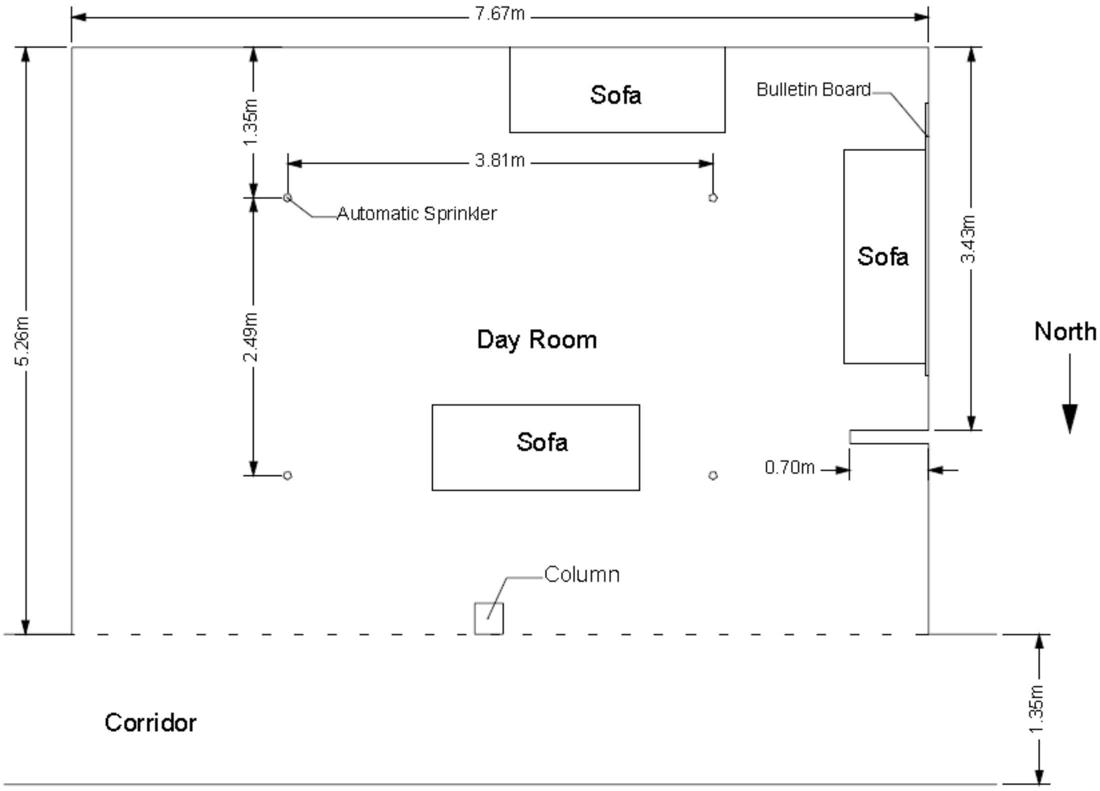


Figure 12: Schematic of the day room fuel load for the dormitory tests and sprinkler locations (Madrzykowski et al., 2004)

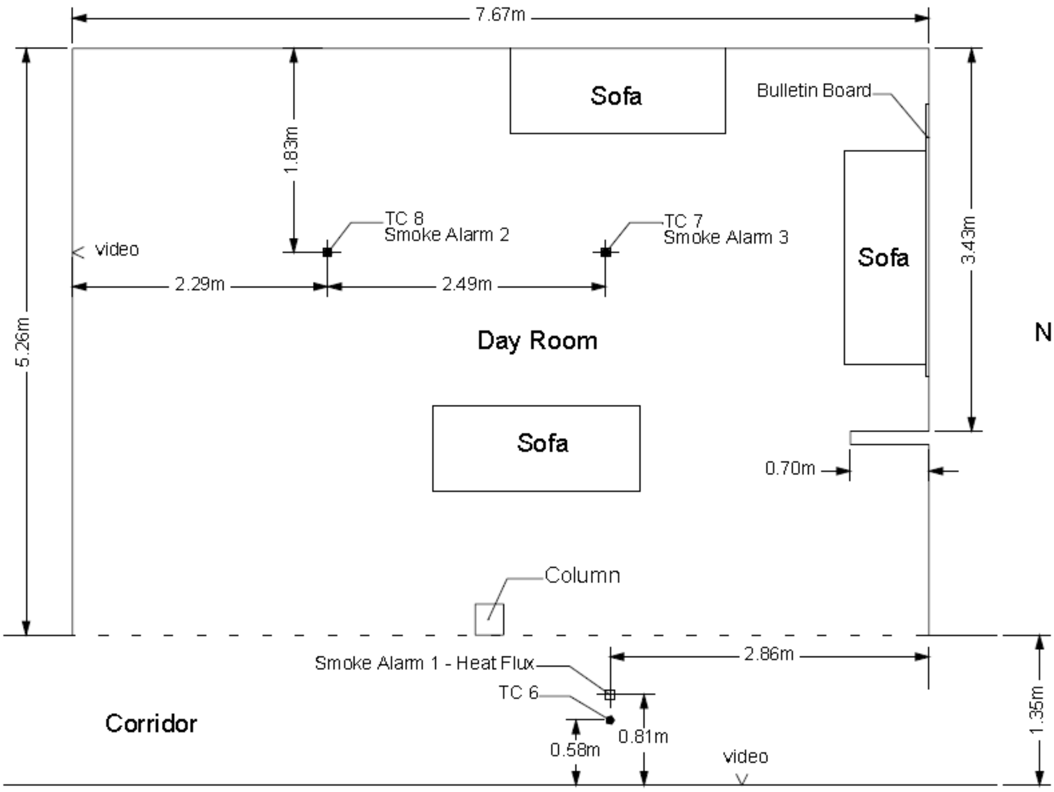


Figure 13: Schematic of the day room instrumentation locations (Madrzykowski et al., 2004)

2.2.3.2.3 Test A.7

Two sprinklered sleeping room fire tests were conducted and three unsprinklered sleeping room fire tests were performed for comparison. The 3.37 x 4.45 m sleeping rooms were part of a dormitory, with a number of individual sleeping rooms off one side of a corridor 19.2 m long by 2.54 m wide, as shown in Figure 14 and Figure 15. The opposite side of the corridor consisted of single pane windows (Madrzykowski and Walton, 2010).

Each sleeping room contained two beds, two desks, two chests, a wooden cabinet three plastic storage crates, a wastepaper basket, and other contents, as shown in Figure 16. Bed-clothes, clothes and paper were also arranged within the room, as shown in Figure 17 (Madrzykowski and Walton, 2010).

The wastepaper basket was located adjacent to a bed and a desk with a plastic storage crate positioned under it. This basket was over-filled with newspaper that was lit to start each of the tests (Madrzykowski and Walton, 2010).

Tests were performed with either the door of the sleeping room open or closed (Madrzykowski and Walton, 2010).

The sleeping rooms and corridor were instrumented with thermocouple trees, gas concentration analysers (for oxygen, carbon dioxide and carbon monoxide), heat flux gauges, smoke detectors, video cameras, and infrared cameras, as shown in Figure 18 (Madrzykowski and Walton, 2010).

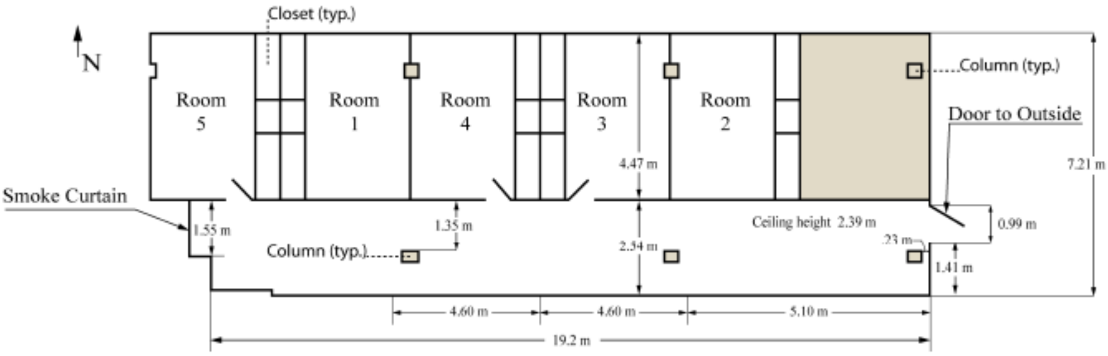


Figure 14: Schematic of the layout of the sleeping room dormitory fire tests (Madrzykowski and Walton, 2010)

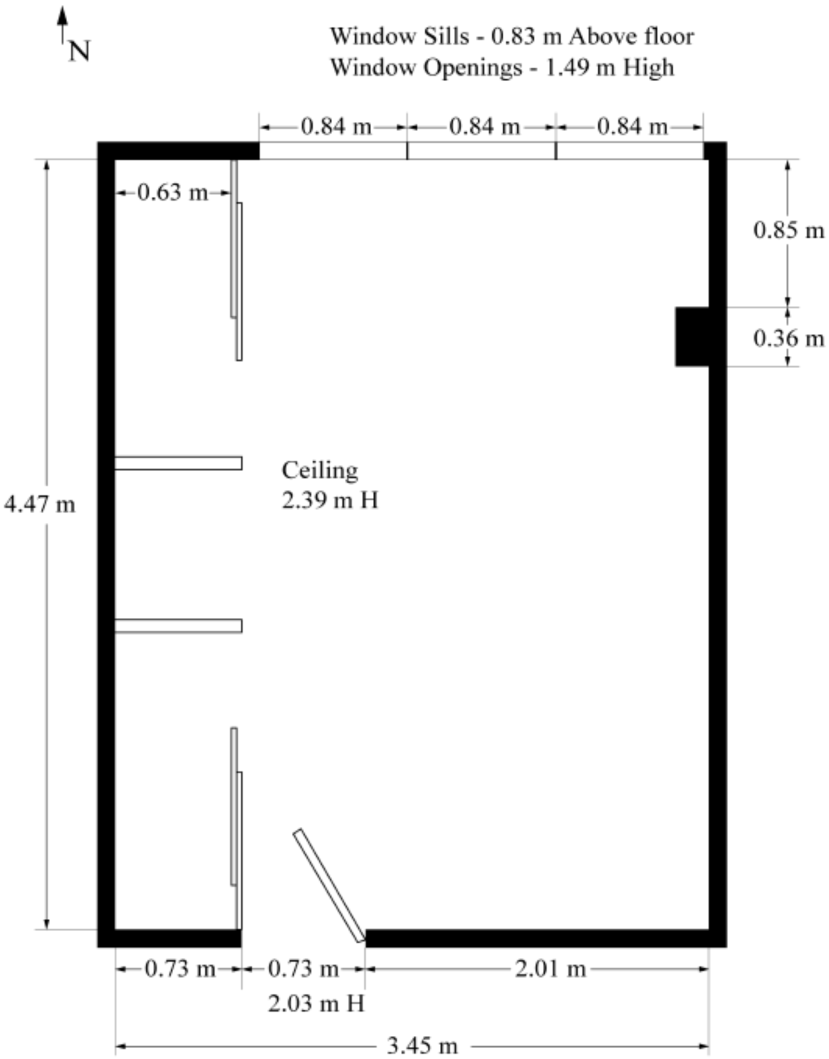


Figure 15: Floor plan of a sleeping room used as the fire room (Madrzykowski and Walton, 2010)

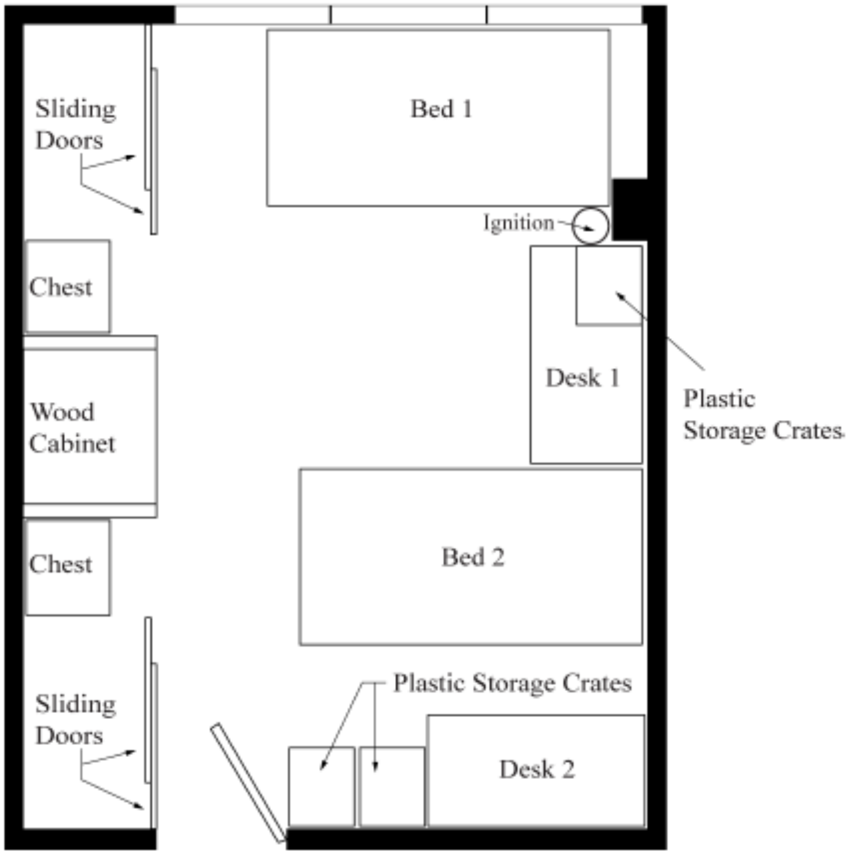
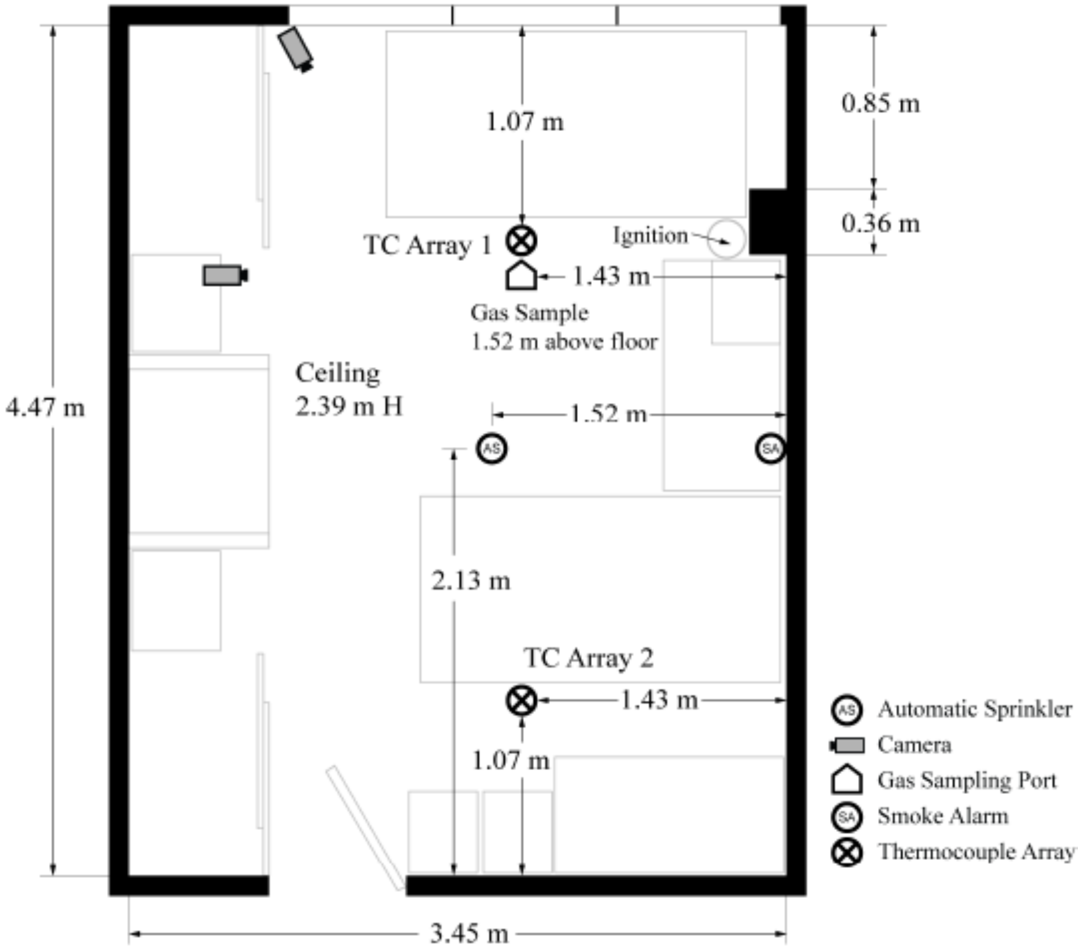
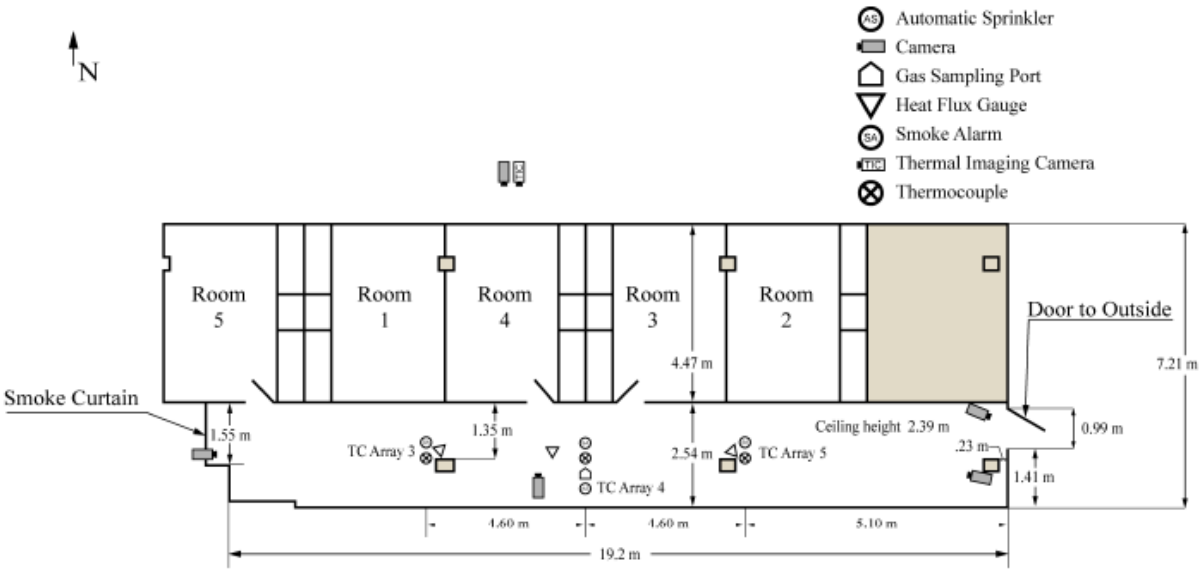


Figure 16: Schematic of contents of a sleeping room in the dormitory building (Madrzykowski and Walton, 2010)

Figure 17: Example of the bed fuel package used in the sleeping room tests (Madrzykowski and Walton, 2010)



(a)



(b)

Figure 18: Schematic of the instrumentation in the (a) sleeping room and (b) corridor of the dormitory tests (Madrzykowski and Walton, 2010)

2.2.3.3 Fire type and size

2.2.3.3.1 Test A.8

A series of tests was conducted to evaluate the use of water mist in ship-board accommodation, specifically marine cabins, large rooms and public spaces, by the Swedish National Testing and Research Institute and Marioff Oy of Finland (Turner, 1993; Arvidson, 1994; Jacobsen, 1993). The spaces were furnished with ordinary combustibles.

Fire types included in these experiments were simulated arson fires, flashover fires and wood crib fires. Tests were performed with open and closed doors. The effects of different types of nozzles, flux density and nozzle location on the water mist fire suppression system performance were investigated (Turner, 1993; Arvidson, 1994; Jacobsen, 1993). The focus of these experimental programs was to evaluate whether or not water mist systems could replace standard sprinkler systems.

More than 60 tests were conducted at the Swedish National Testing and Research Institute (Turner, 1993).

The set of tests forming part of the ship-board accommodation test program (Turner, 1993) were performed in a cabin/corridor test setup, as shown in the example schematic of Figure 1. Variants of the fire types were also tested, including simulated arsonist fires and fires over 1 MW that went to flashover. Thermocouple temperatures, rate of smoke production and HRR were recorded for each test (Turner, 1993).

The full test report is: Arvidson M & Ryderman A. 1992. *Cabin and Public Space Fire Tests with Marioff's Hi-fog Fire Protection System.* Swedish National Testing and Research Institute, 91 R30141, Borås, Sweden (Turner, 1993).

2.2.3.3.2 Test A.9

As part of the ship-board accommodation test program (Turner, 1993), four different wood crib fire tests were conducted in a 100 m² area, based on ISO 6182 Part 1 (ISO, 2004) and Part 2 (ISO, 2005).

The full test report is: Arvidson M & Ryderman A. 1992. *Cabin and Public Space Fire Tests with Marioff's Hi-fog Fire Protection System.* Swedish National Testing and Research Institute, 91 R30141, Borås, Sweden (Turner, 1993).

2.2.3.3.3 Test A.10

As part of the ship-board accommodation test program (Turner, 1993), a closed room fire test was conducted in an unventilated (9.6 x 6.0 m x 3.1 m high) space. Two sofas were placed in the compartment. A fire was initially started in one sofa. A water mist system was present in the compartment.

The full test report is: Arvidson M & Ryderman A. 1992. *Cabin and Public Space Fire Tests with Marioff's Hi-fog Fire Protection System.* Swedish National Testing and Research Institute, 91 R30141, Borås, Sweden (Turner, 1993).

2.2.3.3.4 Test A.11

Eight house fires were conducted with the primary focus of the experiments was to investigate the effectiveness of residential sprinklers as they relate to the life safety of the room of fire origin (Williams and Campbell, 2004). It was noted that sprinkler systems installed in accordance with DD252 (BSI, 2002) are not necessarily intended to extinguish the fire. Instead the design intent is to control the fire to allow escape or rescue of the occupants (Williams et al., 2004).

The house used for testing was a two-storey detached house with a loft conversion (Figure 19). The ground floor consisted of a lounge (4 x 3.5 m wide by 2.4 m high), a kitchen, a dining room and a hallway (Figure 21). The wall between the lounge and hall could be removed, as shown in Figure 20. The first floor consisted of two bedrooms and a bathroom. The stairs between the floors was a straight flight of stairs up to the loft room, which had a fire-resisting door.

Double-glazed windows were used in the lounge, main bedroom and loft windows. These windows were closed for all tests conducted. The door of the main bedroom was partially open. The door of the loft room and bathroom were closed. The doors were also closed and sealed between the dining room and kitchen, back bedroom and landing, and kitchen and hallway (Williams and Campbell, 2004).

Of the house fires, eight tests were conducted with and then without a sprinkler system present. Five of each of these eight tests were conducted using a lounge arrangement where all the walls were present. Three of the tests were conducted with the wall between the lounge and hallway removed, to allow a more open-plan style arrangement (Williams and Campbell, 2004).

The fuel packages were arrays of realistic residential fuel sources. New furniture items, bought from IKEA, were used as the main fuel load in the house. These items had been chosen based on their availability and use by young families and first-home buyers. The main fuel items consisted of a three-seater sofa, two armchairs, a coffee table, a rug, two shelving units, a pair of tab top curtains, a television and a television table.

When the house arrangement without the wall between the lounge and hallway was in use, then there was an additional shelving unit present. The televisions were second-hand and European. Additional items were included in the room, such as new candles, second-hand newspapers, magazines, chair throws, cushions, magazine rack, videos and various ornaments. The arrangement of the fuel items is shown in the schematic of Figure 20. An example of the fuel setup in the lounge is shown in Figure 22 (Williams and Campbell, 2004).

The ignition source was a lit tea-light candle (pre-burnt for 60 s) placed under the front left-hand corner of the television (Williams and Campbell, 2004).

The test parameters investigated included the ventilation by opening or closing the door between the lounge and hallway, water flow rate (60 L/min for one sprinkler or 84 L/min for two sprinklers), sprinkler head configuration (number and location), and sprinkler head type (two pendent types were tested) (Williams and Campbell, 2004).

The results were presented in terms of tenability, as related to carbon monoxide, carbon dioxide and oxygen concentrations at head height, gas temperatures at head height, and optical density. The amount of fuel burnt, in terms of area, was also reported (Williams and Campbell, 2004).

Gas temperatures, concentrations of carbon monoxide, carbon dioxide and oxygen concentrations, smoke optical density and visibility, initial relative humidity within the lounge room, sprinkler water flow rates, time to smoke alarm activation, and time to sprinkler activation were reported. Observations made during the fires and post-fire damage areas were also reported. The locations of the instrumentation used are shown in Figure 21 (Williams and Campbell, 2004).

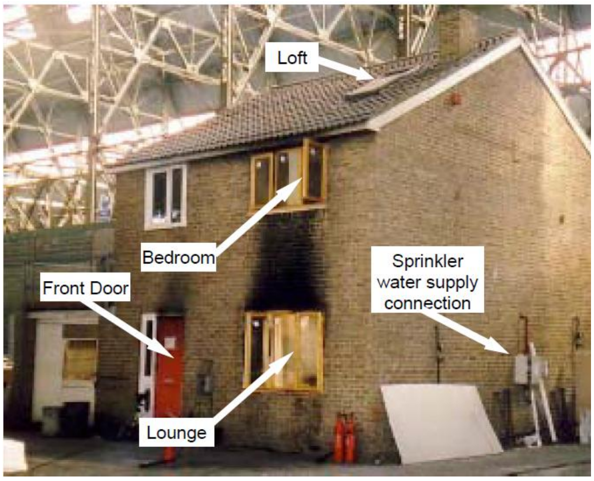


Figure 19: Photo of the external of the house used for fire testing (Williams and Campbell, 2004)

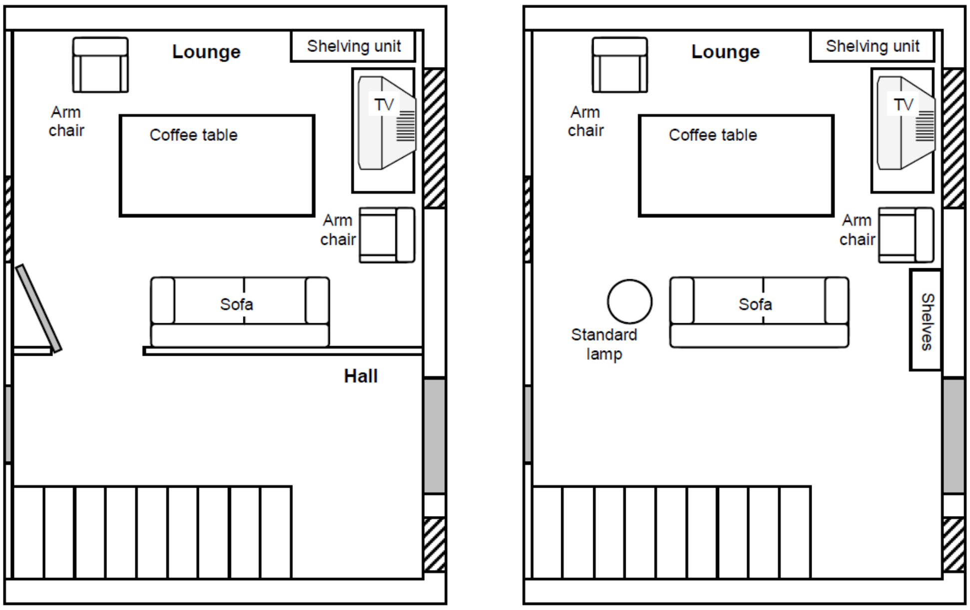


Figure 20: Schematic of the layout of the lounge and hall (a) with and (b) without the wall between the rooms present (Williams and Campbell, 2004)

Figure 21: Schematic of the house and instrumentation used for fire testing (Williams and Campbell, 2004)

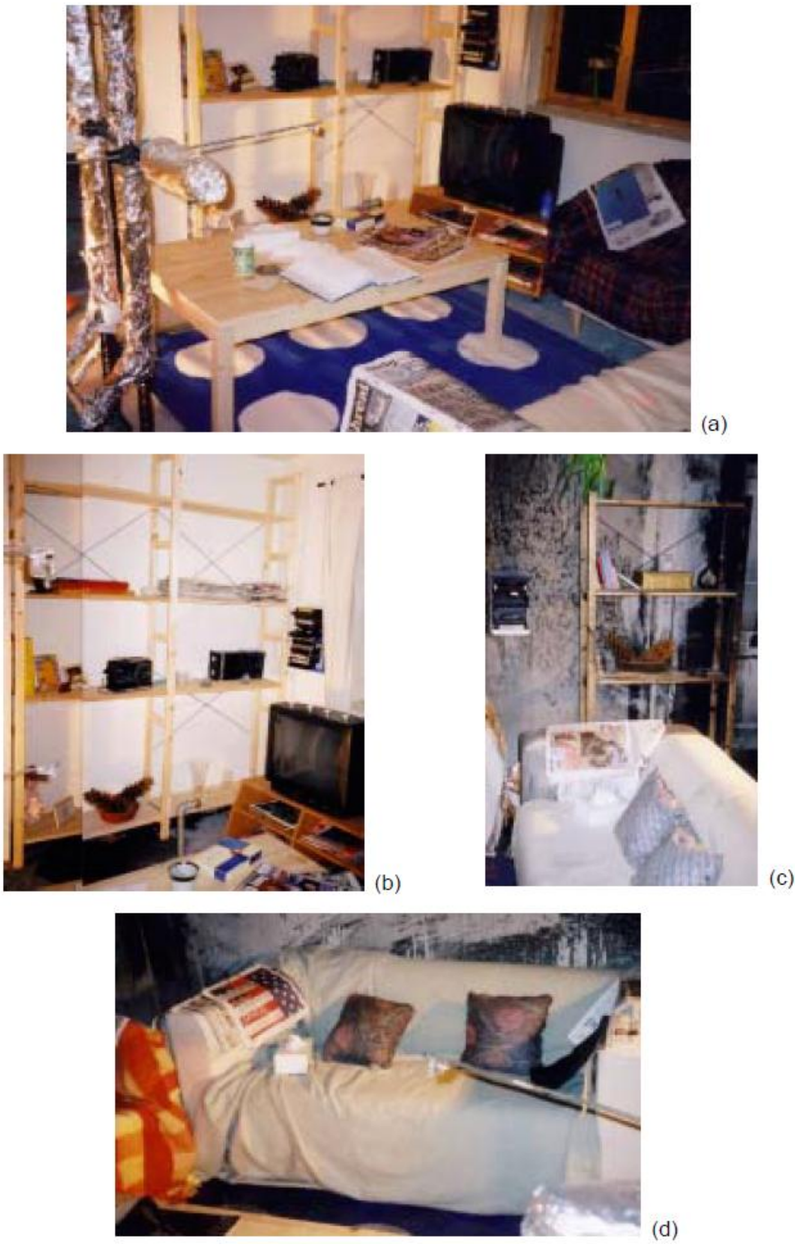


Figure 22: An example of the furnished lounge setup in the house fire test (Williams and Campbell, 2004)

2.2.3.3.5 Test A.12

Twenty-nine compartment fires were conducted with the primary focus of the experiments was to investigate the effectiveness of residential sprinklers as they relate to the life safety of the room of fire origin (Williams and Campbell, 2004). The sprinkler systems tested were installed in accordance with DD252 (BSI, 2002), where the design intent is to control the fire to allow escape or rescue of the occupants (Williams et al., 2004).

The compartment fires were conducted in a test facility formed by a timber frame with plasterboard walls and ceramic fibreboard ceiling. There were two (4 x 4 m wide by 2.5 m high) compartments connected to a centre compartment that was either 3.8 x

4 m (Figure 23 and Figure 24) or 8 x 4 m wide (Figure 30 and Figure 31) by 2.5 m high (Williams and Campbell, 2004).

Smoke alarms were located in the room of fire origin and the adjacent room. These were replaced after each test (Williams and Campbell, 2004).

Five scenarios were investigated (Williams and Campbell, 2004):

1. Lounge, television fire (lit by a nightlight candle), shielded fire.
2. Lounge, fire under table directly below sprinkler head, shielded fire.
3. Bedroom scenario, fire on duvet, unshielded fire.
4. Lounge, fire on sofa (compliant with 1988 Furniture Regulations), unshielded fire.
5. Kitchen, oil pan fire, unshielded.

The lounge scenario (1, 2 and 4) test setup consisted of similar fuel loadings of the compartment, but with different items used as the primary ignition source. The fire load was similar to the house tests that were also conducted by Williams and Campbell (2004). The main furniture items were new and were IKEA-type furniture. The main fuel items consisted of a three-seater sofa, an armchair, a coffee table, a rug, two shelving units, a pair of table-top curtains, a television table and a second-hand television.

Additional items were included in the room, such as new candles, second-hand newspapers, magazines, chair throws, cushions, magazine rack, videos and various ornaments. The layout of the lounge for the television fire scenario (1) is shown in the schematic of Figure 25 (Williams and Campbell, 2004).

The lounge scenario with the fire under a table (2) test setup was similar to that of scenario 1, using similar items. The layout of the lounge for the fire located under the table scenario (2) is shown in the schematic of Figure 26. The table consisted of a single sheet of 1.2 x 0.8 m plywood with eight wooden battens. The mock-up table-top was supported on concrete blocks. Six scrunched newspapers were put under the table on top of a piece of Hessian-backed carpet that was the same size as the table-top. The newspapers were lit to start the test (Williams and Campbell, 2004).

The lounge scenario with the sofa fire (4) test setup was similar to that of scenarios 1 and 2, using similar items. The layout of the lounge for the sofa fire scenario (4) is shown in the schematic of Figure 27. The sofa was the same type as used in the other scenarios. A lit nightlight candle placed below three scrunched up newspapers was used as the ignition source (Williams and Campbell, 2004).

The bedroom scenario with the bed-clothes fire (3) test setup used new Argos-type furniture. The layout of the bedroom fire scenario (3) is shown in the schematic of Figure 28. The main items used in this included a single bed, two bedside cabinets, a wicker chair and a fabric clothes hanging space. Additional items included bedding, bedside table items, a floor rug, cushions, and items of clothing on plastic hangars. The bed was made with fitted sheets, pillow and duvet and an additional small cushion placed next to the pillow. A lit nightlight candle placed under the corner of the pillow, adjacent to the cushion, was used as the ignition source (Williams and Campbell, 2004).

The kitchen scenario with the cooking oil fire (5) test setup was based on BS/EN 1869 (BSI, 1997). The layout of the kitchen fire scenario (5) is shown in the schematic of Figure 29. A 350 mm diameter pan with 100 mm sidewalls was used as the cooking vessel, and 3 L of new sunflower cooking oil was placed in the pan. The pan was placed on a metal frame that was 140 mm high. The frame was placed in the centre of a mock-up table-top made of a sheet of fire-resisting board supported on concrete blocks. The remainder of the compartment was left empty (Williams and Campbell, 2004).

A propane burner was used to heat the oil to the auto-ignition temperature (approximately 360ºC). To prevent the compartment from heating during the initial heating of the oil, the external door to the compartment was left open until the oil temperature reached 350ºC. On ignition of the oil, the gas supply to the burner was turned off (Williams and Campbell, 2004).

Each of the scenarios from (1) to (4) was repeated both with and without sprinklers and with the door to the room of fire origin opened and closed. The kitchen scenario (5) was repeated with and without sprinklers, and two types of pendent sprinkler head were tested (Williams and Campbell, 2004).

For scenarios numbered (1) and (2), the shielded fires involving the television and the table were further investigated in terms of the influence of compartment size (4 x 4 m or 8 x 4 m wide by 2.5 m high), sprinkler head type, sprinkler location, and water flow rate (in the smaller compartment of 60 or 42 L/min for a single sprinkler, and in the larger compartment of 60 L/min for a single sprinkler or 84 L/min for two sprinkler activation) (Williams and Campbell, 2004).

In each case, the fuel was conditioned before each test. In addition, the compartments were allowed to dry out between tests (Williams and Campbell, 2004).

Gas temperatures, concentrations of carbon monoxide, carbon dioxide and oxygen concentrations, smoke optical density and visibility, initial relative humidity within the lounge room, sprinkler water flow rates, time to smoke alarm activation, and time to sprinkler activation were reported. Observations made during the fires and post-fire damage areas were also reported. The locations of the instrumentation used are shown in Figure 23 and Figure 24 (Williams and Campbell, 2004). These are the same types of measurements reported for the house fire tests that were also conducted by Williams and Campbell (2004).

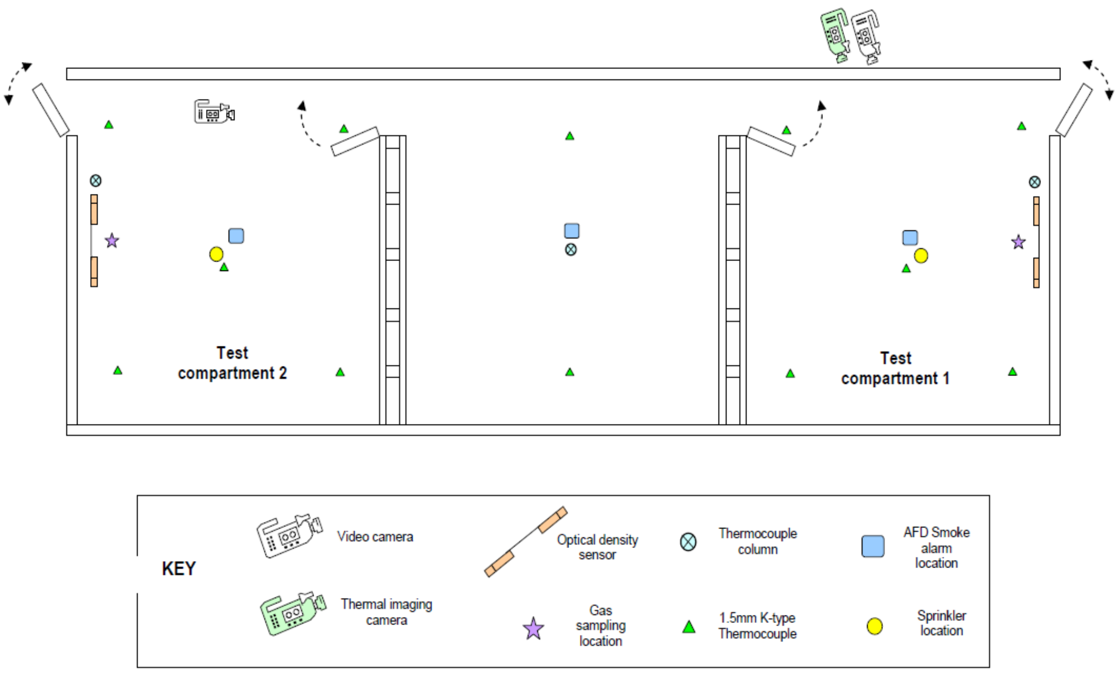


Figure 23: Schematic of the layout and instrumentation of the compartment fires for the 3.8 x 4 m adjacent compartment setup (Williams and Campbell, 2004)

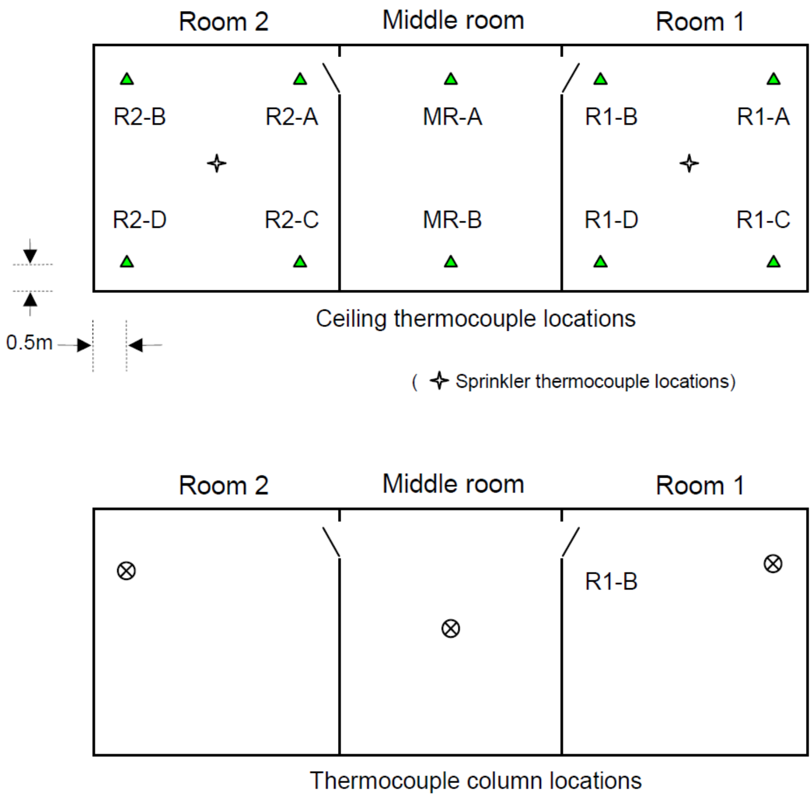


Figure 24: Schematic of the thermocouple locations used in the compartment fires for the 3.8 x 4 m adjacent compartment test setup (Williams and Campbell, 2004)

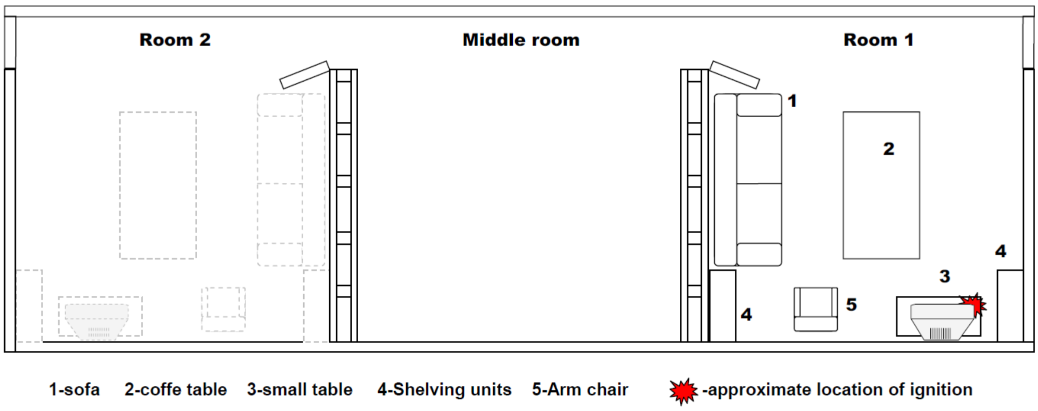


Figure 25: Schematic of the compartment and fuel arrangement for lounge scenario with the shielded television fire (Williams and Campbell, 2004)

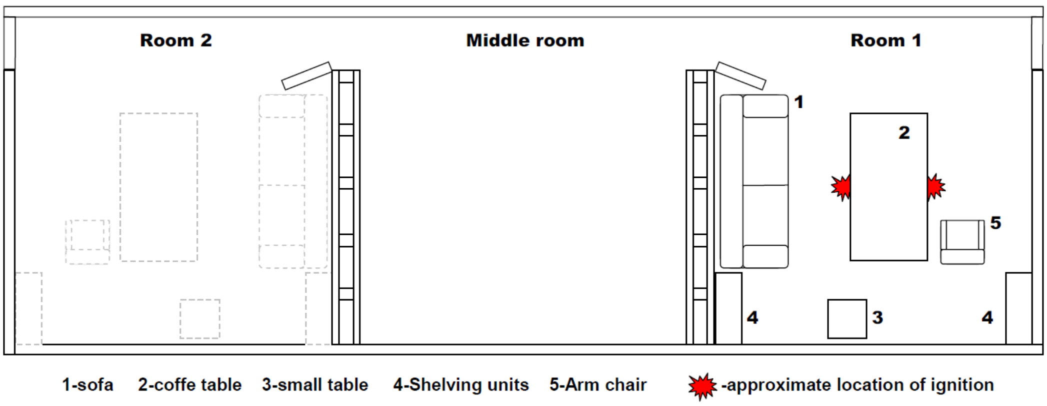


Figure 26: Schematic of the compartment and fuel arrangement for lounge scenario with the shielded fire under the table (Williams and Campbell, 2004)

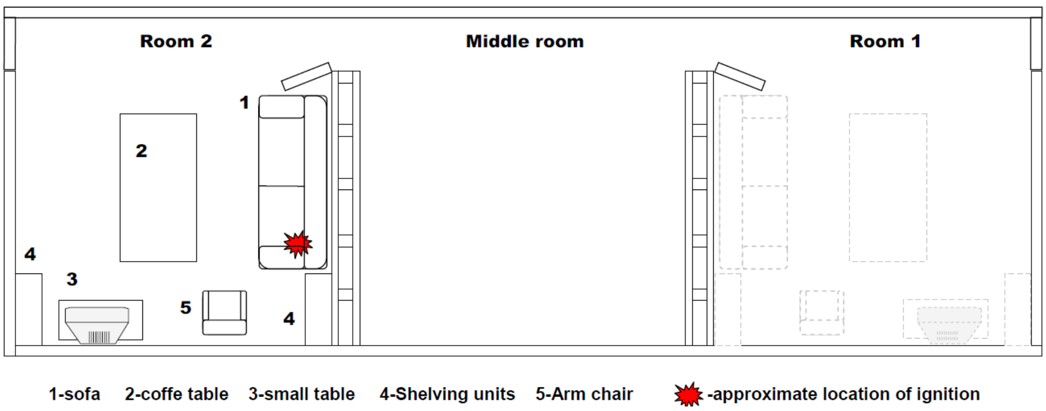


Figure 27: Schematic of the compartment and fuel arrangement for lounge scenario with the sofa fire (Williams and Campbell, 2004)

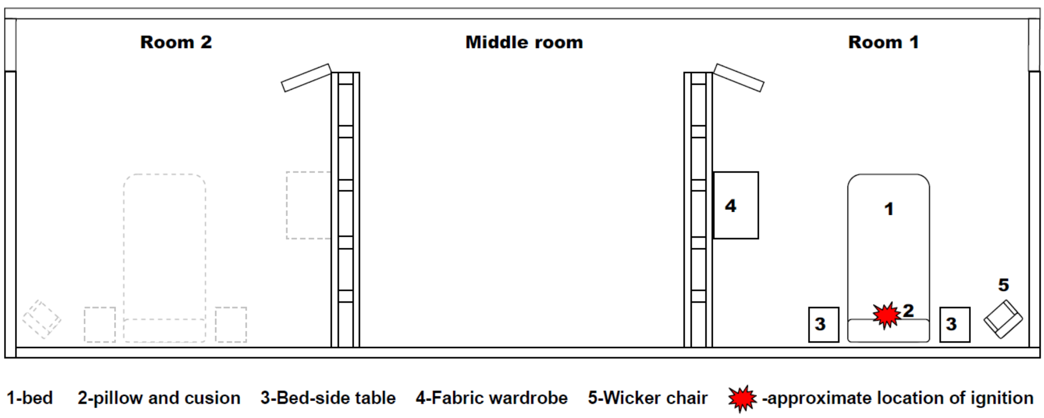


Figure 28: Schematic of the compartment and fuel arrangement for the bedroom scenario with the bed-clothes fire (Williams and Campbell, 2004)

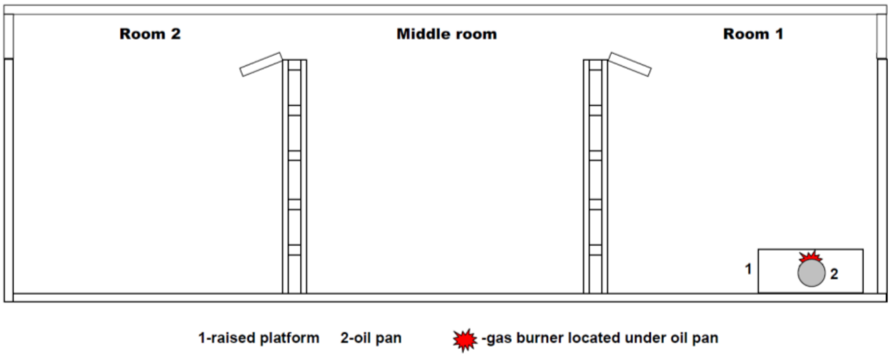


Figure 29: Schematic of the compartment and fuel arrangement for the kitchen scenario with the cooking oil fire (Williams and Campbell, 2004)

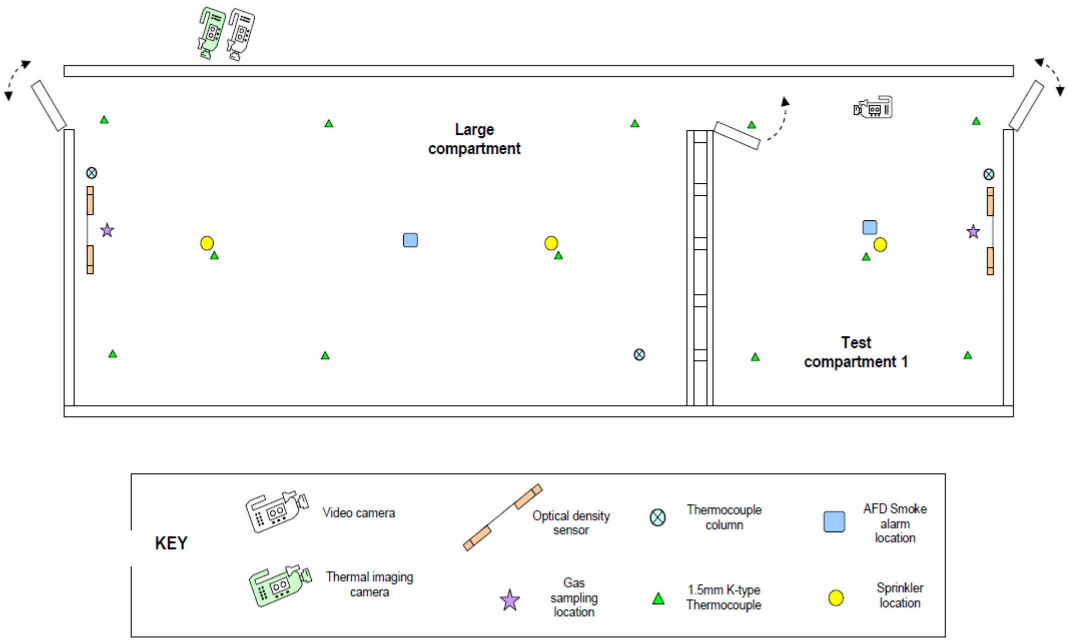


Figure 30: Schematic of the layout and instrumentation of the compartment fires, for the 8 x 4 m adjacent compartment test setup (Williams and Campbell, 2004)

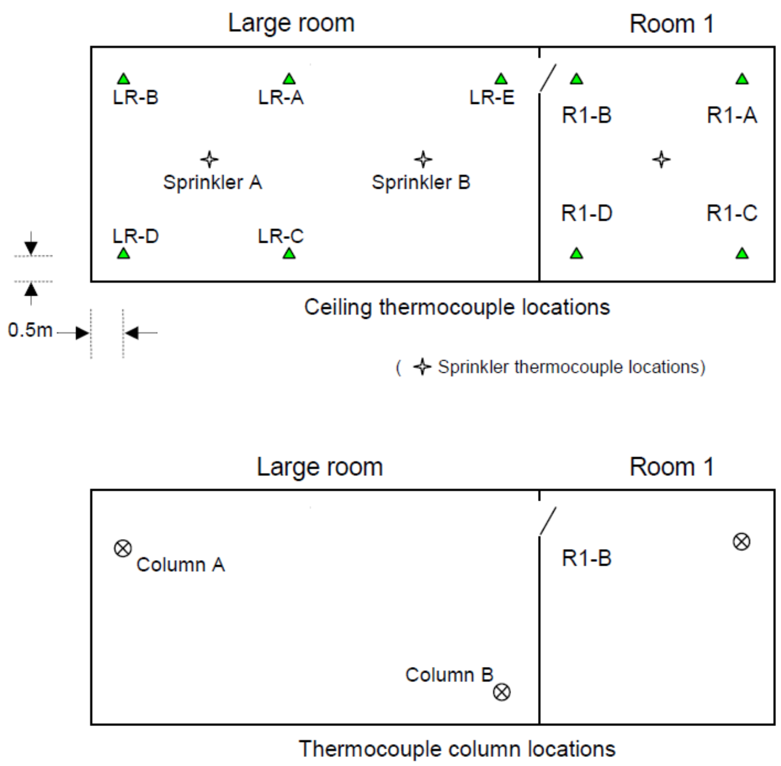


Figure 31: Schematic of the thermocouple locations used in the compartment fires for the 8 x 4 m adjacent compartment test setup (Williams and Campbell, 2004)

2.2.3.4 Suppression system characteristics

2.2.3.4.1 Test A.13

Twenty-two chair fire experiments were conducted in a compartment with two sprinkler heads installed. The 8 x 4 m wide by 2.4 m high compartment was comprised of a timber frame lined with painted 10 mm thick gypsum plasterboard. A closable 0.8 m wide by 2.1 m high door was located in one of the short walls, as shown in Figure 32 (Bittern, 2004).

The fuel package was a mock-up chair using acrylic fabric (10 g/m²) covered polyurethane foam (that was not fire retardant) cushions (28 kg/m³) on a steel frame. The foam blocks were 500 x 400 x 100 mm and approximately 0.56 kg. A sheet of plasterboard, 400 x 500 mm by 10 mm thick, was used as the backing of each cushion to help prevent the burning cushion falling from the frame during each test. General purpose glue and staples were used as fastening of the construction of the cushions. (Bittern, 2004)

Two fire locations were tested: the centre and corner of the compartment. Open and shut door configurations were tested. The test setup with the door open and the fuel package located in the centre of the room was repeated 10 times. Five repeat tests were performed using the test configuration of the door shut and the fuel package (Figure 33) located in the centre of the room or in the corner of the compartment (Figure 32). Four types of pendent sprinkler heads were used in these tests (Bittern, 2004).

Bare wire Type K thermocouples were located adjacent to each sprinkler head. Two vertical thermocouple trees were located on the long wall, closest to the door, at 2 m from each of the shorter walls. Stainless steel sheathed, mineral-insulated Type K thermocouples were located at 0.1, 0.3 and 1.4 m below the ceiling (Bittern, 2004).

Sprinkler activation time, chair mass loss rate and gas temperature profile in the room were reported. An estimate of the HRR, based on the mass loss rate effective heat of combustion of the fuel package, was also reported. Visual observations were also reported (Bittern, 2004).

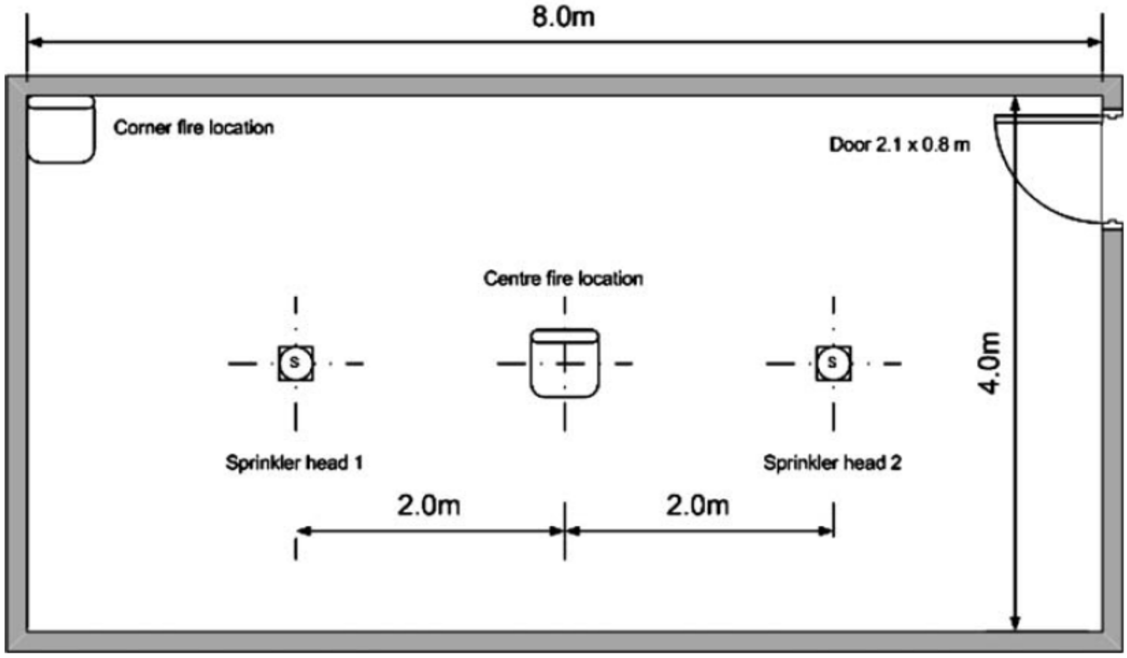


Figure 32: Schematic of the test layout for the chair and two sprinkler head compartment tests (Bittern, 2004)

Figure 33: Chair used as the fuel package for the chair and two sprinkler head compartment tests (Bittern, 2004)

2.2.3.5 Nozzle configuration

2.2.3.5.1 Test A.14

Eighteen tests were conducted in a mock-up residential room (4 x 8 m wide by 2.5 m high), with two door openings and three residential pendent sprinkler heads, based on the work performed in the development of UL 1626 (UL, 2008b). The room was wood framed with plasterboard walls. One door was 0.9 m wide and the other 1.0 m wide. The doors were located on the short walls, opposite each other.

Two sprinkler heads were centrally located in the room, 4.0 m apart. The third head, nearest to a door opening, was deemed one indicator of a successful sprinkler system, if it were to not activate during a test. The time to when the fire was controlled and temperatures within the compartment were additional indicators of a successful test (Williams and Harrison, 2004).

The fuel package was mock-up furniture, wall and ceiling linings arranged inside the room test compartment based on DD252 (BSI, 2002). The mock-up furniture consisted of two polyether foam sheets (775 x 865 mm by 75 mm thick) glued to a wooden backing board and bolted to a wood frame. The wall lining material was four plywood sheets (2.5 x 1.22 m by 12 mm thick). The fuel package was characterised without sprinklers under a furniture calorimeter. Seven of these characterisation tests were conducted (Williams and Harrison, 2004).

The fuel package was placed either in a corner of the room (in a similar setup to that shown in Figure 34, although the fuel package and some instrument details are different), away from the two doors. It was surrounded on four sides with the plywood wall lining, or against the long wall away from the door openings with the plywood wall lining along the wall directly behind the package and at 90º to the wall, either side of the package, so one side of the package was open to the centre of the room (Williams and Harrison, 2004).

The test parameters investigated included: the sprinkler head type (four types of pendent were tested); location of the fuel package (in a corner and directly under a sprinkler head) relative to the sprinkler head; influence of the presence of 0.3 m lintels; and water flow rate to the sprinkler head (3 and 4 mm/min) (Williams and Harrison, 2004).

Gas temperatures were measured using mineral insulated 1.5 mm diameter chromel/alumel (Type K) thermocouples. Additional readings were made using 3.0 mm diameter chromel/alumel thermocouples. Thermocouples were located: 75 mm below the ceiling beside each sprinkler head; in the centre of the room and over the centre of the wood crib; 1.6 m above the floor at the centre of the room; embedded 6.5 mm into the ceiling; and at the ceiling surface over the wood crib.

In addition, two thermocouple trees, made from 0.2 mm diameter bare wire Type K thermocouples with exposed junctions, were also located within the test room. The water flow rate to the sprinklers was reported. Relative humidity within the compartment was also measured. Observations of the behaviour of the fire, sprinkler activation and interaction between the sprinkler and the fire and fuel source were also reported (Williams and Harrison, 2004).

Similar test series were conducted using the same test compartment and sprinkler configuration during the development of the test method (including the standard fuel package) for UL 1626 (UL, 2008b), but using different sprinkler heads, operating conditions and fuel packages e.g. Bill et al. (2002). Therefore the collection of similar tests that could be collated for comparison, depending on the specific interest of the modelling application, may be a greater number of tests than any of the individual investigations alone.

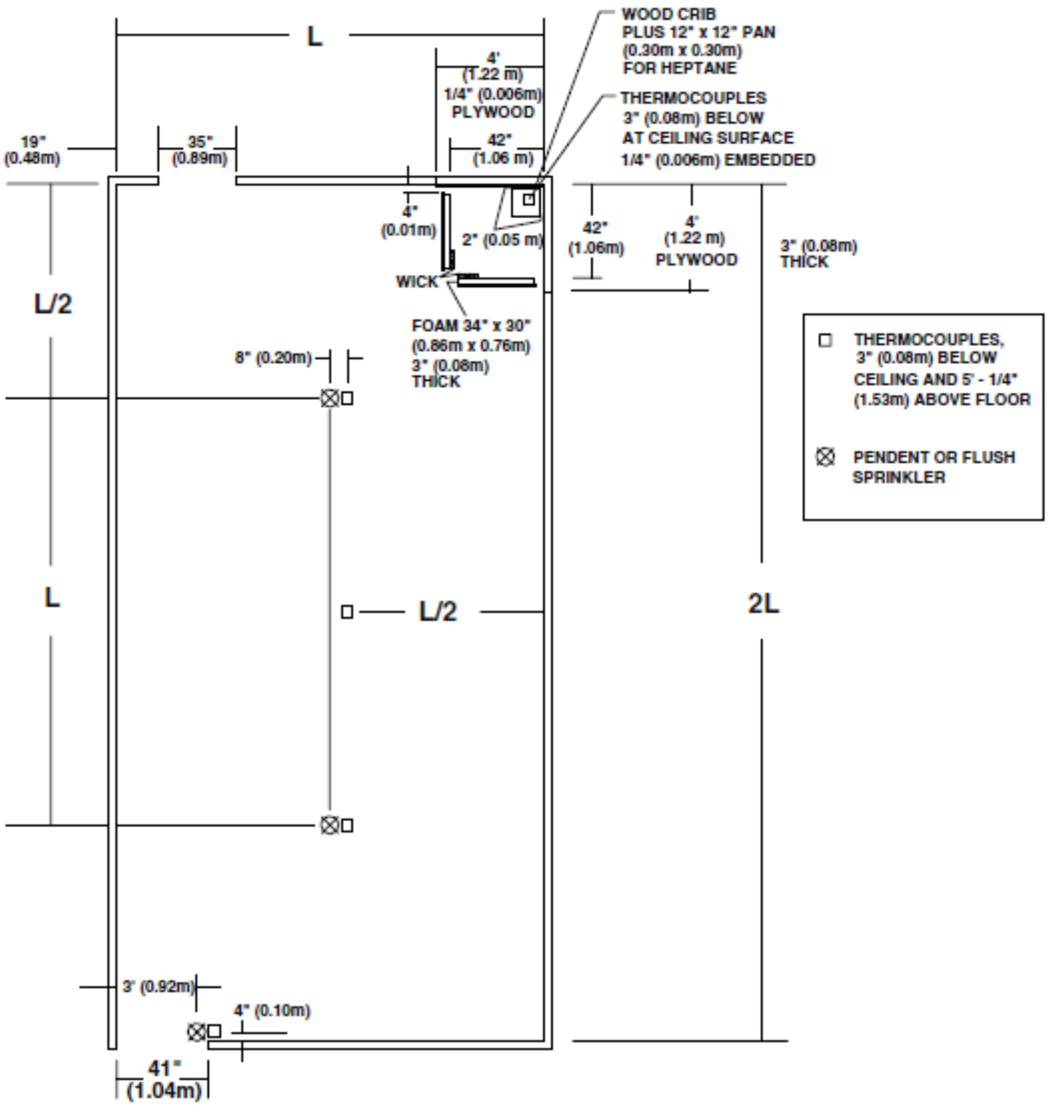


Figure 34: Schematic of the three sprinkler compartment setup with a corner fuel package (Bill et al., 2002)

2.2.4 Kitchen/cooking fires

2.2.4.1 Fire type and size

2.2.4.1.1 Test B.1

Four industrial oil cooker mock-ups were used to test water mist fire suppression, as shown in Figure 35, and each of these was tested in two hood configurations (up and down). Two types of water mist systems (with different water drop size distributions) were also tested on these mock-ups (Liu et al., 2004a, 2005b, 2006b).

- Mock-up 1 was 1.22 m wide by 1.22 m long and 0.343 m deep, with one hole in the 1.27 m long extraction hood.
- Mock-up 2 was 1.22 m wide by 3.05 m long and 0.343 m deep, with two 0.508 m diameter holes in the 3.10 m long extraction hood.
- Mock-up 3 was 1.22 m wide by 4.75 m long and 0.343 m deep, with three 0.508 m diameter holes in the 4.62 m long extraction hood.
- Mock-up 4 was 2.4 m wide by 3.0 m long and 0.343 m deep, with one hole in the 3.05 m long and 2.6 m wide extraction hood.

Two extraction hood locations over the cookers were also investigated: hood up (with a 0.46 m gap between hood and cooker); and hood down (with a 0.05 m gap between hood and cooker) (Liu et al., 2005b, 2006b).

Canola oil was used in the cookers. Fresh oil was introduced to the pan after each test. The oil was continuously heated (3-5ºC/min) using a propane burner, and located centrally below each pan until the oil auto-ignited. At the beginning of each test, after ignition the flames were allowed to spread over the whole surface of the oil. This free-burning situation was maintained for 30 seconds before the water mist system was manually activated (Liu et al., 2005b).

Thermocouple tree temperatures, water pressure, water flow rate, heat flux and oxygen concentrations were reported for each of the tests. Thermocouple trees (each of two thermocouples) were located along the centrelines of each of the mock-ups, as shown in Figure 36 for the example of mock-up 2. Additional single thermocouples were located in and around the oil to monitor the fire and suppression behaviour.

The heat flux meters were located 0.5 m away from each of the pans at heights of 1.2 and 1.9 m above the floor. Three video cameras were used to record the testing process and to assist in the identification of the water mist discharge times and times to extinguishment. Observations of the fire development and water mist suppression performance were also reported (Liu et al., 2005b, 2006b).

In a similar investigation, using the same mock-up industrial oil cookers (Figure 35 and Figure 36) the same test procedure and water mist suppression systems, a different instrumentation setup was used to investigate the cooling of the oil by the water mist suppression systems. Twenty full-scale tests were conducted (Liu et al., 2008).

Fuel area, hood position and fuel depth were varied. The fire sizes ranged from 2.6 to 13 MW. Two types of water mist suppression systems were investigated. Suppression system operation conditions were varied, such as discharge pressure, duration of activation time and amount of water used (Liu et al., 2008).

Thermocouple trees were extended to utilise eight thermocouples of Type K (18 gauge) instead of two thermocouples. The focus of this investigation was the behaviour of the oil during the fire and suppression parts of each test. The aspects focused on during this investigation were the oil cooling rate, rate of expansion of oil due to boiling and bubbling, and formation and temperature distribution of a boiling layer (Liu et al., 2008).

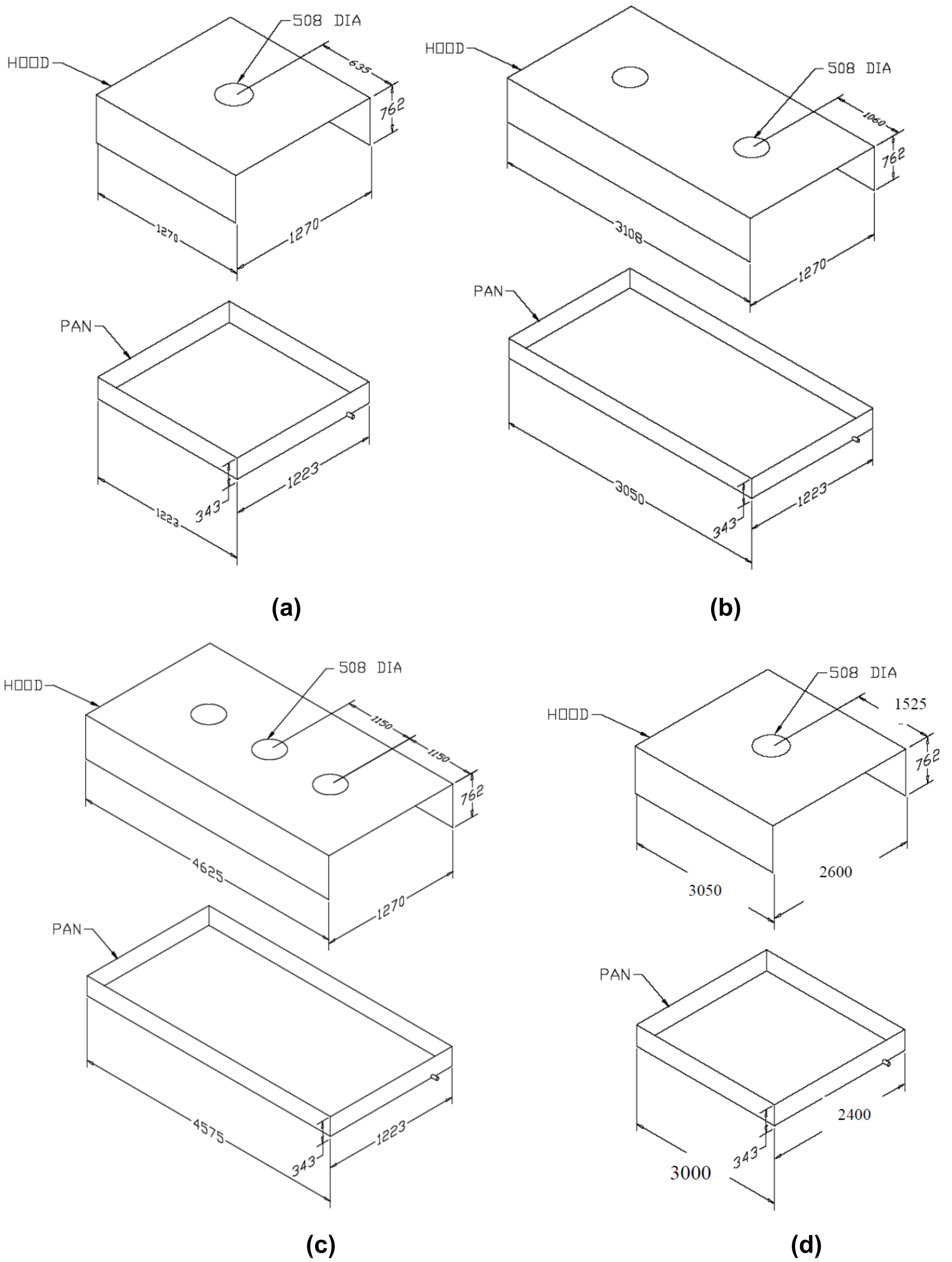


Figure 35: Schematics of the mock-up industrial oil cookers (a) mock-up 1, (b) mock-up 2, (c) mock-up 3 and (d) mock-up 4 (all dimensions are in mm) (Liu et al., 2005b)

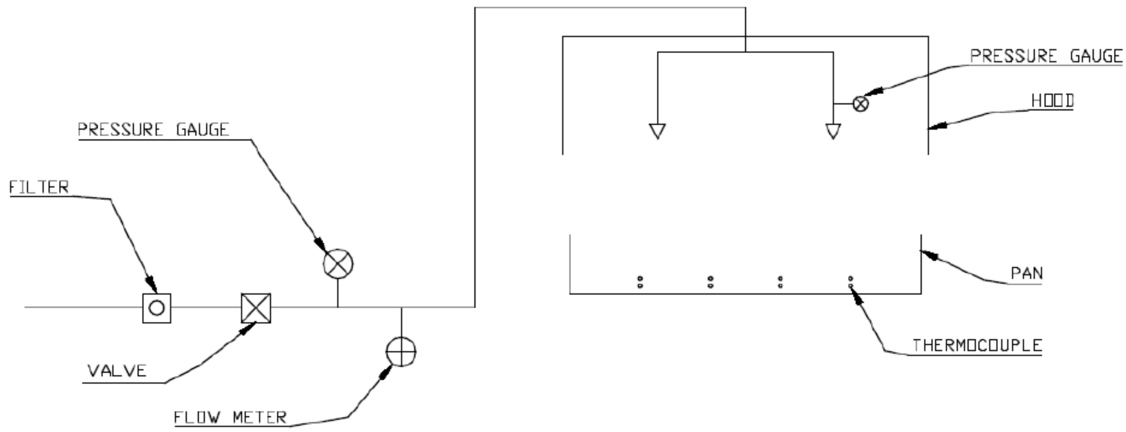


Figure 36: Schematic of the instrumentation of the cross-section of the industrial oil cooker test setups for the example of mock-up 2. (Liu et al., 2005b)

2.2.4.1.2 Test B.2

A full-scale mock-up section of residential kitchen space was used to assess the performance of a localised sprinkler system suppression of stove-top kitchen fires. A stove was used in a partial corridor, as shown in the schematic of Figure 37, located under an extraction hood in the BRANZ ISO-room laboratory. A 280 mm diameter skillet was used with either 200 or 400 ml of cooking (canola) oil as the fuel package to challenge the single automatic quick response residential sprinkler head (Robbins, 2010b).

Thermocouple temperatures (at 1 Hz) were reported for locations: on the surface of the stove; in the thermocouple tree centred on the cooking vessel with the cooking oil; on the ceiling; and at the sprinkler head. Measurements from the plate thermometers (at 1 Hz) located adjacent to the cooking vessel, where flaming would be expected, were reported. HRRs (at 0.33 Hz), estimated using oxygen calorimetry, were also reported (Robbins, 2010a, 2010b).

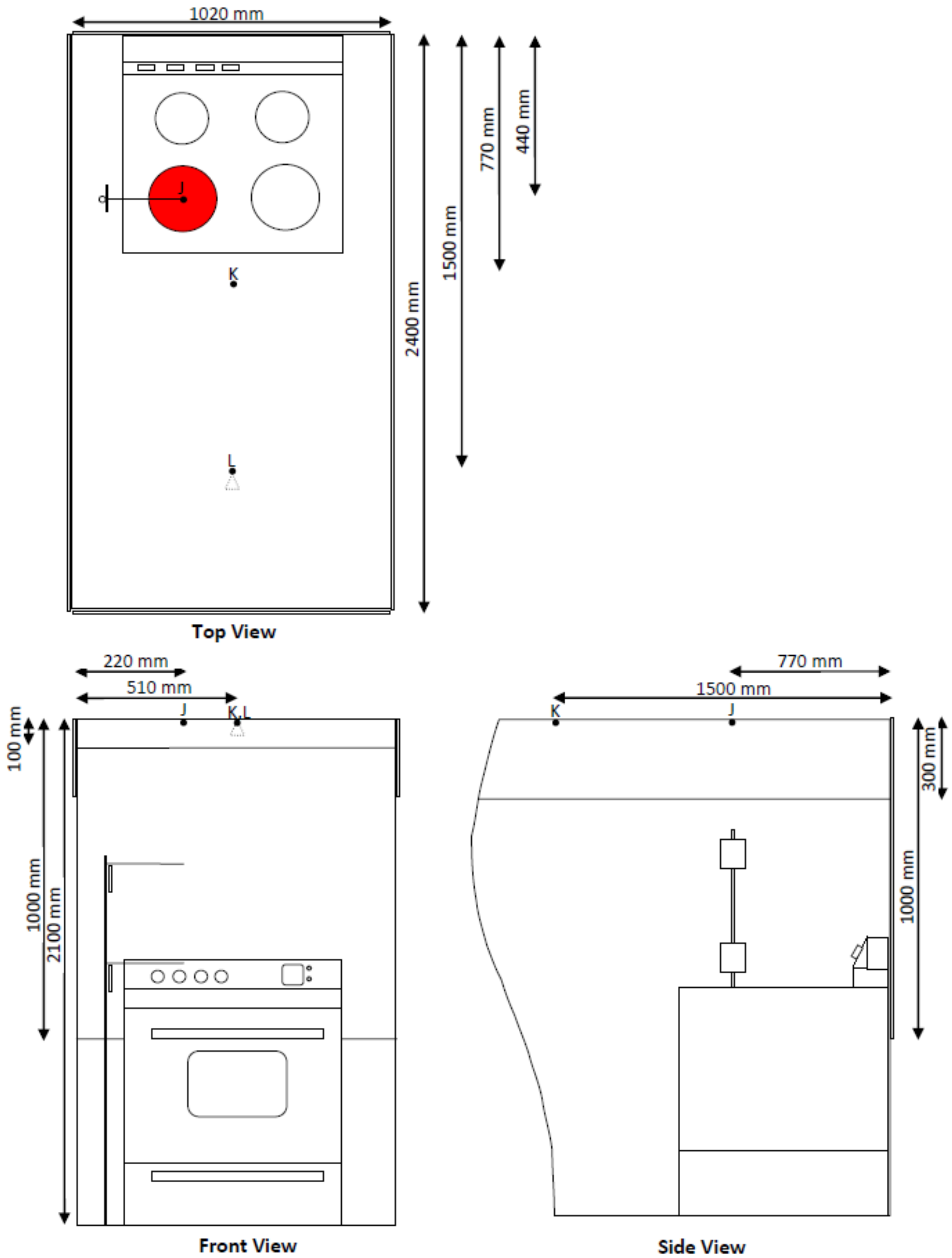


Figure 37: Schematic of the test setup for localised sprinkler fire suppression tests for stove-top fires (Robbins, 2010b)

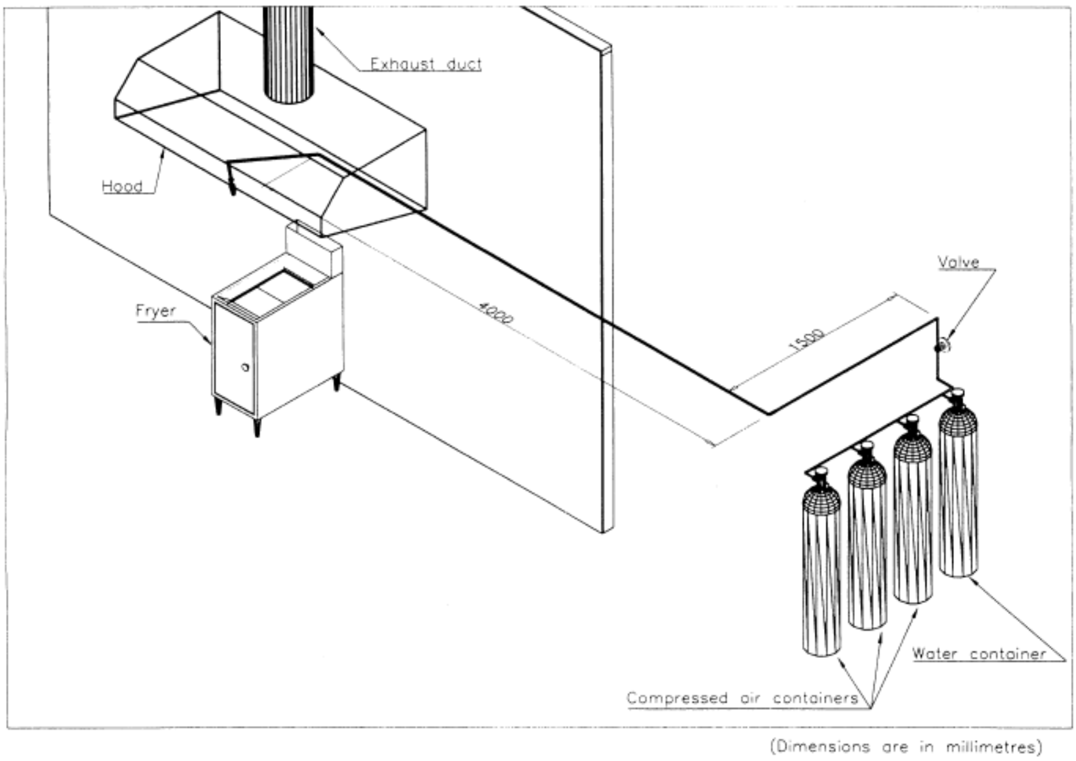
2.2.4.2 Suppression system characteristics

2.2.4.2.1 Test B.3

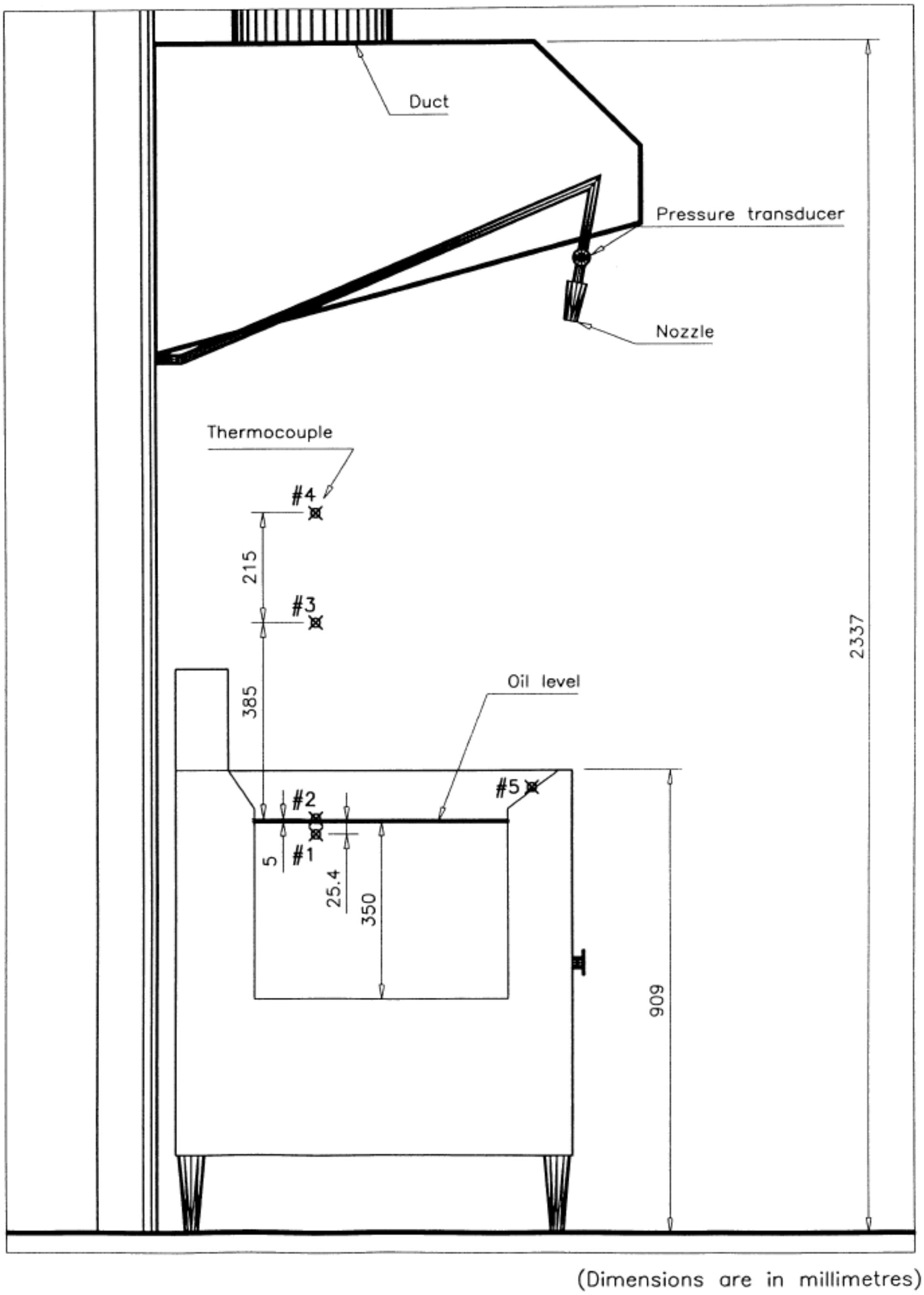
A manually activated water mist fire suppression system was investigated by the National Research Council of Canada (NRCC) for application in the protection of commercial cooking areas. A full-scale mock-up of a section of commercial cooking space (as shown in Figure 38), based on UL 300 “Standard for Fire Testing of Fire Extinguishing Systems for Protection of Restaurant Cooking Areas”, was used for testing.

The influence of water mist characteristics (such as spray angle, drop size, flow rate, discharge pressure and type of nozzle) on the suppression performance of water mist during cooking oil fires was investigated. The potential of oil splash caused by a water mist system discharging over-heated (but not flaming) oil was also investigated. The distance between the nozzle and the oil surface was also varied (Liu et al., 2003, 2004b).

Thermocouple temperatures (1 Hz) were reported for the locations in the thermocouple tree in and above the oil, and one thermocouple was located on the top surface of the fryer. Time to extinguishment and time to cool the oil to 200°C were also reported (Liu et al., 2003). Two video cameras were used to record the fire, water mist discharge, oil splash and fire control. The cooking oil was characterised, using FTIR, at various temperatures and after the fire was extinguished by water. Observations of re-ignition behaviour were also reported (Liu et al., 2004b).



(a)



(b)

Figure 38: Schematics of the tests setup for commercial cooking oil fires (Liu et al., 2004b)

2.2.4.2.2 Test B.4

Two types of water mist systems, with different water drop size distributions, were tested on four industrial oil cooker mock-ups, as shown in Figure 35. They were each tested in two hood configurations (up and down) (Liu et al., 2005b).

Mock-ups 1 to 4 were described in the previous section. Two extraction hood locations over the cookers were also investigated; hood up (with a 0.46 m gap between hood and cooker); and hood down (with a 0.05 m gap between hood and cooker) (Liu et al., 2005b; Liu et al., 2006b).

The water density distributions over the pan surface were also reported for the two nozzle systems tested (Liu et al., 2005a). Low-pressure (414-689 kPa, 28.2-39 L/min) systems were also investigated using the same four industrial oil cooker mock-ups and instrumentation (Yen et al., 2005; Liu et al., 2006a).

Canola oil was used in the cookers. Fresh oil was introduced to the pan after each test. The oil was continuously heated using a propane burner, located centrally below each pan. At the beginning of each test, after ignition the flames were allowed to spread over the whole surface of the oil. This free-burning situation was maintained for 30 seconds before the water mist system was manually activated (Liu et al., 2005b).

Thermocouple tree temperatures, water pressure, water flow rate, heat flux and oxygen concentrations were reported for each of the tests. Thermocouple trees (each of two thermocouples) were located along the centrelines of each of the mock-ups, as shown in Figure 36 for the example of mock-up 2. Additional single thermocouples were located in and around the oil to monitor the fire and suppression behaviour.

The heat flux meters were located 0.5 m away from each of the pans at heights of 1.2 and 1.9 m above the floor. Three video cameras were used to record the testing process and to assist in the identification of the water mist discharge times and times to extinguishments. Observations of the fire development, water mist suppression performance and potential re-ignition were also reported (Liu et al., 2004a, 2005b, 2006a 2006b; Yen et al., 2005).

2.2.5 Office space

2.2.5.1 Fire type and size

2.2.5.1.1 Test C.1

Large-scale experiments were performed in several typical office occupancy configurations in order to estimate the performance of quick response sprinkler technology. The results were used to estimate the HRR of selected office fuel packages with and without sprinklers operating. Eight different fuel packages were evaluated in smaller-scale tests. The results from these experiments were used to develop a time dependent HRR reduction factor (Madrzykowski and Vettori, 1992a; 1992b)

2.2.5.1.2 Test C.2

Sixteen tests were performed in a small enclosure (2.4 x 3.6 m wide x 2.4 m high). The door was kept closed during each of the experiments, but the vent under the door was varied. Three fire types were investigated: a wood crib and Heptane pool fire; a paint and Heptane pool fire; and hydraulic oil pool fire. One sprinkler head was used in the compartment. The sprinkler head was connected to a self-contained pressure bottle, with a maximum amount of 6 L of water available. Both automatic and manual activation were investigated. Temperature and time to extinguishment were reported. Re-ignition was considered, but not observed for any of the tests (Turner, 1993).

The full report is: Tuomissari M. 1992. *Enclosed Space Fire Suppression Tests, PAL 2206/92.* VTT Fire Technology Laboratory. Espoo, Finland (Turner, 1993).

2.2.5.1.3 Test C.3

The influence of ignition location on the activation of sprinklers was investigated during seven tests in a mock-up office in a 5.7 x 4.7 m wide by 3.3 m high compartment. The compartment had two 2.1 x 0.9 m doorways. The entire compartment was located under a 10 MW capacity calorimeter hood (Lai et al., 2010a).

Four sprinkler heads were installed in the compartment (Figure 40) (Lai et al., 2010a). Seven scenarios were tested, each with a different movable fuel package consisting of either wood cribs or sofas, as shown in Figure 35 (Lai et al., 2010a). Thermocouples and smoke detectors were located throughout the compartment, as shown in Figure 40 (Lai et al., 2010a).

Another similar set of tests was also run for the same setup (Lai et al., 2010b). Both of these sets of tests focus on activation times of the first sprinkler head.

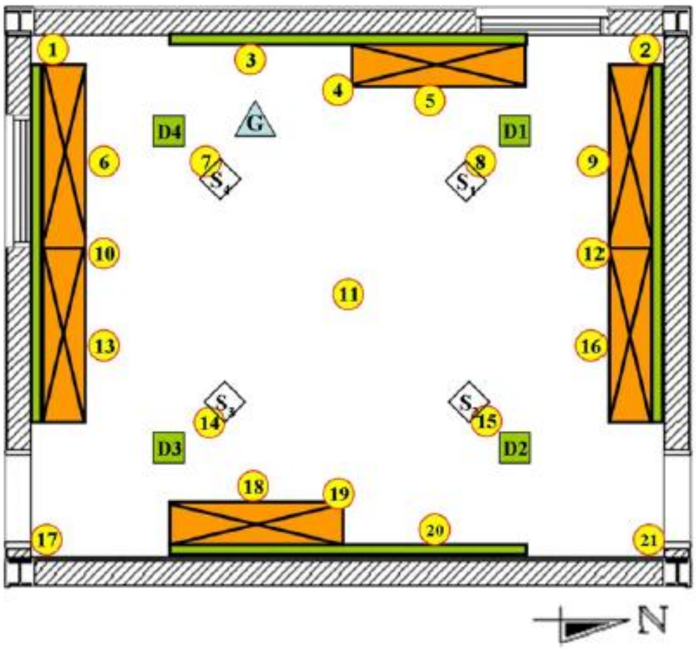


Figure 39: Schematic of the floor plan of the mock-up office (S denotes sprinklers, D denotes smoke detectors and the numbered circles are thermocouple locations) (Lai et al., 2010a)

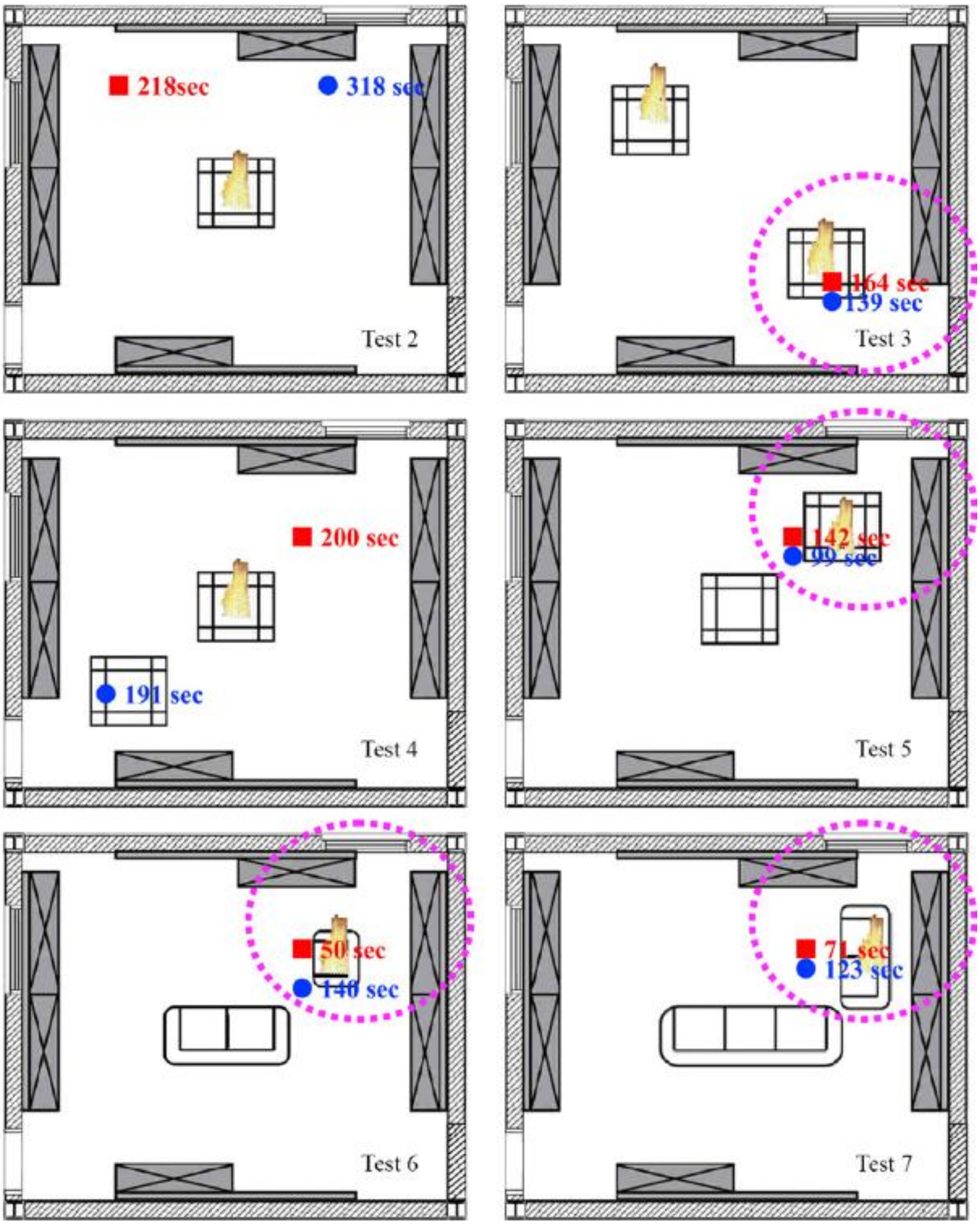


Figure 40: Schematics of the fuel package layouts for each of the scenarios tested in the mock-up office tests (red denotes time to first smoke detector activation and blue denotes time to first sprinkler head activation) (Lai et al., 2010a)

2.2.5.2 Shielding of fire

2.2.5.2.1 Test C.4

Seven full-scale shielded fire tests were conducted in an 8.74 x 10.79 m wide by 2.74 m high compartment mocked up as an open-plan room in an office building. The only obstruction was a 455 x 455 mm cross-sectional structural column located near the centre of the test compartment (Figure 41). A waterproof gypsum board panel suspended ceiling was used as the compartment ceiling. Concrete board was used to line the test facility and the upper 1.2 m of the exhaust hood canopy (Lougheed, 1997).

Based on NFPA 13 (1996), four standard response 74ºC pendent sprinkler heads with a 13 mm diameter orifice were installed at the maximum spacing from the walls (2.3 m) and between sprinklers (4.6 m) at the locations shown in Figure 41. The automatic system was designed for a light-hazard occupancy. The design water flow rate per sprinkler was 86 L/min (Lougheed, 1997).

The fuel package was a representation of a 3 x 3 m section of open-plan office arrangements, including a steel-framed wooden desk, a wood-topped computer table, another steel-framed wooden table, bookshelves above the desk, two or three upholstered pedestal office chairs with metal bases, two four-drawer metal filing cabinets, 1.2 m high cloth-covered partitions with fibre insulation a wood frame and metal mesh components, and a steel-cased computer with monitor and keyboard.

An example of this arrangement is shown in Figure 42b. Commercial-grade carpet was used to cover the 3 x 3 m floor area under the fuel package. Boxes filled with paper were used as the fuel load under each table and desk in the primary test area. Additional office furniture, providing both shielding and potential fuel for fire spread, was located adjacent to the fuel package within the 3 x 3 m area, as shown in Figure 42a (Lougheed, 1997).

Shielded fires of the boxes of paper located under the desks and tables were further investigated with a series of 23 medium-scale tests. The 365 x 500 mm wide by 305 mm high boxes were standard document storage cardboard boxes with a separate lid and filled with cellulosic material. This material consisted of loose paper in manila folders and bound material, such as reports, journals and magazines. The boxes were approximately 50% filled. The total mass per box was 9.5 kg, including the box.

The boxes were tested under a representative desk in combinations of four, eight and 12 boxes in the shielded area. These combinations of boxes were reported to produce peak HRRs of 140, 275 and 400 kW, respectively. The medium-scale tests included some with additional office furniture and sprinklers (Lougheed, 1997). The medium-scale test results compared well with previous similar medium-scale test results involving items of office furniture (Madrzykowski and Vettori, 1992a; 1992b).

The ignition source was a 25 kW propane burner that burnt for 5 min to start the test (Lougheed, 1997).

The amount of fuel load in the shielded areas of the compartment, location of the shielded fire relative to the sprinkler heads, and location of the ignition source (25 kW propane burner) were varied between the seven tests (Lougheed, 1997). A summary of the unsprinklered HRRs and a suggested design fire based on the experimental results are available elsewhere (Lougheed, 2004).

Seven thermocouple trees, with four thermocouples each, were located within the compartment, as shown in Figure 42a. The thermocouples were located at 0.15, 0.61 1.22 and 1.83 m below the ceiling. Each thermocouple was shielded from direct water from each of the sprinkler heads using a 400 x 400 mm piece of sheet metal. Thermocouples were also located adjacent to each sprinkler head.

Thermocouples were also located 50 mm below the underside of each table and desk. Pressure differences between the compartment and the test hall were also reported for three heights in the west wall, located 0.15, 1.22 and 2.29 m below the ceiling. Carbon dioxide and carbon monoxide concentrations were reported for two corner locations in the compartment, as shown in Figure 42a, at 0.15 and 1.2 m below the ceiling. An infrared smoke meter was located 0.2 m downstream of the duct intake for the calorimeter, as shown in Figure 41. Oxygen, carbon dioxide and carbon monoxide concentrations were measured. Oxygen calorimetry was used to estimate the reported HRR (Lougheed, 1997).

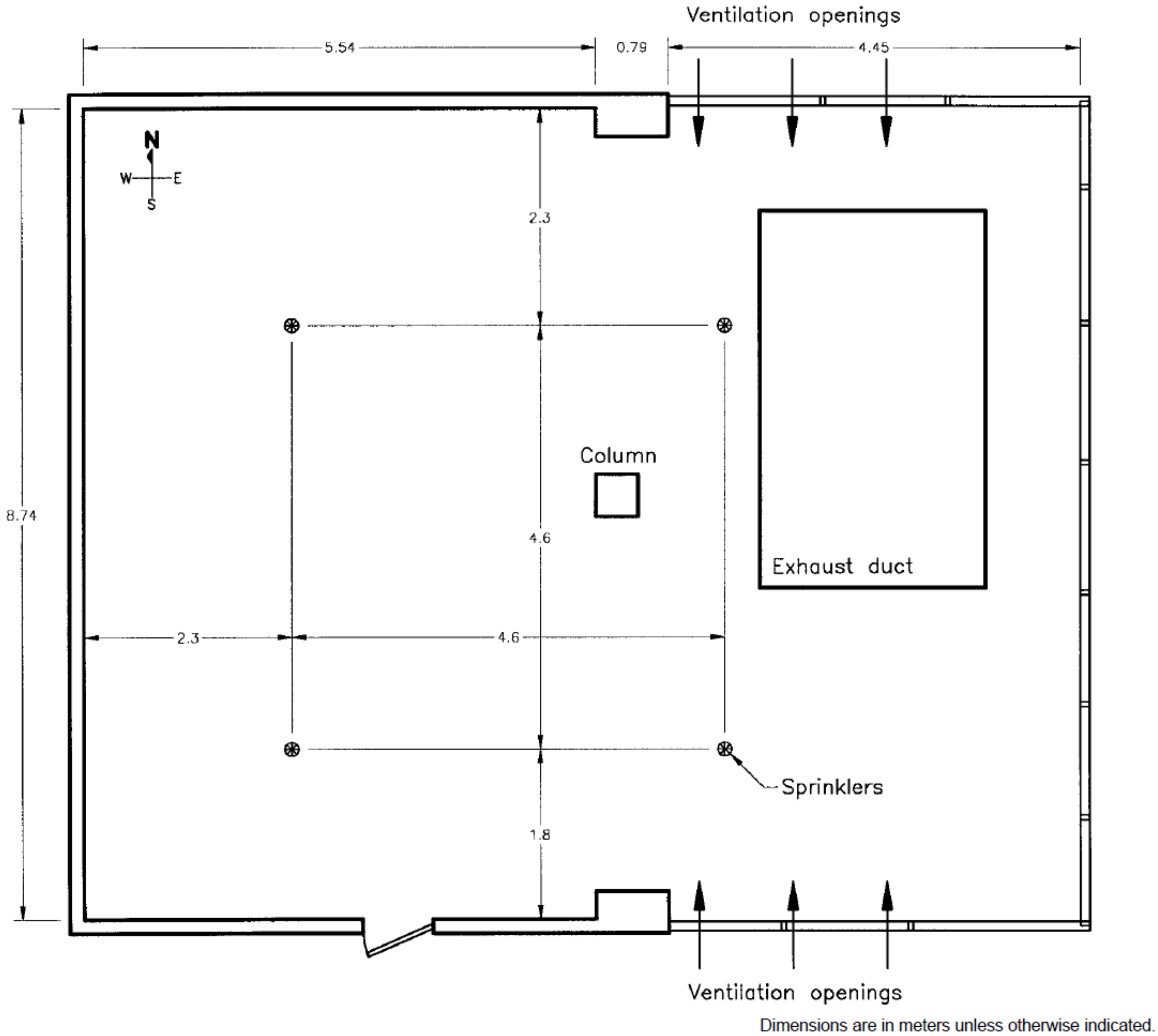
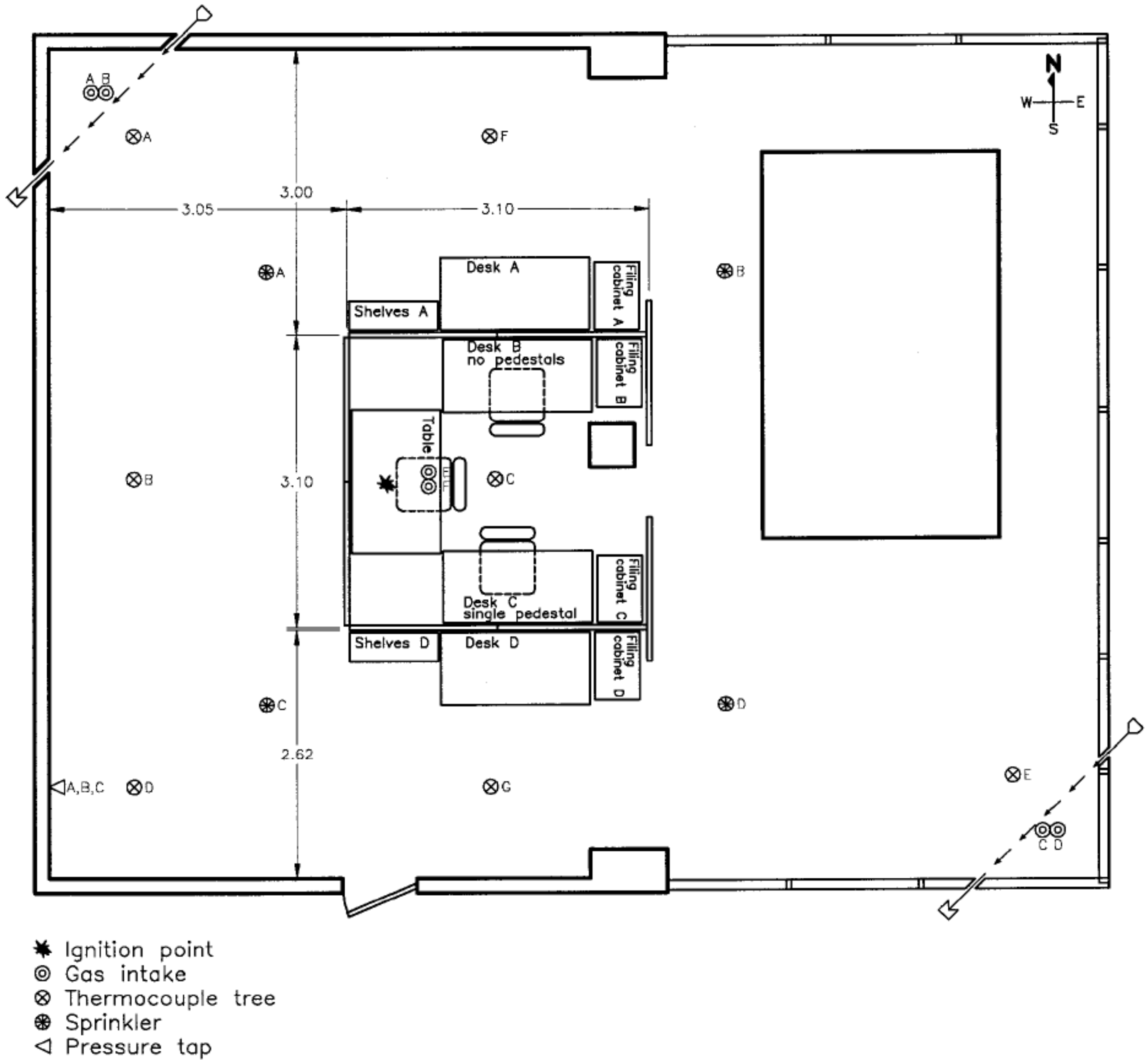
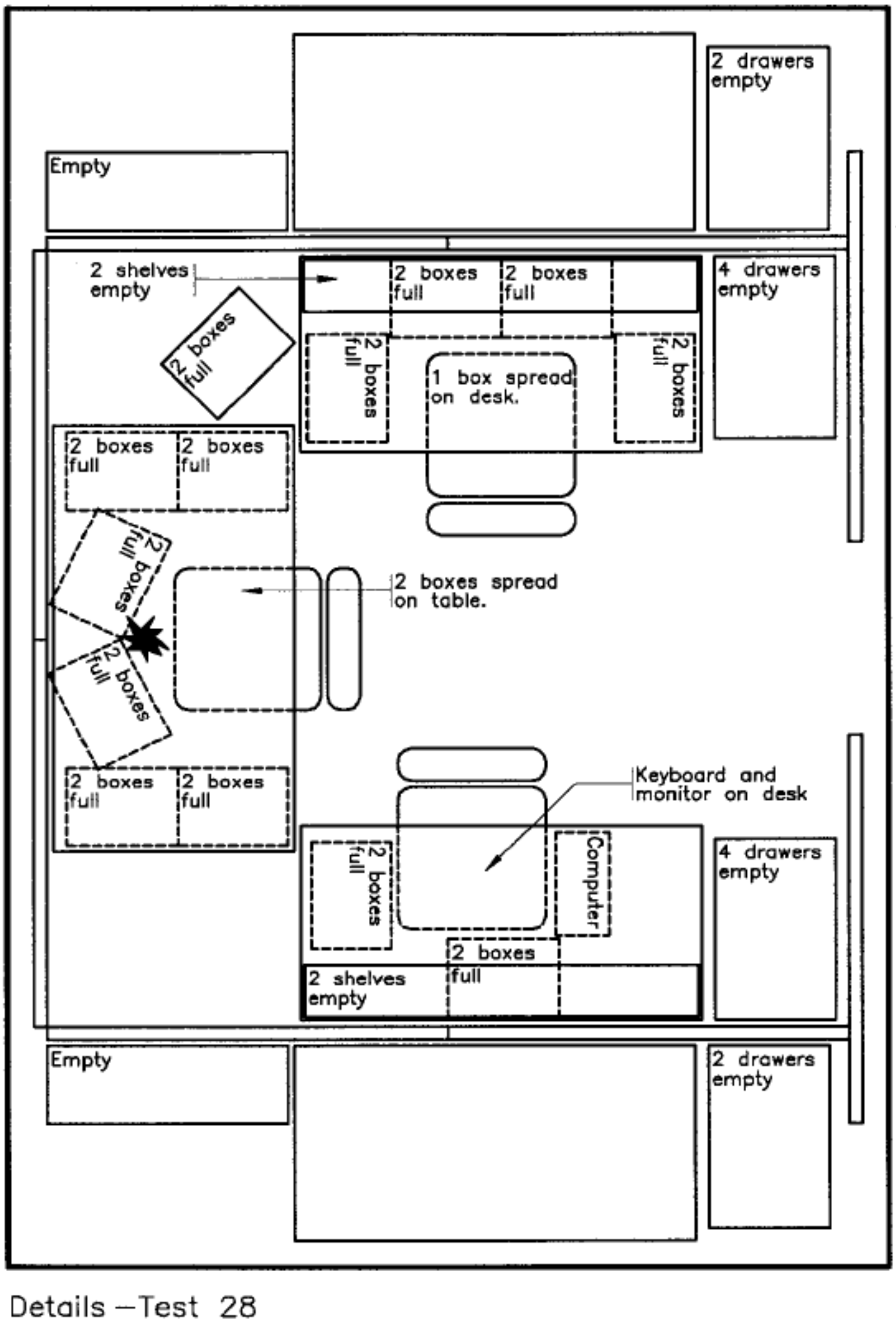


Figure 41: Schematic of the compartment used for the shielded open plan office fire tests (Lougheed, 1997)



Desk A
Shelves A
Filing cabinet A
Desk B no pedestals
Filing cabinet B
Table
Desk C single pedestal
Filing cabinet C
Shelves D
Desk D
Filing cabinet D
3.00
3.05
3.10
3.10
2.62
N
W
E
S
Ignition point
Gas intake
Thermocouple tree
Sprinkler
Pressure tap

(a)



(b)

Figure 42: Schematic of an example of the instrumentation and fuel package test setup for the shielded open plan office fire tests for the (a) entire compartment and (b) details of the fuel package located in the central section of the compartment (Lougheed, 1997)

2.2.5.2.2 Test C.5

Two other shielded fire scenarios were also investigated during the office building testing: a document storage scenario and a single office scenario. HRR, carbon monoxide concentration and smoke obscuration were reported (Lougheed, 1997).

Full report: Lougheed GD and DW Carpenter. 1996. *Probability of Occurrence and Expected Size of Shielded Fires in Sprinklered Buildings, ASHRAE RP-838, Phase 2, Full-scale Fire Tests, Report A4201.10.* National Research Council of Canada, Ottawa, Canada.

2.2.5.3 Suppression system characteristics

2.2.5.3.1 Test C.6

A series of seven compartment fire tests were conducted in several typical office occupancy configurations in order to address the use of quick response sprinkler technology. The compartment fire tests were designed to examine the effectiveness of quick response sprinklers in typical office fires involving a computer work station or an open office module (Walton and Budnick, 1988).

The room was lined with 12 mm thick calcium silicate board and the floor covered with 12 mm gypsum board. The large office test consisting of a 2.44 x 3.66 m wide by 2.44 m high compartment with multiple open office modules was conducted to verify the compartment test results and examine the possibility of multiple sprinkler activation (Walton and Budnick, 1988).

Two fuel packages were used: a computer work station and an open shelf storage system. The computer work station fuel package consisted of a plastic laminated particleboard computer desk and a book case and both were loaded with paper materials. The open shelf storage system consisted of two parallel sets of back-to-back units with six steel shelves, each loaded with paper products. The ignition source for each fuel package was a 50 kW natural gas burner (Walton and Budnick, 1988).

Tests were performed with and without sprinkler systems installed. Two different types of sprinkler head were tested: a standard spray and a quick response residential type (Walton and Budnick, 1988).

The compartment was instrumented to measure estimates of the HRR, total heat released, upper layer temperatures, gas temperature near the sprinkler, and gas species concentrations (Walton and Budnick, 1988).

A portion of the data sets acquired during these tests was analysed to investigate the influence of elevated temperatures in the upper smoke layer and the impact on the thermal response of sprinkler links (Cooper and Stroup, 1987).

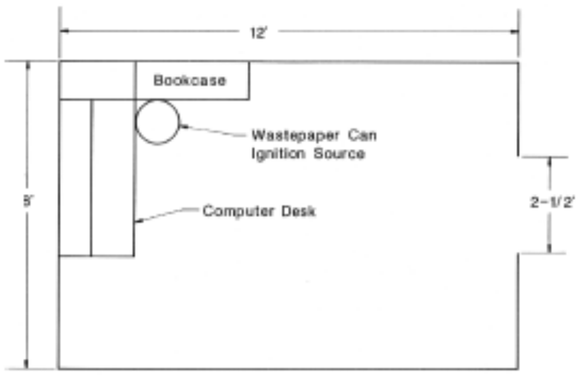


Figure 43: Schematic of the office compartment tests with work station and open shelf storage fuel packages (Walton and Budnick, 1988)

2.2.6 Heritage and library space

2.2.6.1 Fire type and size

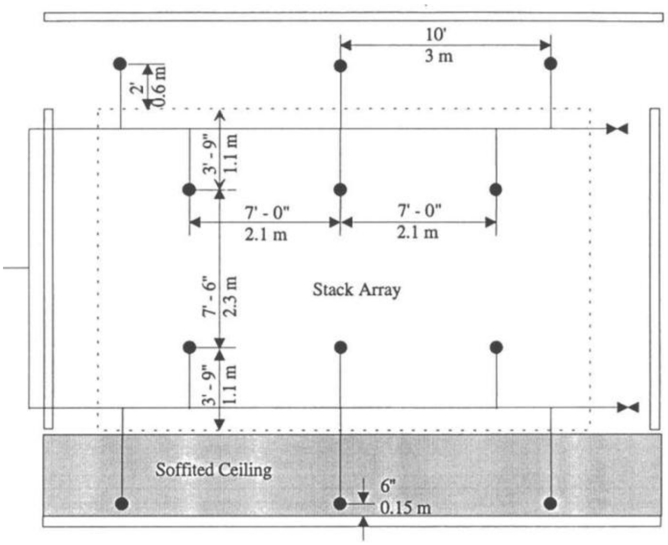
2.2.6.1.1 Test D.1

A full-scale array of shelving to simulate the situation found in the basement of the National Library of Canada was constructed using two fixed shelves with five double-row mobile shelves between them. The compartment area was 4.6 x 6.7 m. The shelves were loaded with corrugated cardboard document storage boxes filled with newsprint, comparable to those used in the library.

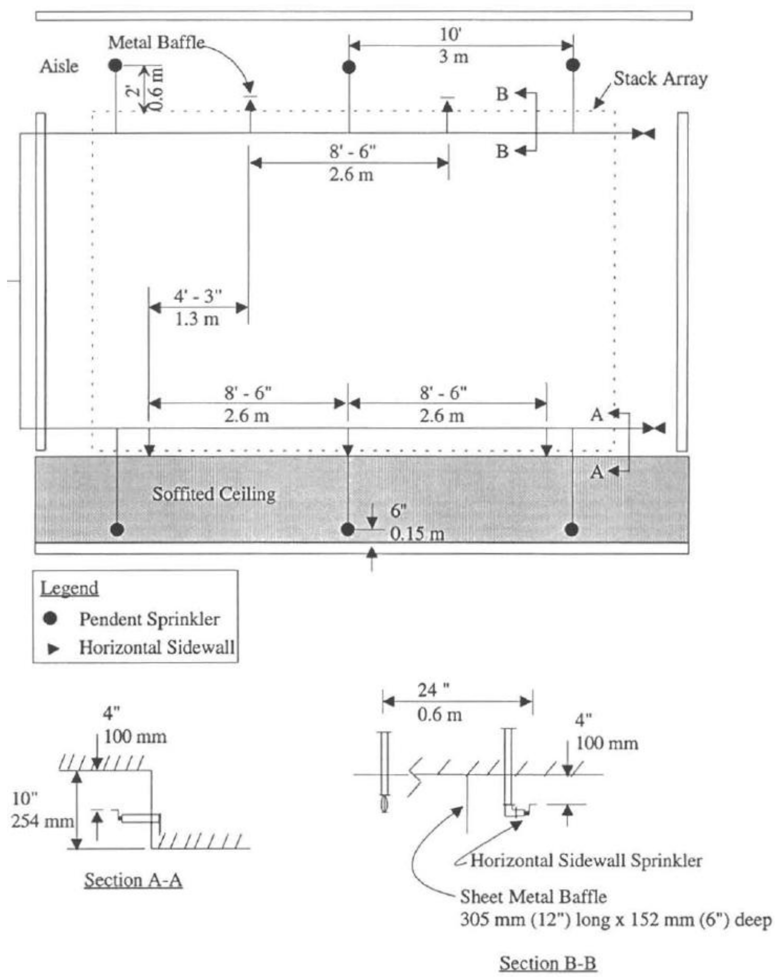
Two sprinkler systems were tested – one pendent configuration and one sidewall configuration – as shown in the example schematics of Figure 68. Cycling application modes of the sprinklers were used in the investigation. Among other influencing variables, the fuel packages were varied, i.e. using open vs closed document boxes (Lougheed and Mawhinney, 2005).

Thermocouple temperatures in the stacks and within the room and smoke obscuration were recorded. Radiometers were used to estimate the radiant flux to adjacent shelving bays. Flow rate and pressure were measured at the base of the riser. Test and post-test observations were also reported (Lougheed and Mawhinney, 2005).

The full report is: *Full-Scale Tests of Sprinklered Mobile Shelving Units for National Library of Canada*, prepared by Gage-Babcock & Associates, Vienna, Virginia, USA.



(a)



(b)

Figure 44: Schematics of the (a) pendent and (b) sidewall sprinkler head layouts for the combined fixed and mobile shelving stack array test setup (Lougheed and Mawhinney, 2005)

2.2.6.2 Shielding of fires

2.2.6.2.1 Test D.2

Five full-scale fire tests were conducted on mobile shelving units, based on those found in the National Archives, National Library of Canada building in Ottawa. This was to assess the influence of the clearance of storage and sprinkler heads (Lougheed et al., 1994).

2.2.6.2.2 Test D.3

A full-scale array of shelving to simulate the situation found in the basement of the National Library of Canada was constructed using two fixed shelves with five double-row mobile shelves between them. The compartment area was 4.6 x 6.7 m. The shelves were loaded with corrugated cardboard document storage boxes filled with newsprint, comparable to those used in the library. Two sprinkler systems were tested – one pendent configuration and one sidewall configuration – as shown in the example schematics of Figure 68. Cycling application modes of the sprinklers were used in the investigation. Among a range of other influencing variables, the clearance distances between the sprinkler head and the storage were also investigated (Lougheed and Mawhinney, 2005).

Thermocouple temperatures in the stacks and within the room and smoke obscuration were recorded. Radiometers were used to estimate the radiant flux to adjacent shelving bays. Flow rate and pressure were measured at the base of the riser. Test and post-test observations were also reported (Lougheed and Mawhinney, 2005).

The full report is: *Full-Scale Tests of Sprinklered Mobile Shelving Units for National Library of Canada*, prepared by Gage-Babcock & Associates, Vienna, Virginia, USA.

2.2.6.2.3 Test D.4

Two large-scale tests were conducted on compact mobile shelving systems under the 30 x 30 m adjustable ceiling in the large-scale fire test facility at Underwriters Laboratories.

Thirty-six quick response, standard spray, pendent-style sprinklers were installed using 4.5 x 4.5 m spacing. The distance between ceiling and deflector was 203 mm. The sprinklers had a temperature rating of 68ºC and a nominal flow coefficient of 80 Imp/bar$^{1/2}$. A looped piping system was used with a 57 mm diameter pipe (SEC, 2008; UL, 2008a)

The shelves tested were combinations of fixed and mobile units. A carriage rail system was used for the mobile units. The mobile units were each 0.9 m wide by 0.6 m deep by 2.4 m high. Each unit had five storage bays, divided by sheet metal barriers. There were eight shelves in each unit. A loading density of 70% was used to fill the shelves with folders and paper. Fifty-six folders were loaded into each bay to fill the 0.3 x 0.9 m volume. The folders were evenly spaced by vertical dividers (SEC, 2008; UL, 2008a).

The configuration used for the first of the two large-scale tests was five compact mobile units and one fixed shelf unit. Four of the mobile units were 0.6 m deep, and the remaining mobile unit and the fixed unit were 0.3 m deep. The shelving units were arranged with a 0.9 m aisle in the centre of the array. The units were arranged with a nominal 25 mm space between them.

The six shelving units were surrounded by a 0.9 m aisle with a paper-faced cardboard target wall on all four sides. The location of ignition was at the centre bottom of the unit on the south side of the open aisle. The ignition source was placed inside one of the folders. A schematic of the setup is shown in Figure 45 (SEC, 2008; UL, 2008a)

The second test configuration utilised the same type and loading of the units. However the ignition location was in the same unit, then two mobile units were moved to form a new aisle between the last mobile unit and the fixed unit on the north side, as shown in the schematic of Figure 46 (SEC, 2008; UL, 2008a).

The ignition source was a 76 x 150 mm cellulosic bundle, soaked in 227 ml gasoline and wrapped in a polyethylene bag (SEC, 2008; UL, 2008a).

Inconel sheathed, 1.5 mm diameter, Type K thermocouples were used. Thermocouples were located below the ceiling next to each sprinkler and below the elevated walkway adjacent to each sprinkler. A three-thermocouple thermocouple tree was used below the ceiling, centred over the ignition location. Five thermocouples were embedded in the surface of a 1.3 m length of steel angle that was attached to the bottom of the ceiling directly above the ignition location. The sprinkler system flow and pressure were reported. Visual observations during the test were also reported. Video and infrared cameras were used during the tests (SEC, 2008; UL, 2008a).

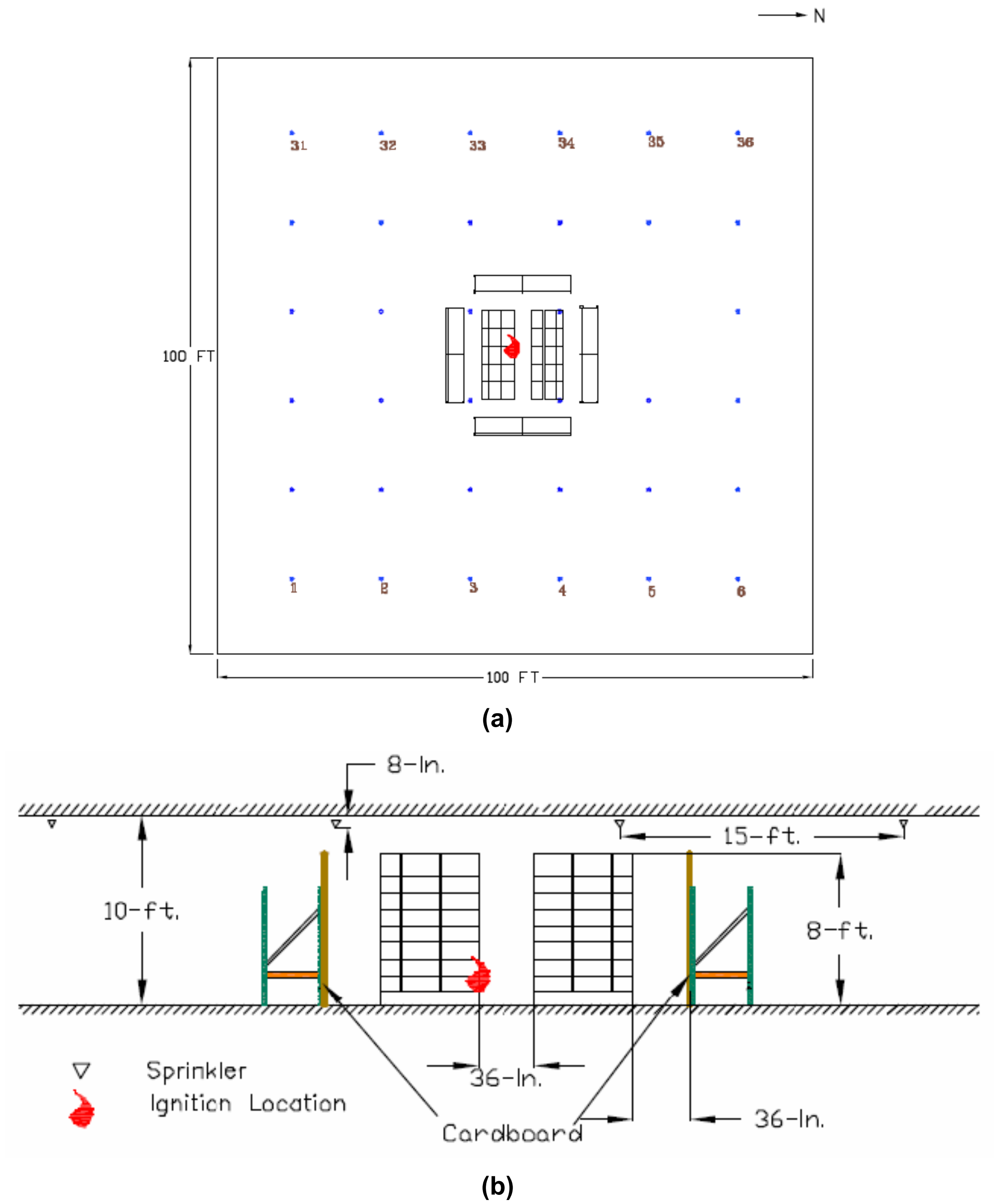
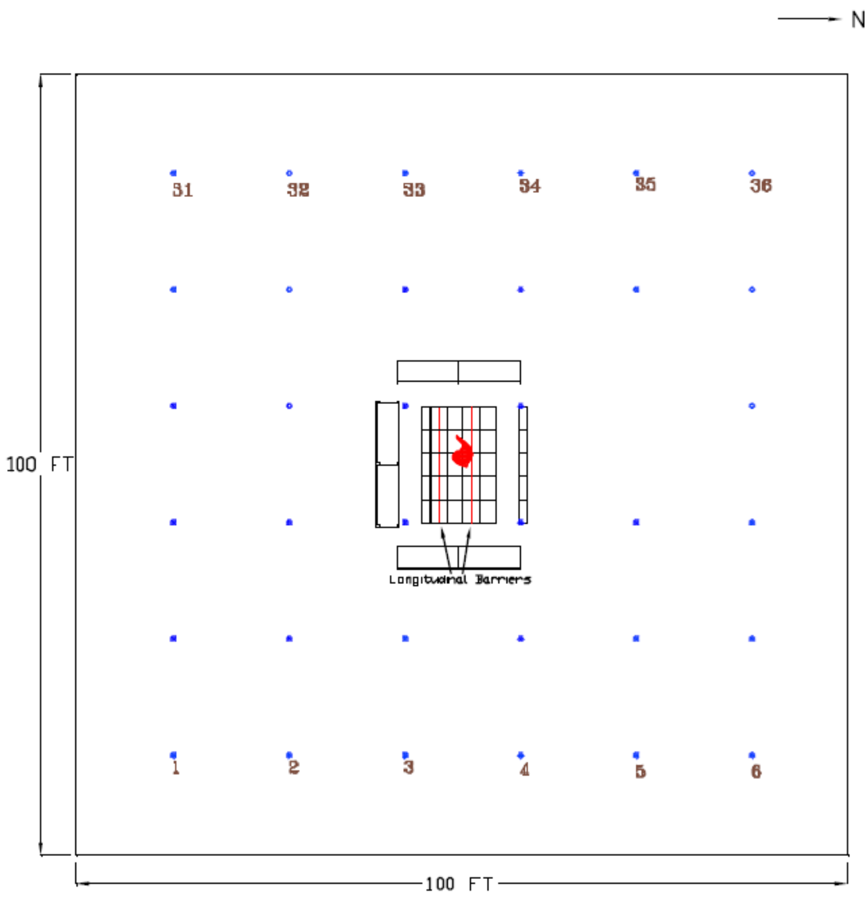
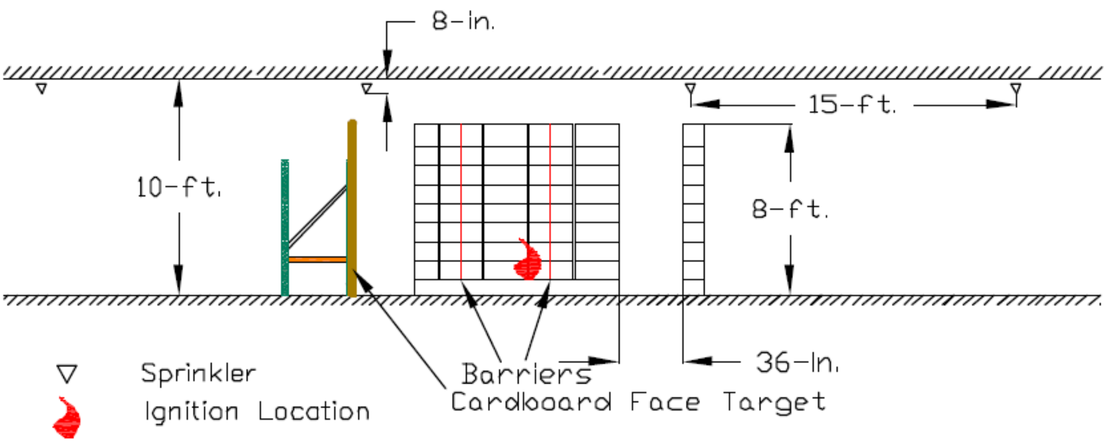


Figure 45: (a) Plan and (b) elevation views of a schematic of test setup and ignition location for compact mobile shelving Test 1 (SEC, 2008; UL, 2008a)



(a)



(b)

Figure 46: (a) Plan and (b) elevation views of a schematic of test setup and ignition location for compact mobile shelving Test 2 (SEC, 2008; UL, 2008a)

2.2.6.3 Suppression system characteristics

2.2.6.3.1 Test D.5

Water mist suppression tests were conducted in a compartment (7.9 x 4.0 m wide x 2.3 m high), with three rows of book shelves holding 500 books (an assortment of hard cover and soft-bound) located at one end of the room. Nozzles were installed in the aisles and in the flue space. Thermocouple temperatures in the compartment and post-fire observations of the fire damage of the books and shelves were reported (Milke and Gerschefski, 1995).

2.2.6.3.2 Test D.6

A full-scale array of shelving to simulate the situation found in the basement of the National Library of Canada was constructed using two fixed shelves with five double-row mobile shelves between them. The compartment area was 4.6 x 6.7 m. The shelves were loaded with corrugated cardboard document storage boxes filled with newsprint, comparable to those used in the library.

Two sprinkler systems were tested – one pendent configuration and one sidewall configuration – as shown in the example schematics of Figure 68. Cycling application modes of the sprinklers were used in the investigation. Among other potentially influencing variables, the response time of the sprinkler heads was also investigated. Sprinkler flow rates, and subsequently the water density delivered over the stacks, was varied between different tests as well as during some tests (Lougheed and Mawhinney, 2005).

Thermocouple temperatures in the stacks and within the room and smoke obscuration were recorded. Radiometers were used to estimate the radiant flux to adjacent shelving bays. Flow rate and pressure were measured at the base of the riser. Test and post-test observations were also reported (Lougheed and Mawhinney, 2005).

The full report is: *Full-Scale Tests of Sprinklered Mobile Shelving Units for National Library of Canada*, prepared by Gage-Babcock & Associates, Vienna, Virginia, USA.

2.2.6.4 Nozzle configuration

2.2.6.4.1 Test D.7

A full-scale array of shelving to simulate the situation found in the basement of the National Library of Canada was constructed using two fixed shelves with five double-row mobile shelves between them. The compartment area was 4.6 x 6.7 m. The shelves were loaded with corrugated cardboard document storage boxes filled with newsprint, comparable to those used in the library.

Two sprinkler systems were tested – one pendent configuration and one sidewall configuration – as shown in the example schematics of Figure 68. Cycling application modes of the sprinklers were used in the investigation. The influence of the response time of the sprinkler heads was also investigated. The fuel packages were varied, i.e. using open vs closed document boxes. Sprinkler flow rates, and subsequently the water density delivered over the stacks, were varied between different tests as well as during some tests. Clearance distances between the sprinkler head and the storage were also investigated (Lougheed and Mawhinney, 2005).

Thermocouple temperatures in the stacks and within the room and smoke obscuration were recorded. Radiometers were used to estimate the radiant flux to adjacent shelving bays. Flow rate and pressure were measured at the base of the riser. Test and post-test observations were also reported (Lougheed and Mawhinney, 2005).

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2.2.7 Electronic equipment fires

2.2.7.1 Fire type and size

2.2.7.1.1 Test E.1

Full-scale tests of a water mist system were conducted in a simulated computer room (10 x 10 m wide by 3.54 m high), as shown in the schematic of Figure 47. A sub-floor was constructed using 0.61 x 0.61 m steel tiles, with a 0.457 m vertical clearance. Five tiles were replaced with pegboard, to simulate ventilation openings that are usually present in between the subfloor and compartment. A computer cabinet (0.645 x 0.914 m wide by 1.575 m high) was placed within the compartment and partially filled with circuit boards.

The top part of the cabinet was left empty for the application of test fires. The fire types tested included initial small fires (60 ml Heptane floating on 500 ml water pool fires, and candles) for preliminary investigation of the test setup and then cable bundle fires.

The cable bundles consisted of eight 0.508 m lengths of PVC insulated wire (using SO 24 AWG stranded conductors, with a 12 mm nominal exterior diameter). The cable bundles were attached to a 650 W tubular heater, and the transition to flaming was aided using a propane burner that was shut off when flaming was achieved. The small Heptane pool fires and candles were tested at various locations within the cabinet. The cable bundles were tested in either the cabinet or the subfloor.

The fire suppression system was manually activated. Tests of the cable bundle fuel packages with and without the smoke scrubbing turned on were conducted to estimate the efficiency of the system (Tuomisaari, 1999).

Oxygen concentrations within the enclosure were reported for eight locations. Carbon monoxide and carbon dioxide concentrations were reported for one location within the enclosure, and hydrogen chloride concentrations were reported for three locations.

Thermocouple temperatures were reported for the same locations as the oxygen concentration measurement locations, in addition to the fire location for each test. Pressure was measured at the top and bottom of the height of the wall of the enclosure. Time to extinguishment was also reported (Tuomisaari, 1999).

The full report is: Forssell EW and DiNenno PJ. 1999. *Tests of Marioff Computer Room Fire Protection System*, June 27, Hughes Associates Inc, Baltimore, MD, USA.

2.2.7.2 Suppression system characteristics

2.2.7.2.1 Test E.2

Experiments were used to identify basic design requirements for a multi-zone water mist suppression system to provide protection for specific areas of a control room (Mawhinney, 1996):

- underfloor
- individual electronic switchgear cabinets
- arrays of cables in trays.

The results from the experimental program were used to identify the feasibility of using water mist to suppress fires in electronic equipment cabinets and rooms. These experiments were part of a three-year study was conducted at the NRCC (Mawhinney, 1996) that had been jointly funded by the NRCC and the Department of National Defence, Canada.

The study was to investigate the performance criteria for a combined fire detection and zoned water mist fire suppression system, where the fire detection system automatically identified the location of the fire and activated only the local nozzles. The original summary of the experiments prepared for the Department of National Defence, Canada, were not found to be available during the compilation of this literature review. A summary was produced by Mawhinney (1996), upon which this description is based.

The first conclusion supported by the results from the experiments was that water mist did not perform well when applied in a “total flooding” mode in obstructed compartments. Unpredictable variations in local spray velocity and flux density distribution were reported as the results of “random splashing”. Extinguishment during this scenario was reported to be equally unpredictable (Mawhinney, 1996). Therefore the relevant tests may be included in the “unsuccessful fire suppression system” for comparison (i.e. Section 2.4).

The second conclusion was identification of the most important factor in determining suppression performance. This factor was determined to be the control over the directionality of the water mist relative to the desired application. It was suggested that the direction of application of the spray was more important than drop-size distribution and mass flow rate (Mawhinney, 1996).

2.2.7.2.2 Test E.3

The efficiency of smoke scrubbing that utilised the entrained air in a water mist fire suppression system was investigated using preliminary tests of a small ventilated enclosure located in the big fire test hall at VTT. The enclosure was 2.1 x 2.1 m wide by 1.2 m high. A crib fire was made of PVC-insulated 20-way ribbon cable (commonly used in computers and interface units) that was supported by four layers of metal trays 30 mm apart.

Each tray had a double layer of 18 strands of 250 mm long cable. The mass of the crib was 0.78 kg; 0.52 kg of this was PVC. The crib was ignited using a small Heptane pool fire located under it. Tests with and without smoke scrubbing were conducted for comparison. Concentrations of gas species (hydrochloric acid, carbon monoxide and methane) for locations in the test hall outside of the enclosure were reported (Tuomisaari, 1999).

2.2.7.2.3 Test E.4

Full-scale tests of a water mist system were conducted in a simulated computer room (10 x 10 m wide by 3.54 m high), as shown in the schematic of Figure 47. A sub-floor was constructed using 0.61 x 0.61 m steel tiles, with a 0.457 m vertical clearance. Five tiles were replaced with pegboard to simulate ventilation openings that are usually present in between the subfloor and compartment.

A computer cabinet (0.645 x 0.914 m wide by 1.575 m high) was placed within the compartment and partially filled with circuit boards. The top part of the cabinet was left empty for the application of test fires. Various fire types and locations were tested, as discussed in a previous section (Section 2.2.7.1). The fire suppression system was manually activated at intentionally unrealistic late stages to provide a large challenge to the suppression capabilities of the system. Tests with and without the smoke scrubbing turned on were conducted to estimate the efficiency of the system (Tuomisaari, 1999).

Oxygen concentrations within the enclosure were reported for eight locations. Carbon monoxide and carbon dioxide concentrations were reported for one location within the enclosure, and hydrogen chloride concentrations were reported for three locations.

Thermocouple temperatures were reported for the same locations as the oxygen concentration measurement locations, in addition to the fire location for each test. Pressure was measured at the top and bottom of the height of the wall of the enclosure. Time to extinguishment was also reported (Tuomisaari, 1999).

The full report is: Forssell EW and DiNenno PJ. 1999. *Tests of Marioff Computer Room Fire Protection System*. Hughes Associates Inc, Baltimore, MD, USA.

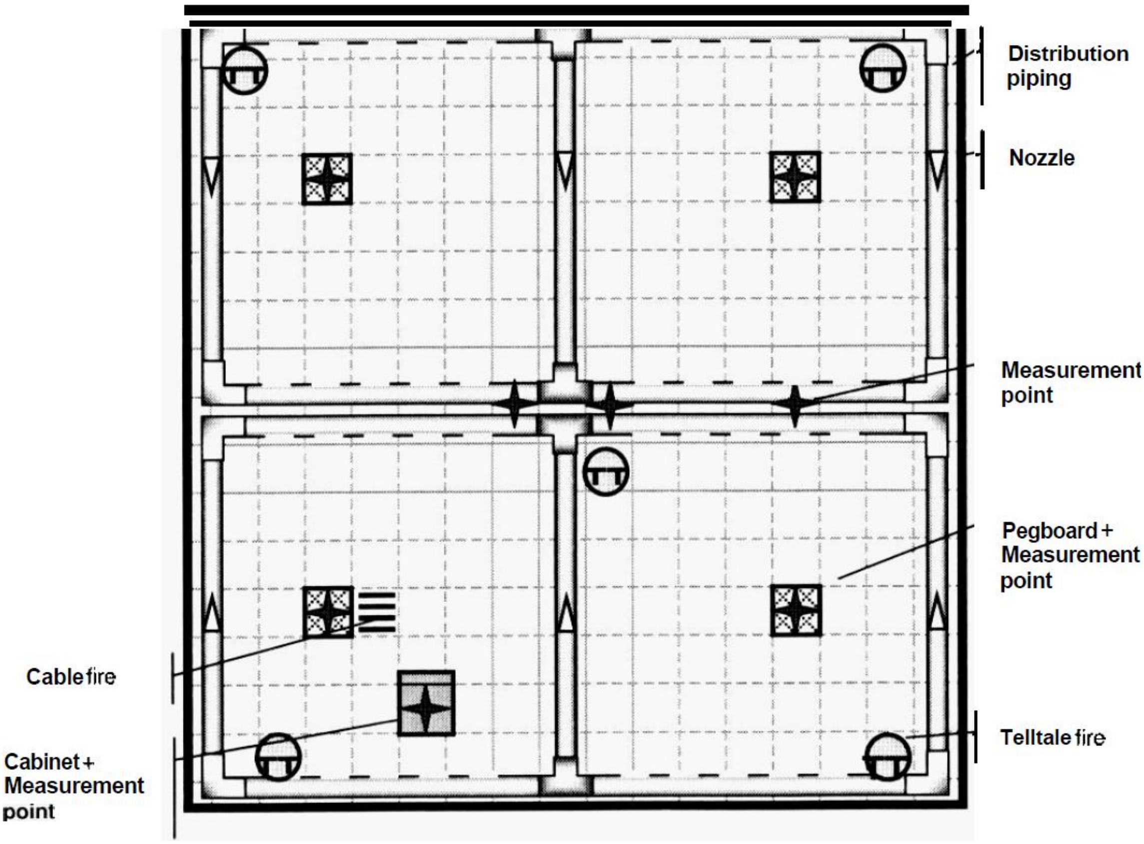


Figure 47: Schematic of the full-scale simulated computer room test compartment (Tuomisaari, 1999)

2.2.8 Entertainment space

2.2.8.1.1 Test F.1

A full-scale mock-up of approximately 20% of the Station Nightclub was tested with and without automatic sprinklers. The mock-up consisted of the platform, main floor and alcove of the original building on which the fire was based. The mock-up was in a 10.78 x 7.0 m wide by 3.8 m high compartment. A single 0.91 x 2.0 m doorway was located in the wall opposite the alcove, as shown in Figure 48 (Madrzykowski et al., 2006; Grosshandler et al., 2005a, 2005b; Bryner et al., 2007).

The compartment consisted of a steel frame and two layers of 12 mm thick calcium silicate board and a layer of 12 mm thick gypsum board. The walls and ceiling of the alcove and walls of the main stage were covered with non-fire-retarded ether-based polyurethane foam, down to 1.35 m above the floor level. The floor of the alcove and main stage were covered with nylon carpet.

A section of 5.2 mm thick panelling was used to line 3.6 m of the wall of the main floor in front of the raised stage. The remainder of the compartment walls, ceiling and floor was finished with gypsum board (Madrzykowski et al., 2006; Grosshandler et al., 2005a).

Two tests were conducted: one with automatic sprinklers and one without a sprinkler system (Madrzykowski et al., 2006; Grosshandler et al., 2005a; Bryner et al., 2007). Ignition was initiated using electric matches on the polyurethane foam in two locations, at 1.66 m above the floor level, simultaneously (Grosshandler et al., 2005a).

The compartment was instrumented with thermocouples, gas sampling ports (to measure oxygen, carbon dioxide, carbon monoxide, and hydrogen cyanide), heat flux gauges, bi-directional probes and video cameras. A schematic of the layout of the instrumentation is shown in Figure 49. Various heat detectors were also installed and monitored (Madrzykowski et al., 2006; Grosshandler et al., 2005a, 2005b; Bryner et al., 2007).

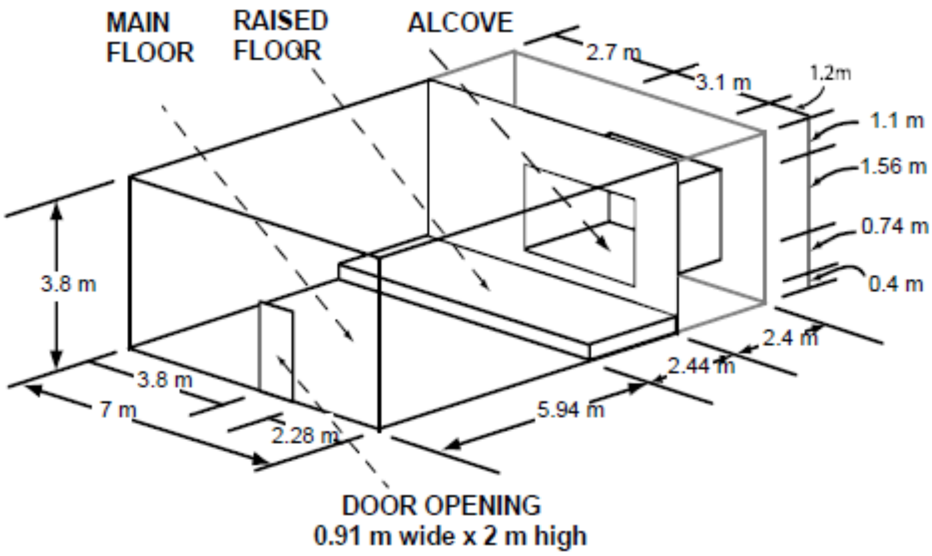


Figure 48: Isometric view of the mock-up of a section of the Station Nightclub fire (Grosshandler et al., 2005a)

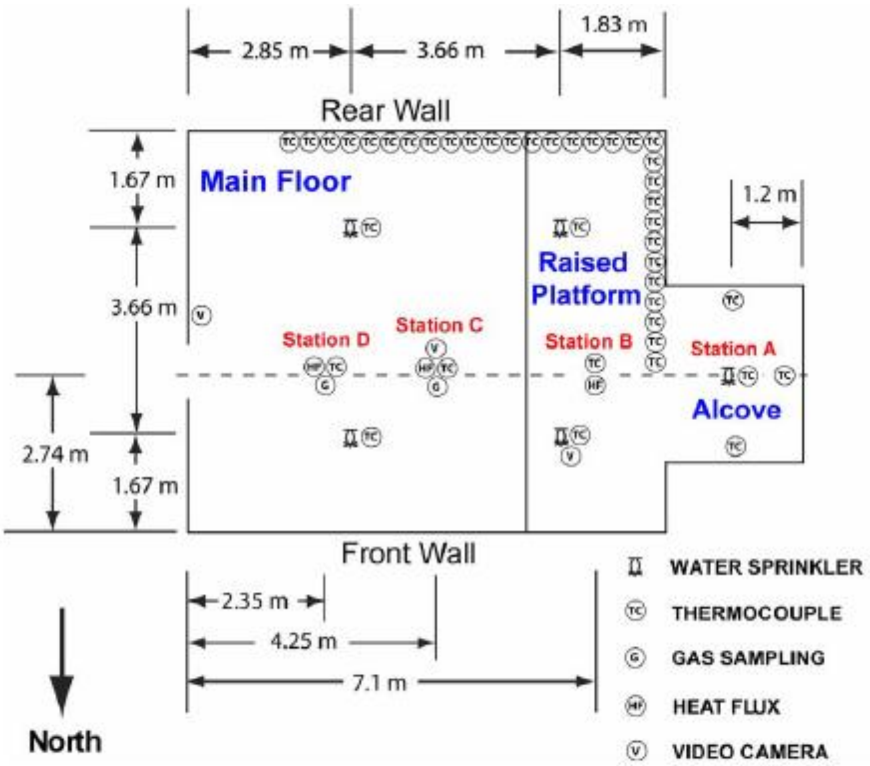


Figure 49: Schematic of the instrumentation within the compartment used as a mock-up of a section of the Station Nightclub (Grosshandler et al., 2005a)

2.2.9 Factory/machinery space

2.2.9.1 Compartment size and configuration

2.2.9.1.1 Test G.1

Experiments were carried out by in a large test facility using a compartment area of 2800 m² with a height of 18 m where the ceiling could be dropped to 5 m. The nozzles were installed at a 5 m height and 1.5 m spacing in the compartment without any additional enclosure surrounding the nozzles. Various fires sizes (1 to 6 MW shielded and unshielded spray fires, and a wood crib fire and a 2 m² pan fire) were investigated.

A high-pressure (6.9 MPa) and a low-pressure (1.2 to 1.5 MPa) water mist system were used in various tests. The number of the nozzles was increased from 30 to 100. In each case, the suppression system was unable to control the fire. The reported oxygen concentration in the compartment was not reduced significantly by the discharge of water mist and remained above 20.5% during the tests (Bill et al., 1997).

However, when a 940 m³ enclosure was formed using the previously installed ceiling and installing tarpaulins for walls, a 6 MW unshielded spray fire was reported to be successfully extinguished (Bill et al., 1997).

2.2.9.2 Ventilation

2.2.9.2.1 Test G.2

Pool fires were tested in a compartment (Figure 76) with a mock-up diesel engine, and the influence of natural and forced ventilation conditions was investigated in relation to water mist suppression performance. Fire size, type and location were also investigated. Single-fluid and twin-fluid water mist systems were tested (Liu et al. 1999, 2001).

HRR (at 1 Hz), based on oxygen consumption calorimetry, was reported for each test. Time to extinguishment was also reported. Thermocouple measurements were reported for three thermocouple trees (each consisting of six thermocouples) in the room. The thermocouples were 30-gauge, chromel-alumel Type K, and stainless steel sheathed and recorded at 1 Hz. Carbon dioxide and carbon monoxide concentrations (at 1 Hz) were reported for two locations within the room.

Oxygen concentrations were also reported for the higher location where the carbon monoxide and carbon dioxide measurements were taken. Nine pressure measurements were also reported for locations on the west wall. Two video cameras were used to record the water mist activation and behaviour of the fires during control and suppression (Liu et al., 2001; Kim and Zhigang, 2002).

2.2.9.2.2 Test G.3

Tests conducted at NRCC compared continuous to cyclic discharge application of a twin-fluid, low-pressure water mist system to a range of fire challenges in a compartment with a mock-up engine. The test room was an irregular shape; a rectangular room (9.7 x 4.9 m wide by 2.9 m high) with a corner (2.9 x 2.2 m removed) (Figure 76). The compartment had a 0.9 x 2.0 m high door and three 0.56 x 0.56 m viewing windows. During forced ventilation conditions, the pressure relief vent (0.5 x 0.5 m) close to the floor, in the west wall, was also open. The flow rate of the exhaust fan was 0.737 m^3/s. Various fire sizes, up to 700 kW, were investigated (Liu et al., 1999; Kim and Liu, 2006).

HRR (at 1 Hz), estimated from oxygen consumption calorimetry, was reported for each test. Time to extinguishment was also reported. Thermocouple measurements were reported for three thermocouple trees (each consisting of six thermocouples) in the room. The thermocouples were 30-gauge, chromel-alumel Type K, and stainless steel sheathed and recorded at 1 Hz. Carbon dioxide and carbon monoxide concentrations (at 1 Hz) were reported for two locations within the room.

Oxygen concentrations were also reported for the higher location where the carbon monoxide and carbon dioxide measurements were taken. Nine pressure measurements were also reported for locations on the west wall. Two video cameras were used to record the water mist activation and behaviour of the fires during control and suppression (Kim and Liu, 2006).

2.2.9.2.3 Test G.4

The influence of forced ventilation has also been investigated. For example, full-scale fire tests were conducted on a representative section of high-rack storage to investigate the influence of high-volume low-speed fans on the performance of Early Suppression Fast Response (ESFR) sprinklers (SEC, 2009).

The tests were carried out in a 36 x 36 m wide by 16 m high fire test laboratory at Underwriters Laboratories Inc. A 30 x 30 m adjustable flat ceiling was located 9 m above the floor. Make-up air for the laboratory was supplied by four inlets located in the walls at a rate of approximately 28 m^3/s. The laboratory floor was flat and surrounded with a drainage trench connected to a water treatment system (SEC, 2009).

One hundred pendent ESFR sprinkler heads (with an activation temperature of 73.8ºC and discharge coefficient of 200 $L/min.kPa^{1/2}$) were installed at 3 x 3 m spacing in a closed-head, wet pipe, automatic sprinkler system in the adjustable ceiling, as shown in Figure 50. The 57 mm diameter pipes were used in a looped system. The distance between the ceiling and the deflectors of each sprinkler was 0.35 m. Nominal flow was 0.37 m^3/min and nominal pressure 345 kPa at each sprinkler (SEC, 2009).

The fuel packages were a Group A Plastic Commodity that consisted of boxed rigid crystalline polystyrene cups (16 oz size). The cups were packaged in individual compartments in single-wall, corrugated cardboard cartons. Each box contained five layers of 25 cups per layer. The individual compartments within each box for each cup were made with layer sheets and interlocking vertical panels of single-wall, corrugated cardboard sheets. Each packed box was 0.53 m cubed. Each pallet contained eight of these packed boxes. The pallets were made from 127 mm slatted deck hardwood. An example of a fuel package is shown in Figure 51 (a and b) (SEC, 2009).

Class II packages consisted of double tri-wall corrugated cardboard cartons with steel stiffeners in five sides for stability (Figure 51c). The cartons were 1.1 x 1.1 x 1.1 m in size and place on 1.1 x 1.1 m wide by 0.13 m high hardwood pallets. The Class II packages were loaded into the ends of the outer racks (Figure 52) (SEC, 2009).

A high-volume low-speed six-blade 7.3 m diameter fan was located 4.6 m south from the centre point of the adjustable ceiling (Figure 52 and Figure 53). The fan was installed such that the blade was 1.27 m below the ceiling (SEC, 2009).

Two rack storage arrangements were tested. The racks used in testing consisted of steel upright and steel beam construction, 4.9 m high by 0.82 m wide. The central rack was arranged in a double-row configuration with four 2.4 m bays and four tiers in each row. In the first test arrangement, the geometric centre of the double-row rack was located under two sprinklers in the test room (Figure 52). In the second test arrangement, the geometric centre of the double-row rack was located under four sprinklers in the test room, directly below the location of the fan (Figure 53).

In both arrangements, the target arrays were single-row racks utilising steel construction. The single-row rack system was also 4.9 m high by 0.82 m wide with four 2.4 m bays and four tiers in each row and located at either side of the double-row rack, with 1.2 m aisles. The fuel packages were loaded into the double-row and the centre of the single-row racks to provide 15 mm wide longitudinal and transverse flue space throughout the test array (Figure 52 and Figure 53) (SEC, 2009).

Four cotton bundles soaked in gasoline and wrapped in polyethylene bags were used as the ignition source for the test. The four cotton bundled igniters were located 25 mm off the floor in the centre of the double-row, as shown in Figure 54 (SEC, 2009).

Each sprinkler was instrumented with a 1.5 mm diameter Type K Inconel sheathed thermocouple, recorded at one measurement per second. Three additional thermocouples were located at 152, 305 and 457 mm below the ceiling over the centre of the ignition source. Five additional thermocouples were embedded in a 1.28 m long piece of steel angle that was attached to the ceiling directly above the ignition location (Figure 50). The water pressure and flow rate for the sprinkler system was also reported. Video and infrared cameras were used to record the fire spread (SEC, 2009).

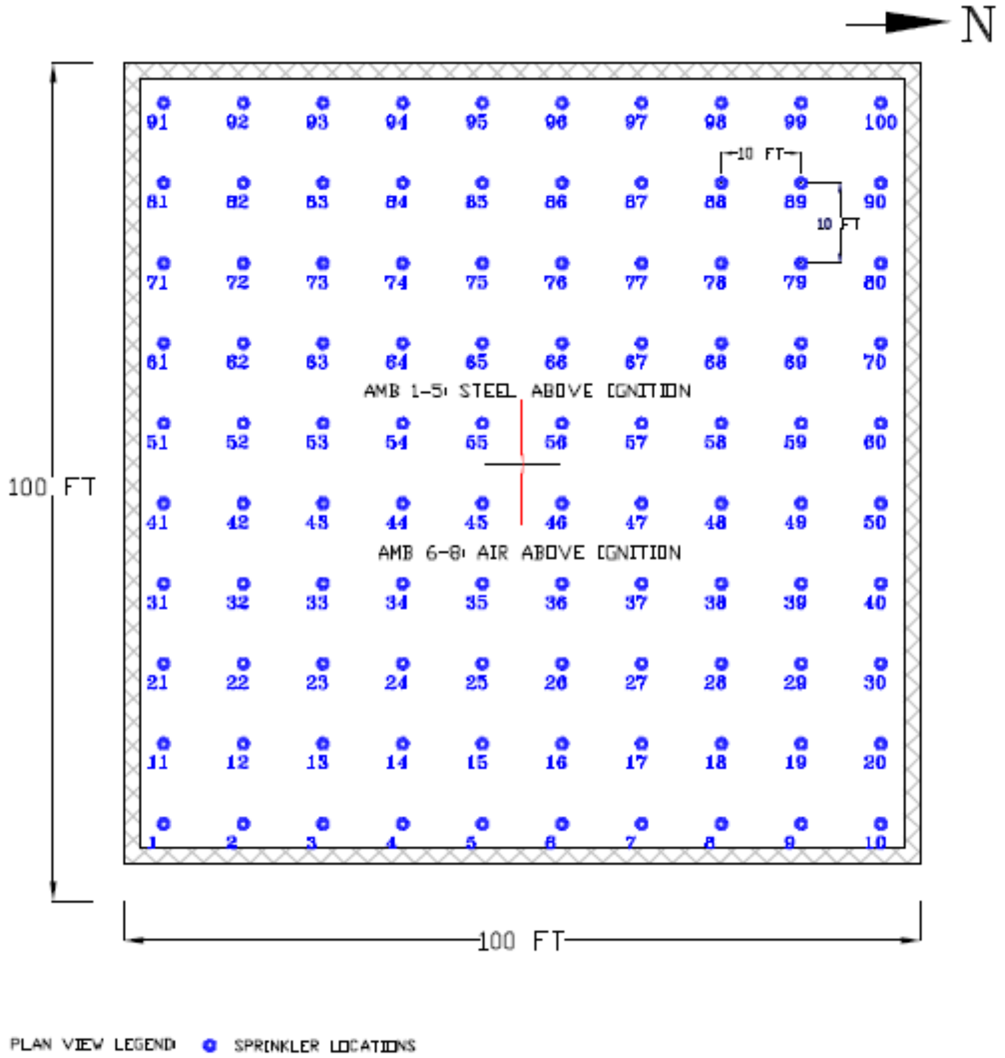


Figure 50: Schematic of the plan view of the high-rack storage section test for sprinkler and instrumentation location (SEC, 2009)

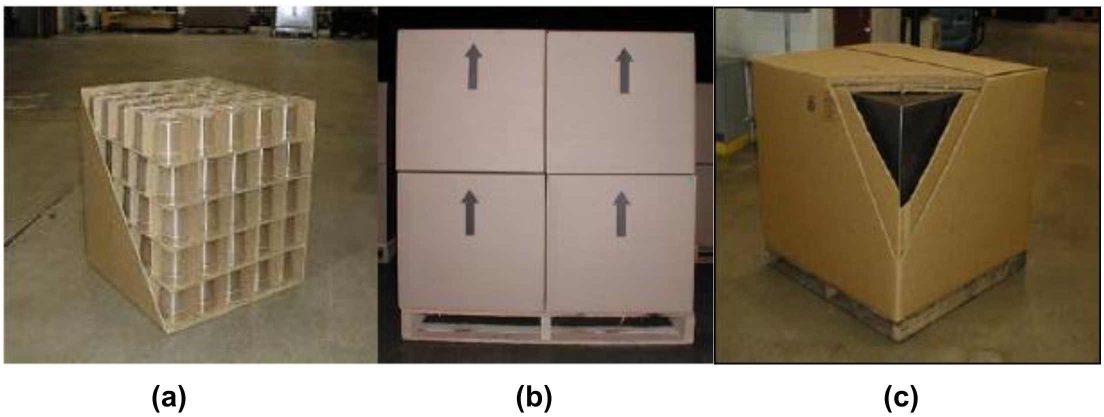


Figure 51: Example of the (a) sectioned and (b) stacked Group A Plastic Commodity fuel package (SEC, 2009) and the (c) Class II package (AFPE, 2011)

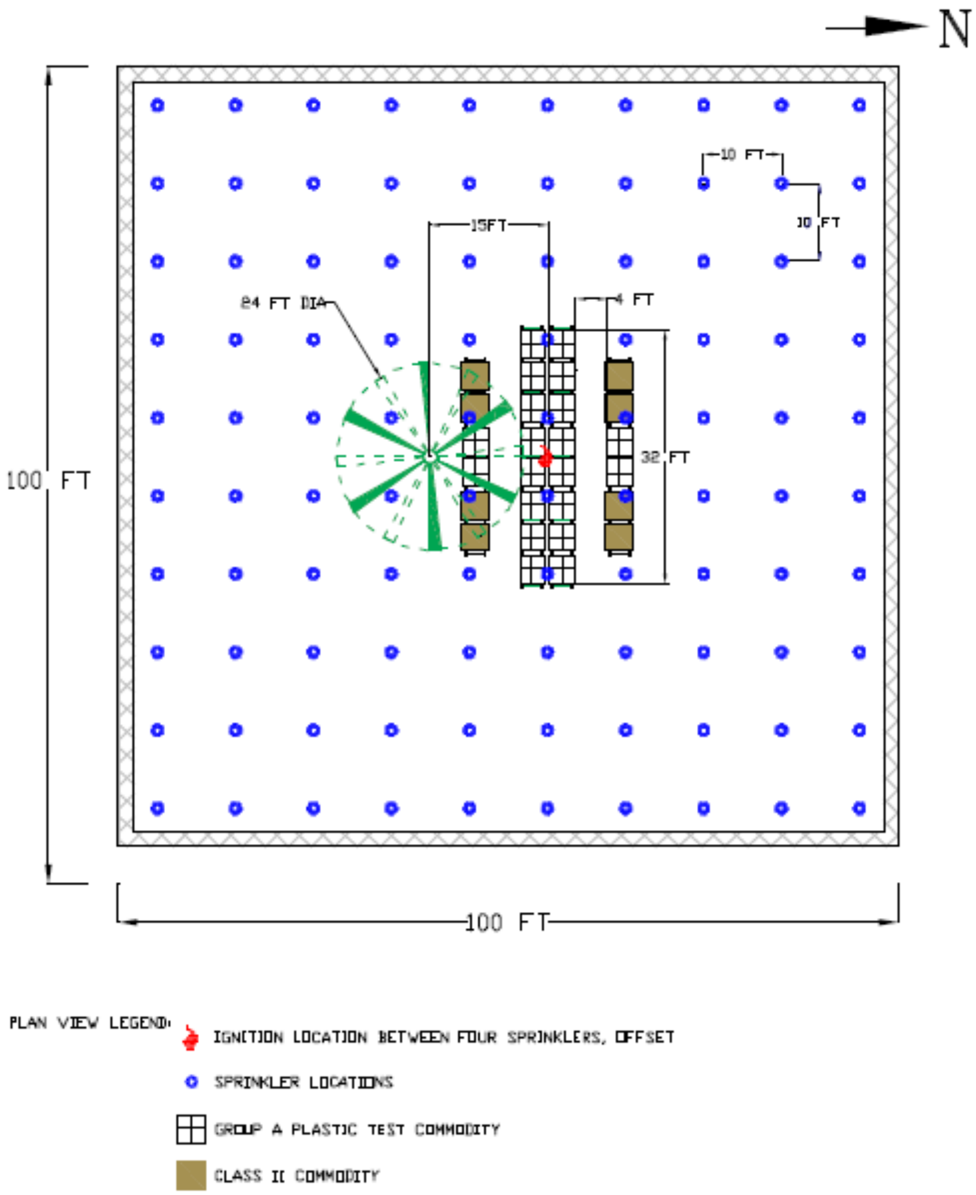


Figure 52: Schematic of the plan view of the storage racks, fuel packages, ceiling fan and ignition location for the high-rack storage section tests, for test arrangement 1 (SEC, 2009)

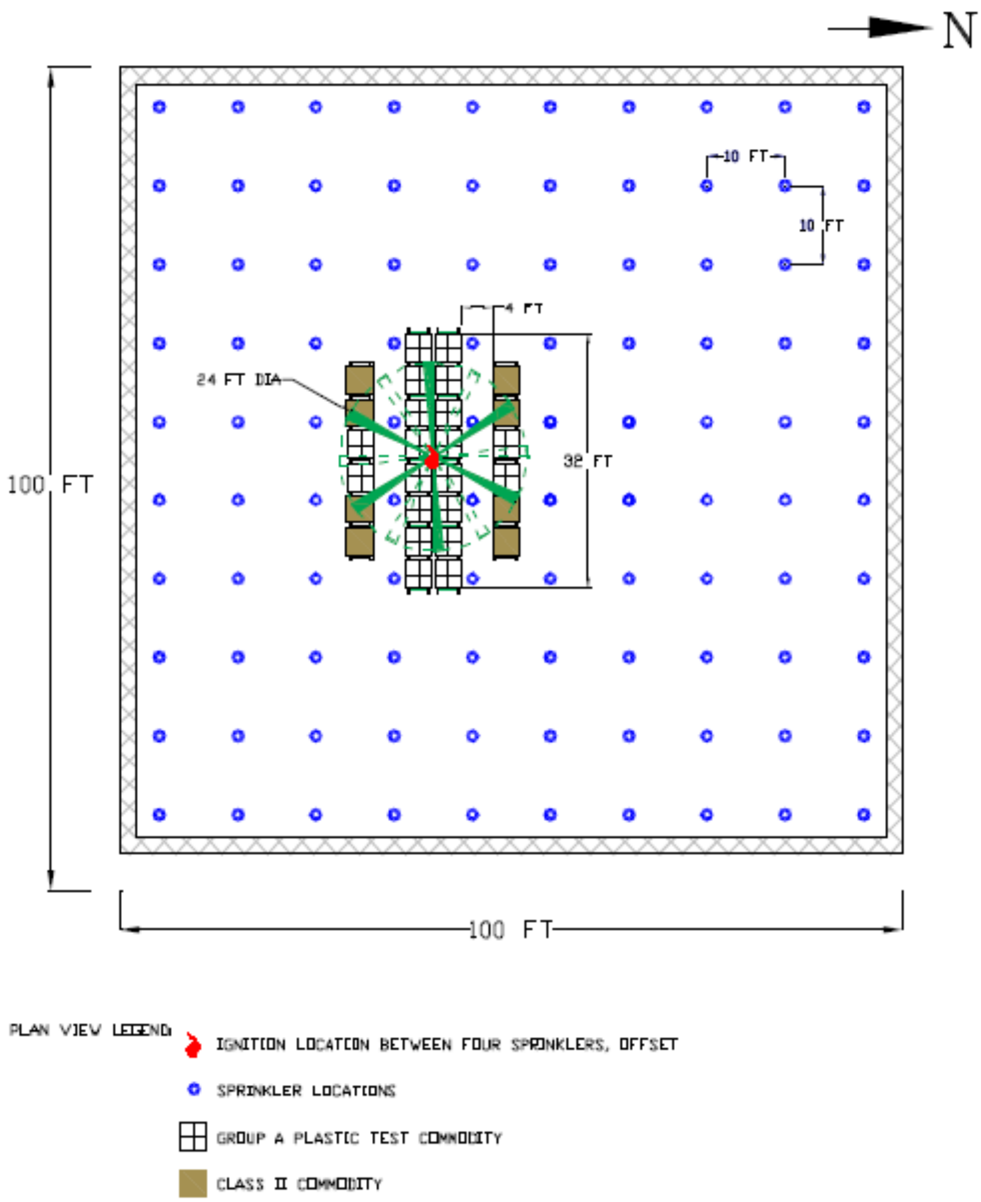


Figure 53: Schematic of the plan view of the storage racks, fuel packages, ceiling fan and ignition location for the high-rack storage section tests, for test arrangement 1 (SEC, 2009)

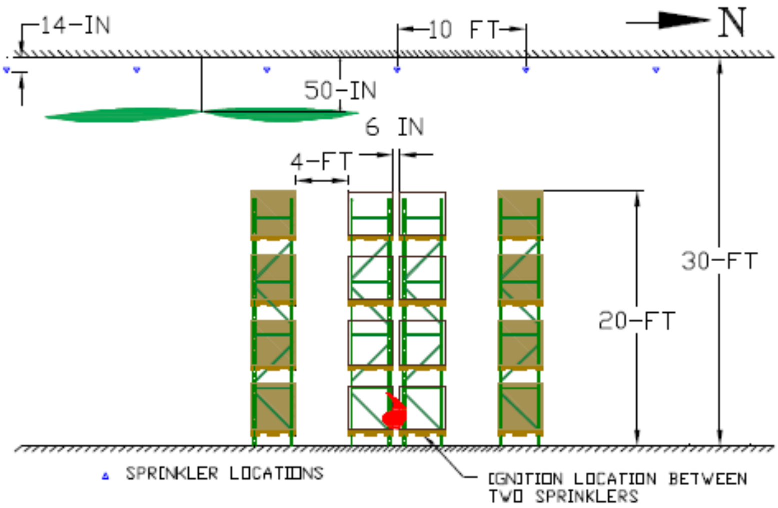


Figure 54: East/west elevation view of storage racks, fuel packages, ceiling fan and ignition location for the high-rack storage section tests (SEC, 2009)

2.2.9.2.4 Test G.5

Ten forced ventilation tests involving high volume, low-speed ceiling fans were also conducted using the (24 x 24 m) movable ceilings at the Large Burn Laboratory in the GM Global Research Fire Technology Laboratory. An additional six tests were conducted using the 30 x 30 m adjustable flat ceiling at the Underwriters Laboratory large-scale fire test facility (AFPE, 2011).

Two fans were used in testing: one was a 7.3 m diameter, six-blade, 63 rpm fan; and the second was a 7.3 m diameter, four-blade, 48 rpm fan. Velocity data was collected to improve the understanding of the air movement produced by the different fans through the array or racks. Two types of sprinkler were tested: ESFR and Control Mode Density Area (CMDA). The ceiling height was also varied between tests, depending on the type of sprinkler used (AFPE, 2011).

Class A Plastic Commodity was used as the fuel packages (Figure 51 a & b). These were described in the previous test series summary above. Class II packages were similarly used at the ends of racks (Figure 51c) (AFPE, 2011).

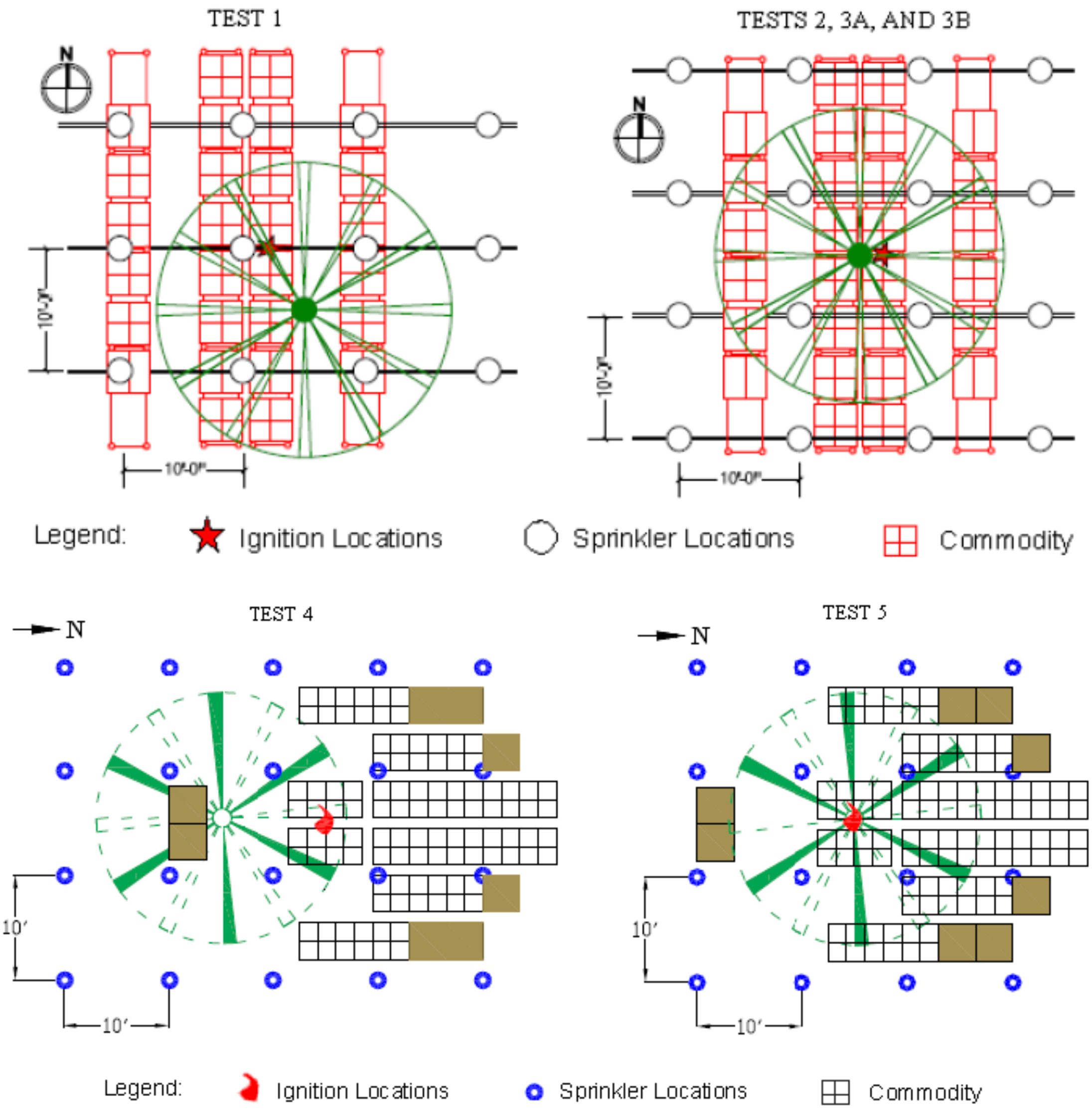
Various configurations of rack, fan and ignition location were tested, as summarised in Figure 55 (AFPE, 2011).

The igniter was 76 x 76 mm rolled cotton bundles, soaked in 118 ml gasoline and wrapped in a polyethylene bag. Two of these bundles were used as the ignition source for each test. Two ignition locations relative to the fan were used in testing; either in line with the tip of the fan blade or directly under the centre of the fan. Also two ignition locations relative to the sprinkler heads were also used; either under a single sprinkler head or equidistant between four sprinkler heads. The ignition source was set in the array between two bottom pallets in a double-row rack, with an approximately 0.6 m offset from the central flue between the packages (AFPE, 2011).

All tests were conducted with the exhaust set to 5663 m³/min (AFPE, 2011).

Not all of the tests had successful suppression outcomes. Some test results were reported as a failure in relation to the focus of the test series of suppression, and instead represented a fire control situation (AFPE, 2011) However, the data is still relevant in terms of potential validation evaluation.

Ceiling temperature data was collected for a grid over the adjustable test ceiling, as shown in the schematic of Figure 56. Here 125 bare-bead, 0.8 mm diameter wire, chromel-alumel thermocouples were located 165 mm below the ceiling. Steel temperature measurements were also reported. Sprinkler pressure and flow were reported with test duration. The extent of damage of the commodity packages was also reported. Air velocities were reported for 130 mm above the arrays of racks and at the end of five of the transverse flues formed within the loaded double-row racks (AFPE, 2011).



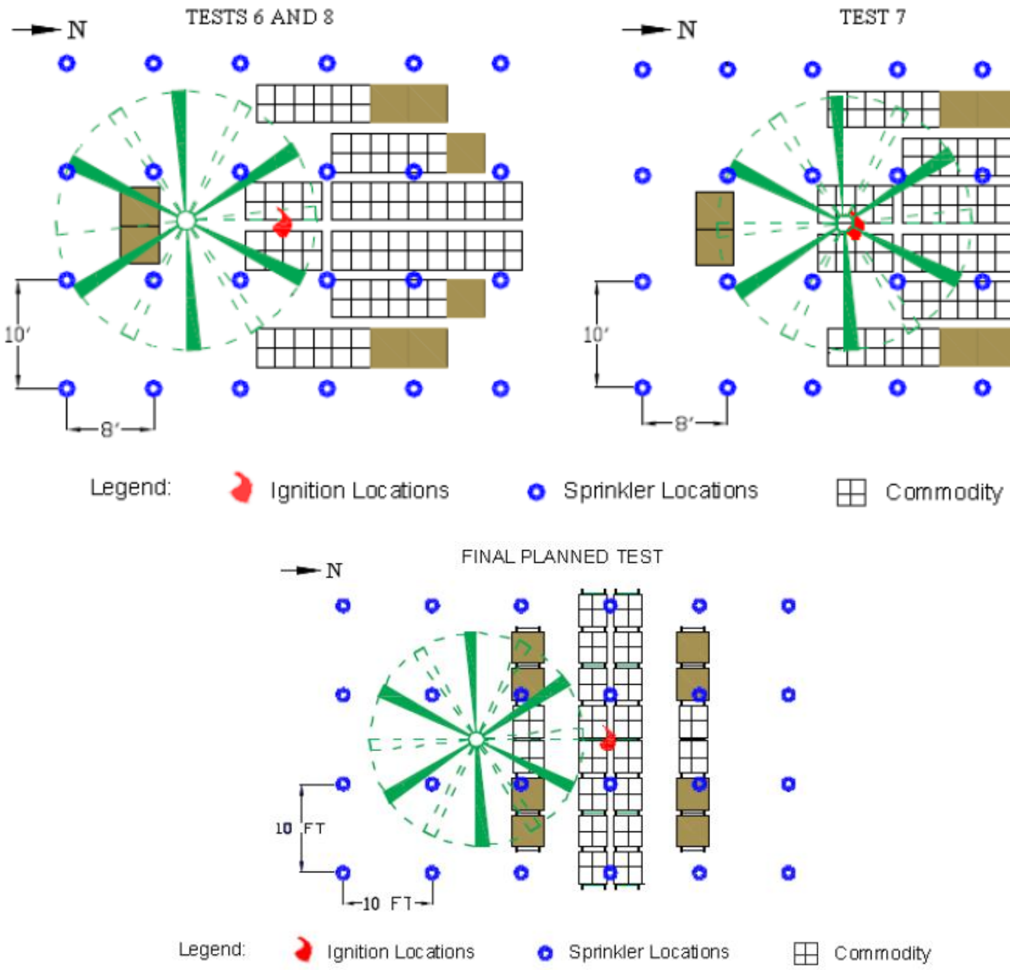


Figure 55: Schematics of the configurations of fan, loaded racks and ignition location tested in the series of fan and sprinkler interaction tests (AFPE, 2011)

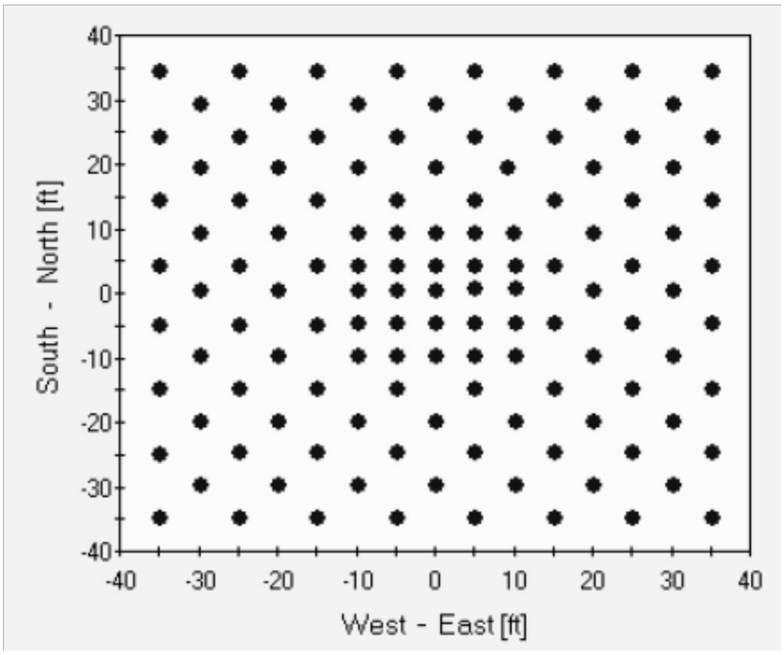


Figure 56: Schematic of the layout of ceiling thermocouples for the series of fan and sprinkler interaction tests (AFPE, 2011)

2.2.9.3 Fire type and size

2.2.9.3.1 Test G.6

In the evaluation of early suppression fast response automatic sprinklers for high rack storage applications, series of large-scale tests were performed as part of the National Quick Response Sprinkler Research Project instigated by the National Fire Protection Research Foundation. These test series were conducted through the late 1980s into 1990.

In most cases similar experiments or aspects of this test series have been also investigated in more recent test programs, with potentially more easily accessible data. However some of the reports that may be useful as background material (Chicarello et al., 1986; Beitle, 1990; UL, 1990b, 1990a) to assist in identification of potential phenomenon or situations of relevance within these scenarios.

2.2.9.3.2 Test G.7

Approximately 150 full-scale tests were conducted in a simulated ship engine room for various pool and spray fires. Two different compartments were used. The one at the Swedish National Testing and Research Institute (SP) was 8 x 10 m wide x 4.8 m high (the fire hall), and the other space was at Upinniemi, Palokoulutuskeskus (a naval base in Finland). Ventilation was varied using natural ventilation through available doors and hatches. The same setup was used for the engine, bilge area and nozzle locations for both testing locations. Time to extinguishment was reported (Turner, 1993).

The full test report is: Arvidson M & Ryderman A. 1992. *Tests in Simulated Ship's Engine Rooms with Hi-fog Fire Protection Systems.* Swedish National Testing and Research Institute, 91 R30189, Borås, Sweden (Turner, 1993).

2.2.9.3.3 Test G.8

Eight full-scale tests of the Upinniemi engine mock-up in a large unenclosed space (using the large test hall of the VTT Fire Technology Laboratory) were conducted for various fire sizes. The fires consisted of pool and spray fires. The most intense fire scenario consisted of four pool fires below the engine, one pool fire located above the engine, and a spray fire located beside the engine (with a combined estimated HRR of 20 MW). A water mist system, using a combination of low-pressure and high-pressure nozzles, was manually activated two minutes after lighting the spray fire (Turner, 1993).

The full test report is: Tuomissari M. 1992. *Fire Suppression Tests in Simulated Ship's Engine Room with a Hi-fog Fire Protection System, PAL 2210/92.* VTT Fire Technology Laboratory. Helsinki, Finland (Turner, 1993).

2.2.9.3.4 Test G.9

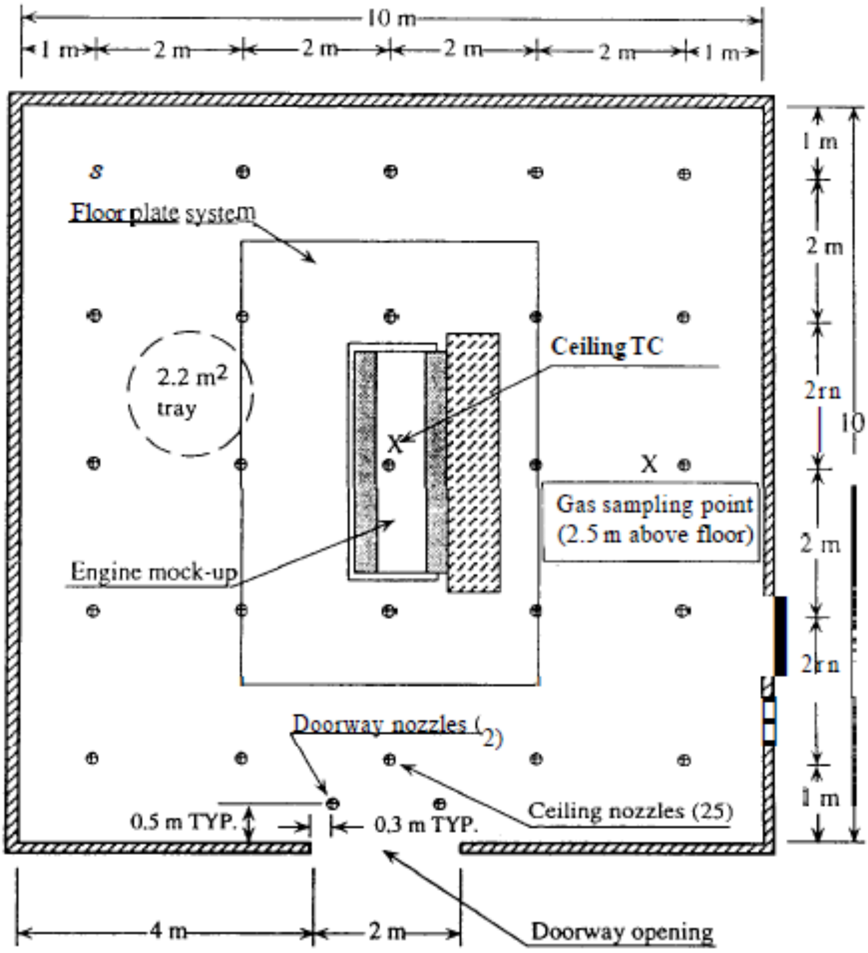
Experiments reported by Pepi (1995, 1998) investigated the influence of fire size on water mist system suppression performance. A low-pressure water mist system was subjected to Heptane and light diesel oil pool and spray fires of various sizes from 1 to 6 MW. The spray fires were from 1 MW up to 6 MW. The fire scenarios tested were related to the scenarios (1 and 2) of the International Maritime Organization (IMO) test protocol (Pepi, 1995).

A sheet steel mock-up (Figure 58) of an engine or machinery was located in the centre of the 1280 m³ (10 x 16 m wide by 8 m high) compartment on raised floor plates, as shown in Figure 57. A 2 x 2 m doorway was screened by four nozzles. Eight nozzles were installed at 4 x 4 m spacing. Nozzles at the outer part of the grid, near the walls, were located 3 m off the walls (Pepi, 1998).

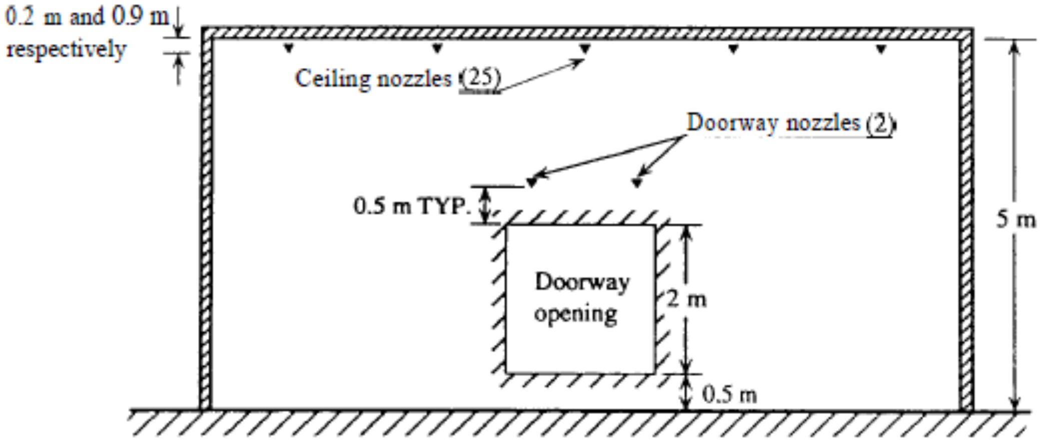
Smaller compartments were also tested, including 500 m² by 5 m high and 800 m² by 5 m high. The spacing of the nozzles was also varied (Pepi, 1998).

In total, considering the compartment size, nozzle spacing and size and shielding of the fires, 13 different fire scenarios were tested (Pepi, 1998).

Oxygen concentrations (at 3 m above the floor on the room centreline and 3 m either side of it) and times to extinguishment were reported for the various sizes of spray fires for the types of nozzles and compartment sizes tested (Pepi, 1995, 1998).



(a)



(b)

Figure 57: Schematic of the (a) plan and (b) elevation views of the compartment with instrumentation for the sheet steel mock-up tests (Pepi, 1995)

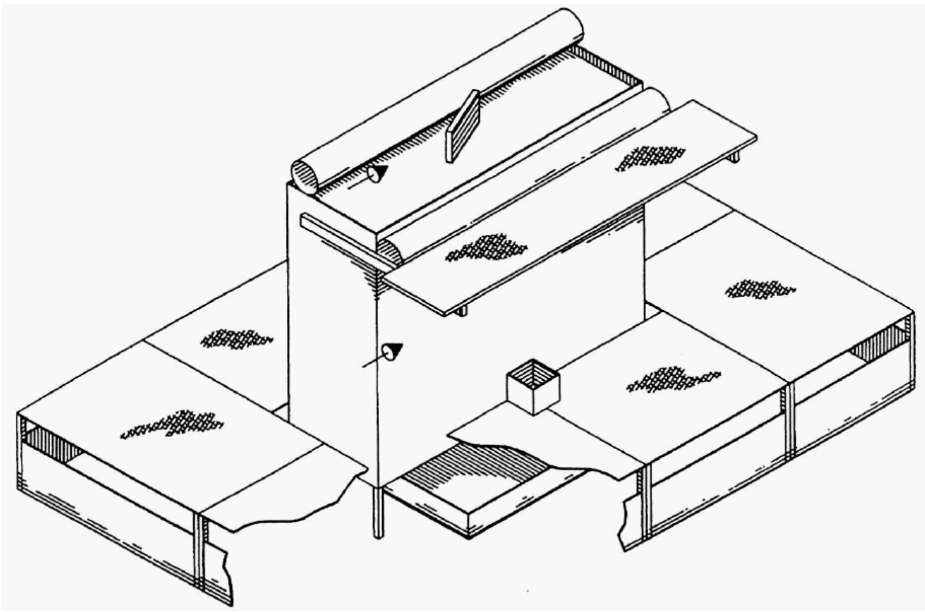


Figure 58: Sheet steel mock-up used in testing engine room or machinery room fire scenarios (Pepi, 1998)

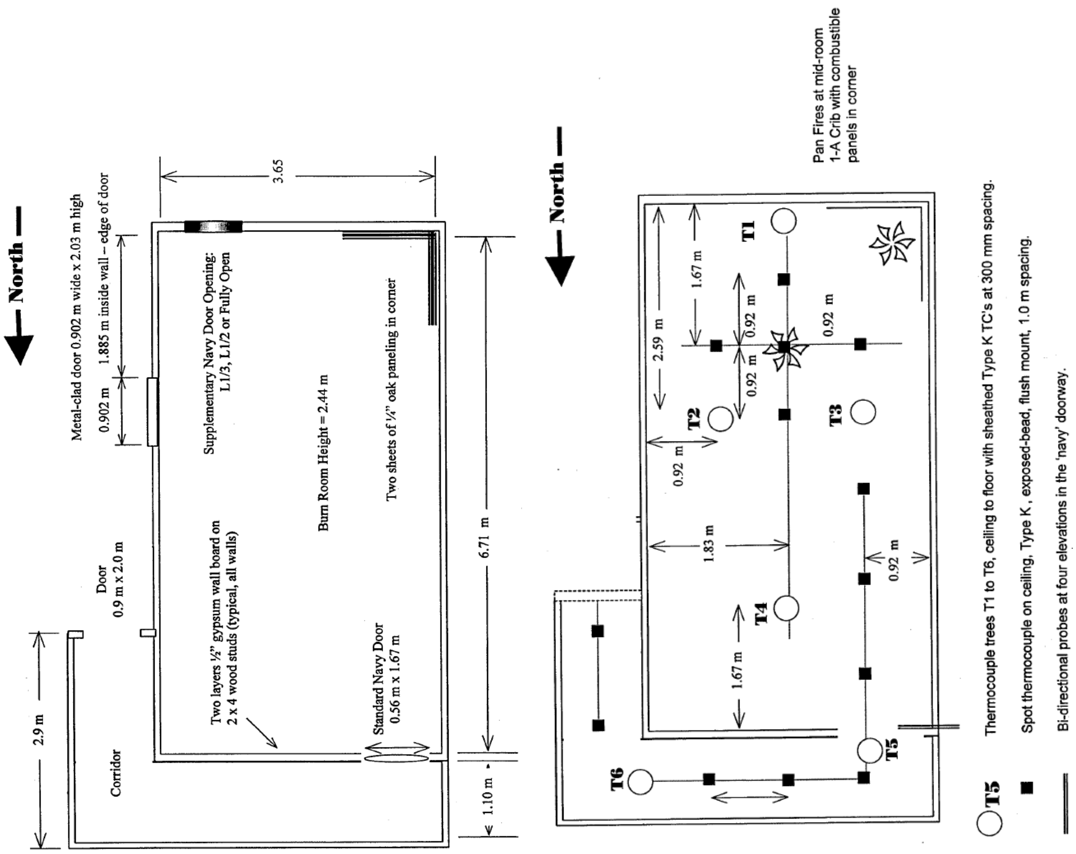
2.2.9.3.5 Test G.10

Flashover fire suppression experiments using water mist systems have been successfully conducted on mock-ups of Navy ship cabin and corridor sections (6.7 x 3.65 m wide x 2.44 m high, Figure 59a). Flashover suppression was defined as the ability of water mist to keep compartment ceiling temperatures below 400ºC (Mawhinney et al., 1999a, 1999b).

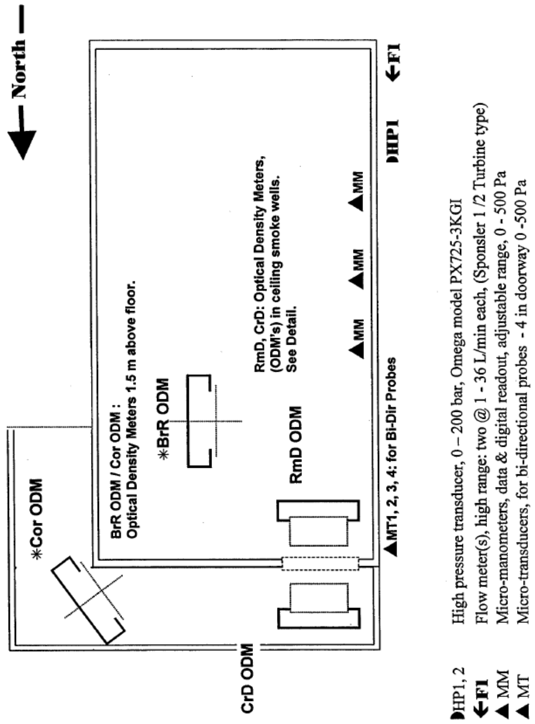
The fuel packages tested were either a (508 x 508 mm wide by 380 mm high) wood crib (made from 10 layers of five 38 x 38 mm wide by 508 mm long dried pine sticks) in a corner with wall panels (1.2 x 2.4 m x 3 mm thick Georgia Pacific medium-density fibreboard), or a square pan of 8.0 L of Heptane. The Heptane pool fires were unable to bring the compartment to flashover, and the fires were easily controlled by the water mist systems. The wood crib (ignited by a 100 ml 100 x 100 mm Heptane pan fire) and wall panel fire heated the compartment to the point where an array of cardboard boxes ignited. This was considered near-flashover conditions and the suppression system was manually activated (Mawhinney et al., 1999a).

Water mist characteristics were reported for flow. Pressure, water density distributions, spray velocity and drop size distributions were reported for the nozzles tested (Mawhinney et al., 1999a, 1999b).

Compartment temperatures for both suppressed and unsuppressed compartment conditions were reported, for thermocouple trees, with eight thermocouples each located within the compartment (Figure 59). Oxygen, carbon dioxide and carbon monoxide concentrations and room pressures were also reported. Several variations of the locations of nozzles relative to the ventilation openings were also tested. The influence of cycling application of the spray was also investigated (Mawhinney et al., 1999a, 1999b).



(a) (b)



(c)

Figure 59: Schematic of flashover suppression in a shipboard cabin with corridor test setup for (a) dimensions and fuel package locations, (b) thermocouples and gas species measurement locations, and (c) optical density meters and all the water mist nozzle locations used (Mawhinney et al., 1999b)

2.2.9.4 Shielding of fires

2.2.9.4.1 Test G.11

Full-scale tests carried out by Pepi (1995, 1998) showed that 0.5 m² Heptane pool fires positioned underneath an engine block (based on Scenario 9 of the IMO test protocol), within a ventilated enclosure, were challenging because the fires were fully shielded from the attack of water mist (Pepi, 1995, 1998).

2.2.9.4.2 Test G.12

Shielded and unshielded spray fires were investigated in a large compartment (2800 m² by 18 m high) with a high-pressure (6.9 MPa) and a low-pressure (1.2 to 1.5 MPa) water mist system. In each test, the suppression system was unable to control the fire. The oxygen concentration in the compartment was reported not to be significantly reduced during the tests (Bill et al., 1997).

2.2.9.4.3 Test G.13

The compartment was part of a ship, 9 x 18 m wide by 6 m high, including a bilge area approximately 1 m deep and two levels of catwalks. Mock-ups of typical machinery (such as engine, gears, ductwork, etc) were made from sheet metal to provide obstructions for the tests (Back et al., 1996c).

Onboard ventilation, using both supply and exhaust fans, provided 20 air exchanges per hour (Back et al., 1996c). Two water mist nozzle configurations were used: one overhead only configuration and one bi-level configuration (Back et al., 1996c).

Five tests were conducted each with four fires set at the same time. The individual fires varied from 0.2 MW pool fires to 0.25 to 6.5 MW spray fires (Back et al., 1996c).

The compartment was instrumented with thermocouples, radiant and total heat flux gauges, optical density meters and ports for oxygen, carbon monoxide and carbon dioxide concentration analysis. Visual observations were also reported (Back et al., 1996c).

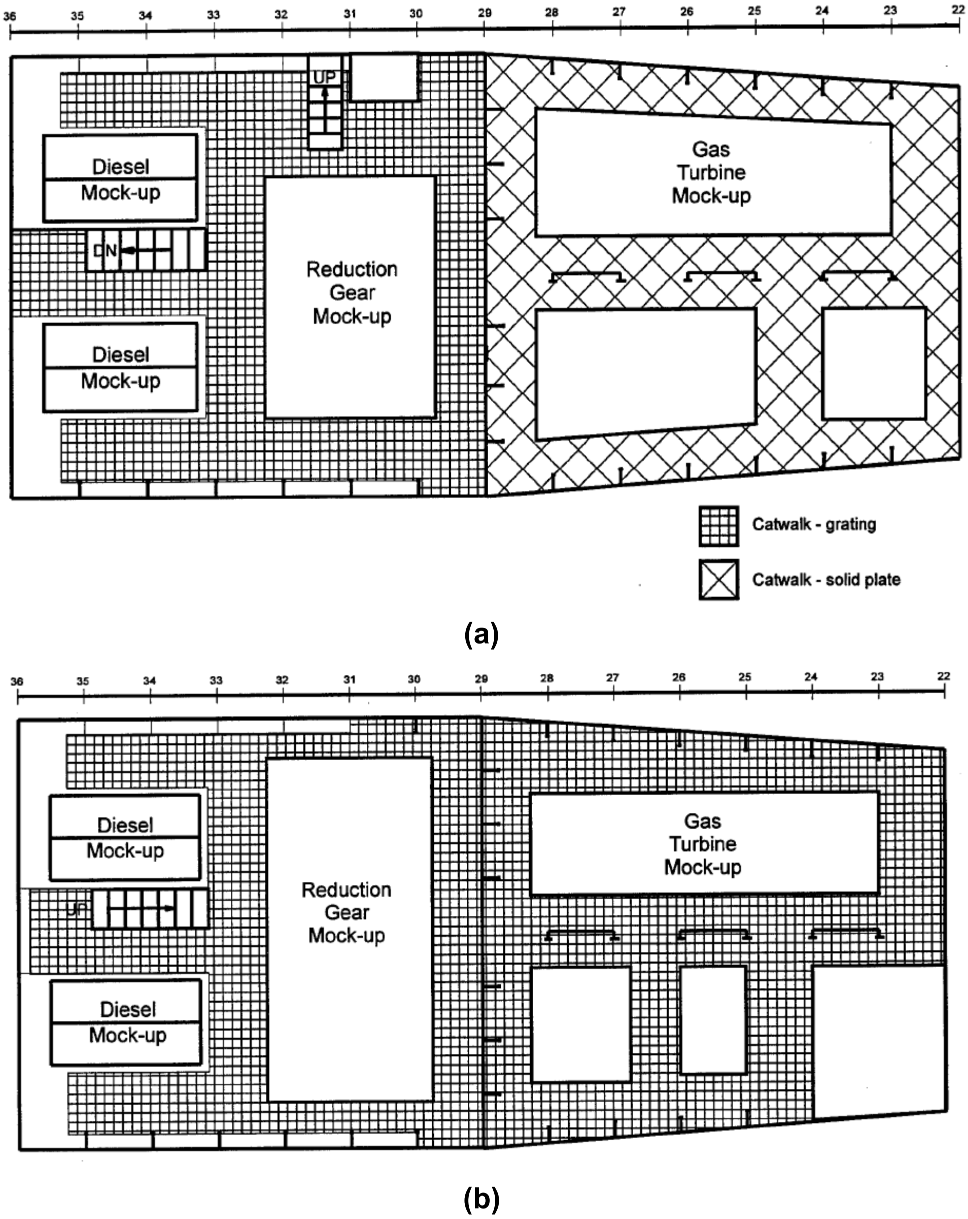


Figure 60: Schematics of the (a) fourth deck and (b) hold level of the layout for testing of machine engine compartment obstructions (Back et al., 1996c)

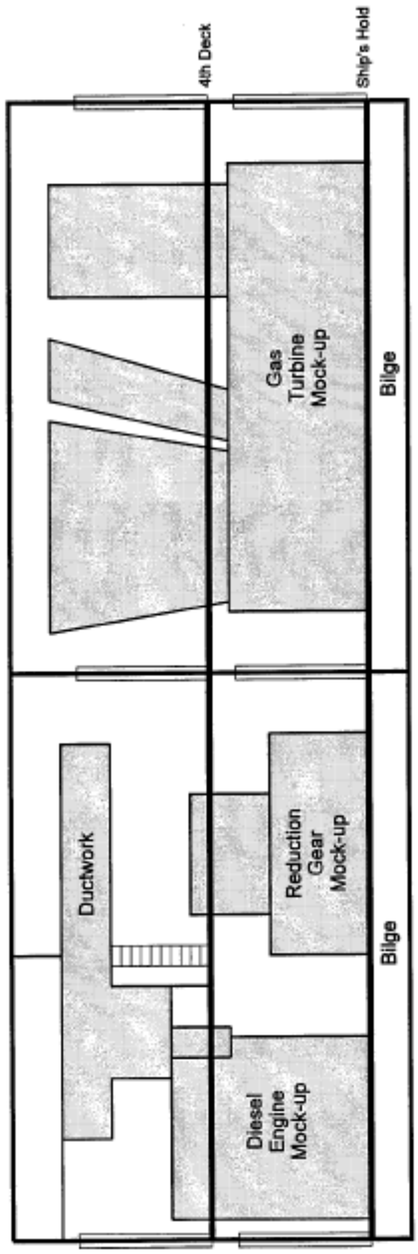


Figure 61: Schematic of the elevation view of the machine engine compartment test (Back et al., 1996c)

2.2.9.5 Interaction with other fire protection systems

2.2.9.5.1 Test G.14

A concerted effort to investigate the influence and interaction between sprinklers, smoke and heat vents, and draft curtains included 39 full-scale experiments representing a section of a high-rack storage scenario. A summary of the experimental and numerical modelling efforts were summarised by McGrattan et al. (1998).

The experiments were collated into three types: Heptane spray burner tests Series I and II and cartoned plastic commodity fire tests (McGrattan et al., 1998a, 1998b; McGrattan and Evans, 1998).

The tests were carried out in a 36 x 36 m wide by 16 m high fire test laboratory at Underwriters Laboratories Inc. A 30 x 30 m adjustable flat ceiling was located 8.2 m above the floor. Make-up air for the laboratory was supplied by four 1.5 m diameter inlets located in the walls at a rate of approximately 28 m^3/s. The laboratory floor was flat and surround with a drainage trench connected to a water treatment system (Sheppard, 1998).

One hundred upright, standard response, spray-type sprinkler heads (with an activation temperature of 73.8ºC, response time index (RTI) of 148 $(m.s)^{½}$, nominal orifice of 15 mm, and conductivity factor of 0.7 $(m/s)^{½}$) were installed at 3 x 3 m spacing in an automatic sprinkler system in the adjustable ceiling, as shown in Figure 62. The pipes were 50 mm in diameter. The distance between the ceiling and the deflectors of each sprinkler was 76 mm. The vents were numbered for data recording. The designed flow provided to each sprinkler was 198 L/min at approximately 131 kPa (Sheppard, 1998).

Five roof vents (1.2 x 2.4 m by 0.3 m deep) were mounted in the ceiling. Each was located between two sprinklers, as shown in Figure 62. The bottom of each vent was flush with the bottom of the ceiling (Sheppard, 1998).

For the Heptane spray burner tests – Series II of McGrattan et al. (1998) – 13 tests were conducted. Seven tests were conducted using the plastic commodity fuel package (Sheppard, 1998)

The Heptane burner was constructed from a 15 mm diameter pipe manifold formed into a square with 1 m sides. Four atomising spray nozzle were used, one in each side of the square manifold, to provide a free spray of Heptane that was then ignited. The maximum fire size was 10 MW, with a flame height that was almost the distance to the test ceiling. The burner locations used in the testing are shown as locations A to F in Figure 63. During the tests the room exhaust was set to 28 m^3/s, then the Heptane burner was ignited and the fuel flow increased until 10 MW was achieved. The 10 MW fire was held constant for the duration of the test (Sheppard, 1998).

The racks used in testing consisted of steel upright and beam construction, 4.6 m high by 0.4 m wide, with four 2.4 m bays and four tiers in each row either side of a 2.4 m aisle. The central rack was arranged in a double-row (0.82 m wide) configuration, with two single-row racks on the aisles to either side. The central array was loaded with Group A Plastic commodity fuel packages (Figure 64), such that a 15 mm flue space was provided along the length of the rack and 15-20 mm flue space was provided between each pallet.

The outer racks were loaded with Group A Plastic commodity fuel packages in the centre two bays and Class II commodity packages in the outer bays. Three rack configurations were tested (Figure 64). The ignition location of the rack was always located between two sprinklers (Sheppard, 1998).

Class II packages consisted of double tri-wall corrugated cardboard cartons with steel stiffeners in five sides for stability. The cartons were 1.1 x 1.1 x 1.1 m in size and place on 1.1 x 1.1 m wide by 0.13 m high hardwood pallets. The Class II packages were loaded into the ends of the outer racks. This ignition location was always located between two sprinklers (Sheppard, 1998).

The ignition source for the rack tests consisted of two 8 mm diameter, 15 mm long cellulosic bundles soaked with 237 ml of gasoline. The igniters were located on a brick so that the igniter bundle was level with the bottom of the boxes on the lowest tier. The bundles were positioned either side of the space between the two centre pallets, at the meeting of the two boxes, as shown in Figure 65. During the tests the room exhaust was set to 28 m^3/s, then the cellulosic bundles were ignited and the fire was allowed to grow. The fire was manually extinguished at 30 minutes after ignition of the bundles (Sheppard, 1998).

Thermocouple measurements were recorded at 146 locations (1 Hz) during each test (Figure 66). Two types of thermocouple were used; 1.5 mm diameter ungrounded, sheathed Type K thermocouple; and slow, medium and fast (based on measured RTI's of 32, 164 and 287 $(m.s)^{½}$) brass disk thermocouples. Thermocouples were used to measure (Sheppard, 1998):

- Temperatures near each sprinkler head, using the sheathed thermocouple located 100 mm below the ceiling near each sprinkler head, so as to be wetted when the head activated
- Temperatures near the ceiling, using a 3 x 3 m grid 100 mm below the ceiling
- Temperatures of the ceiling jet, using thermocouple trees of a combination of Type K sheathed thermocouples and slow, medium and fast disk thermocouples hung from the ceiling, so that instrumentation was at five vertical locations below the ceiling
- Temperatures near the vent, using a sheathed thermocouple and slow, medium and fast disk thermocouples adjacent to the fusible link.

Smoke obscuration measurements were taken during the rack tests at 1.5 m above the floor, 1.9 m below the ceiling and 0.9 m above the ceiling. These measurements were taken at the same location for all rack tests (Figure 66) (Sheppard, 1998).

Time to sprinkler activation was reported, based on a 30ºC drop in thermocouple temperature near to each sprinkler head (Sheppard, 1998).

Air velocities, measured with bi-directional probes, were reported for two locations: one located within the throat of the vent in the northwest corner of the smoke reservoir; and the second located at the thermocouple tree within the ceiling jet (Sheppard, 1998). Visual observations during the tests were also reported (Sheppard, 1998).

The results from these tests were further analysed as the initial part of a validation evaluation for various versions of a numerical modelling package, Fire Dynamics Simulator (FDS) (McGrattan et al., 1998 a, 1998b, 2010; McGrattan and Evans, 1998).

These tests utilised similar layout and test facilities as the high-rack storage section tests, with various locations of a ceiling fan (SEC, 2009), summarised in a previous section. Therefore, depending on the specific interest of the modelling application, a larger collection of similar tests could be collated for validation use.

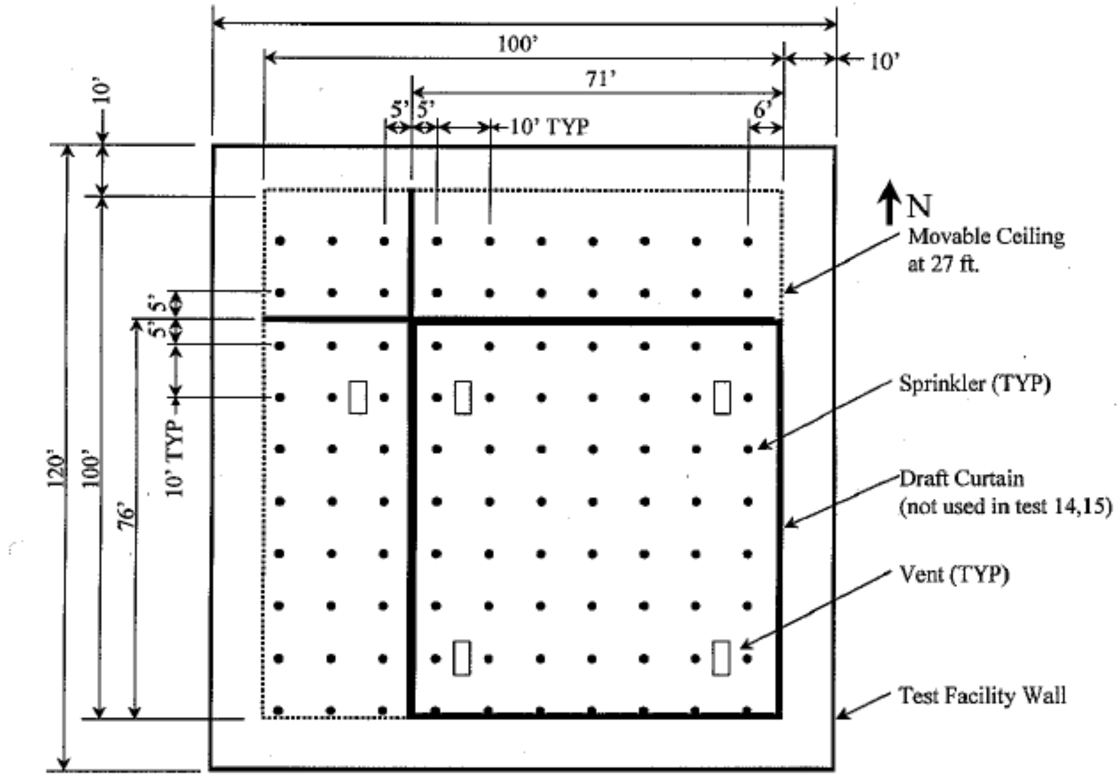


Figure 62: Schematic of the test configuration for the sprinkler, vent and draft curtain interaction test series (Sheppard, 1998)

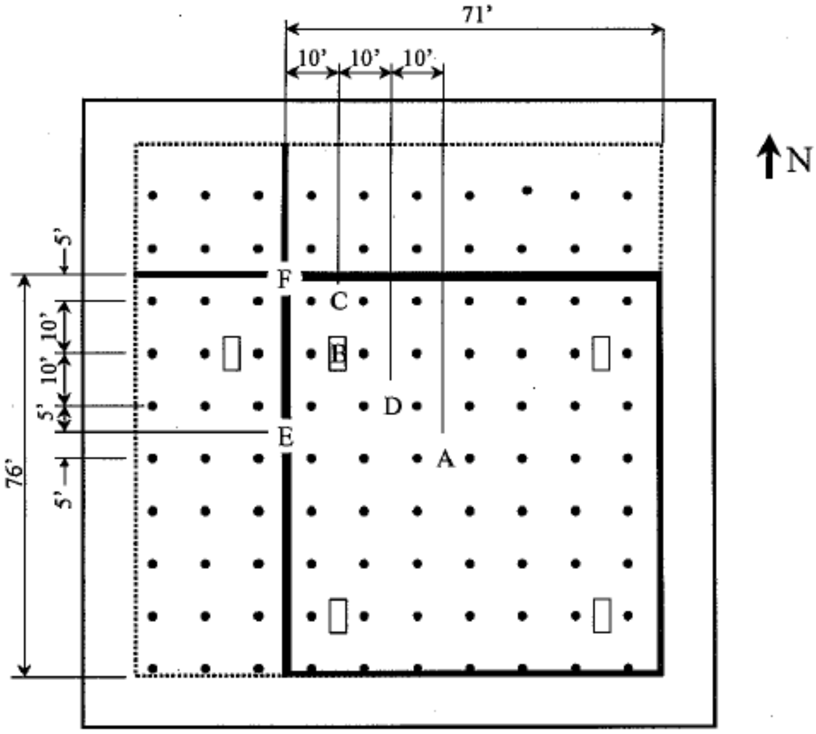


Figure 63: Schematic of the test configuration for the sprinkler, vent and draft curtain interaction test series with locations of the Heptane burner (A to F) (Sheppard, 1998)

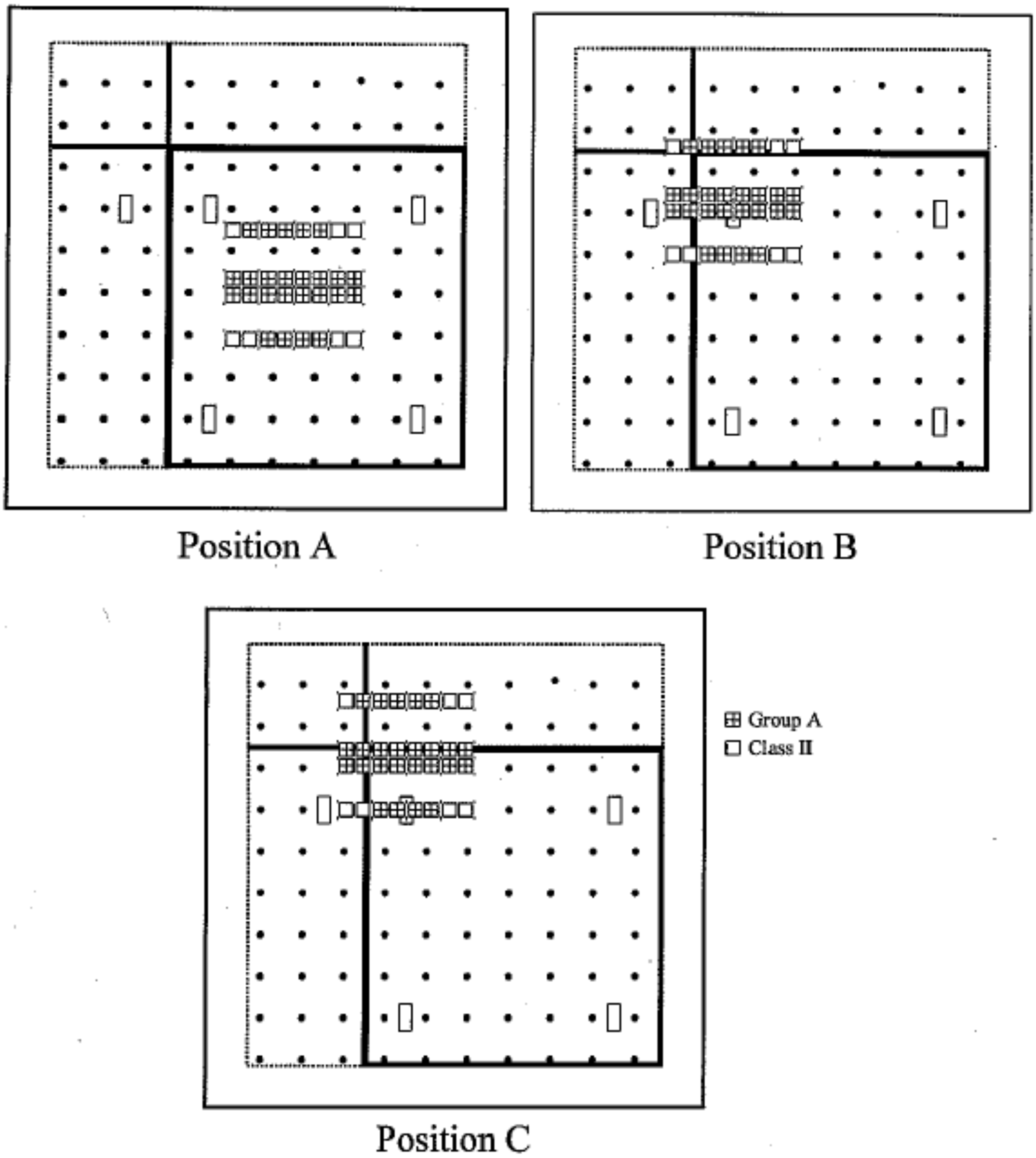


Figure 64: Schematic of the test configuration for the sprinkler, vent and draft curtain interaction test series with three locations of the plastic commodity fuel package tests (Sheppard, 1998)

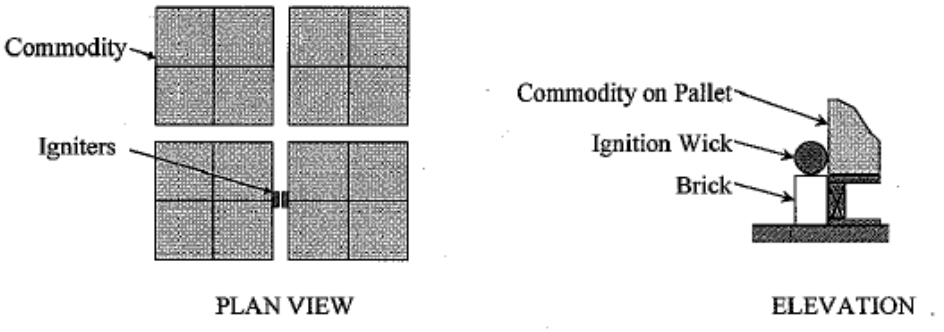


Figure 65: Schematic of the igniter location for the plastic commodity fuel package tests (Sheppard, 1998)

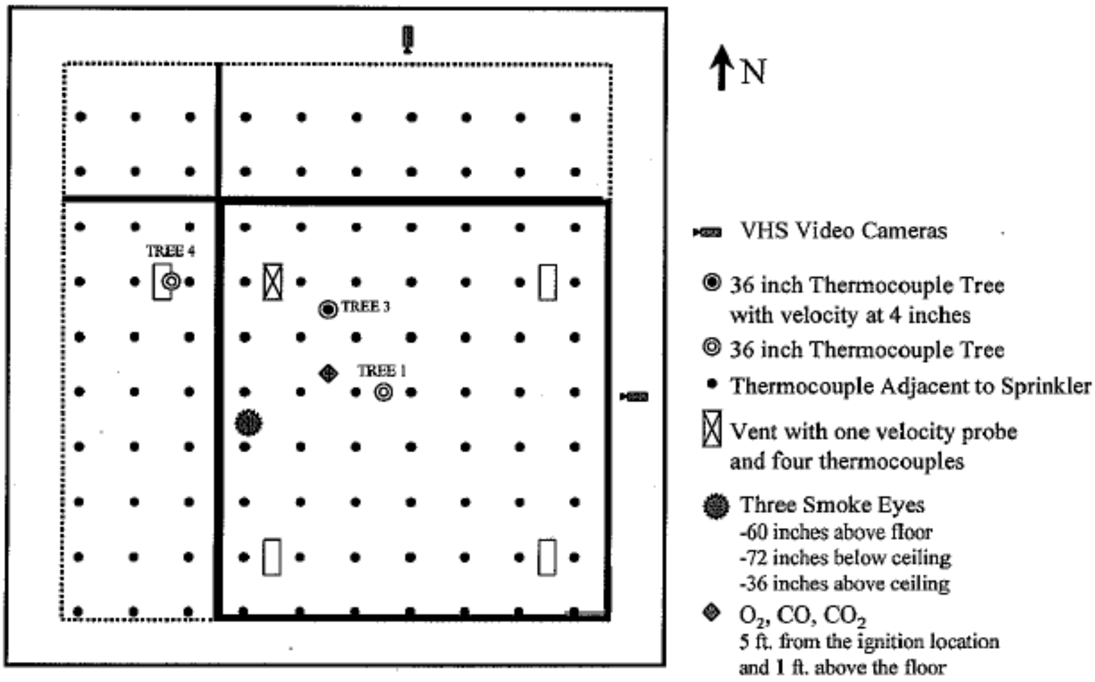


Figure 66: Schematic of the ceiling instrumentation locations for the sprinkler, vent and draft curtain test series (Sheppard, 1998)

2.2.9.6 Suppression system characteristics

2.2.9.6.1 Test G.15

Low-pressure water mist system experiments for a range of scenarios (Back et al., 1996a, 1996b; Edwards and Watkins, 1997; Edwards et al., 1999; Darwin and Williams, 1999) demonstrated that these systems have good extinguishing performance for unshielded wood crib and pool fires.

Results from ventilated fire experiments using low-pressure water mist systems by Pepi (1995, 1998) showed that the times to extinguishment increased by 30% to 70% compared to a high-pressure system. These tests were conducted using Fire Scenarios 5, 6 and 11 of the IMO test protocol, where a 4 m² door was kept open in an 8 m high, 1280 m³ space (Pepi, 1995, 1998).

2.2.9.6.2 Test G.16

In another investigation, five commercially-available total flooding water mist systems and two total flooding generic systems were investigated for suppression performance for a simulated flammable liquid storeroom (3.0 x 3.0 x 2.4 m) (Back, 1995; Back et al., 1995) The test compartment was metal walled, with a door of 0.56 x 1.68 m and two 0.3 x 0.3 m vents, one located low and one located high (Figure 67). A table, shelves and a metal locker were located against each of the compartment walls.

The tested suppression systems varied by nozzles, including impinging nozzles, twin-fluid nozzles and pressure jet nozzles with different structures and working pressures (0.55 to 20 MPa). A range of flow rates and nozzle configurations were also included in the variables. The tested fire scenarios involved preliminary small pool fires, and then larger fire scenarios that are more representative of the potential hazards associated with flammable liquid storerooms. These fire scenarios were a wood crib fire, trash can fire, large pool fire and cascading fuel fire. The preliminary fire scenarios tested were a small (0.05 m diameter) Heptane pan fire that was tested in 10 different locations within the compartment (Back, 1995; Back et al., 1995).

Results for temperature, radiant and total heat flux, optical density, oxygen, carbon monoxide and carbon dioxide gas species, and time to extinguishment were reported for locations within the test compartment (Figure 68). Extinguishment was determined based on the measured temperature directly above the fire and visual observations (Back, 1995; Back et al., 1995).

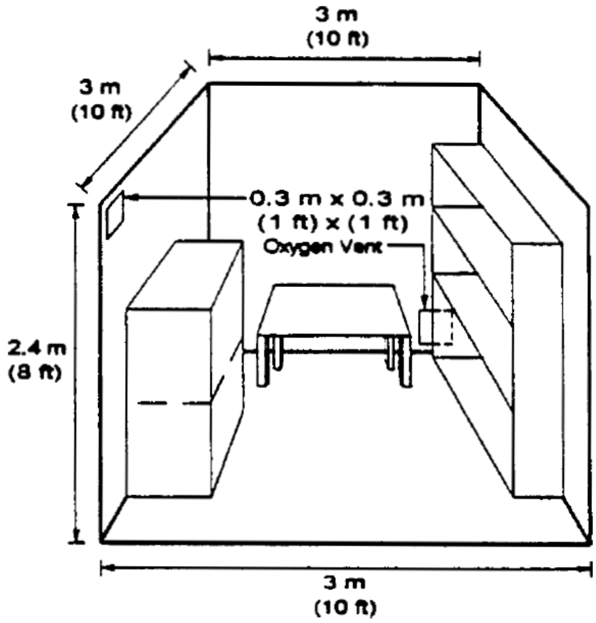


Figure 67: Schematic of the test compartment for flammable liquid storeroom fire scenarios (Back, 1995)

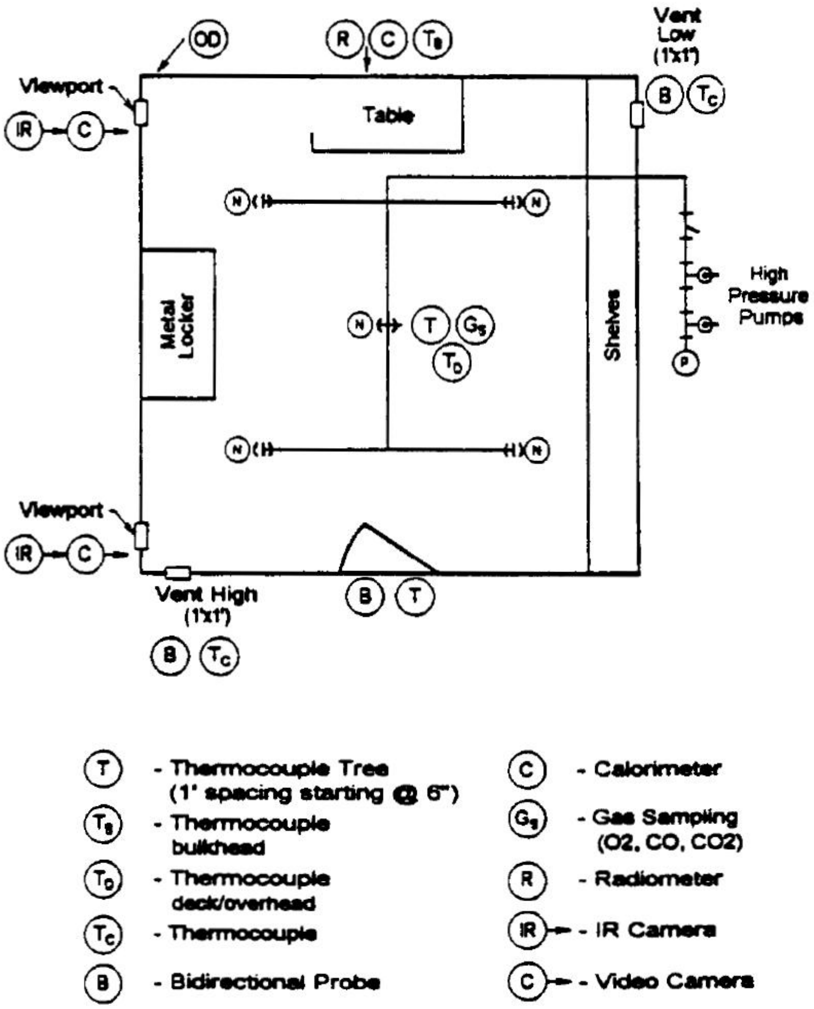


Figure 68: Schematic of locations of instrumentation the test compartment for flammable liquid storeroom fire scenarios (Back, 1995)

2.2.9.7 Additives

2.2.9.7.1 Test G.17

Tests involving additives to the water mist system included the use of salts, such as potassium lactate and potassium acetate, to reduce the freezing point of the water. Tests of suppression systems used in compartments, such as combat vehicle fire scenarios, were reported to also show suppression performance improvements from the addition of these salts (Finnerty, 1996; McCormick et al., 2000). This improvement in the suppression performance was suggested by Finnerty (1996) to be associated with the formation of solid particles in the flame zone that will help quench the flames from the evaporation of water from a salt-containing additive.

2.2.9.7.2 Test G.18

Three full-scale rack storage tests of 3.8 and 18.9 L metal containers of Class IB flammable liquids were conducted at Underwriters Laboratories as part of the International Foam-Water Sprinkler Research Project initiated by The National Fire

Protection Research Foundation. The tests were performed under the 9.8 x 9.8 m adjustable ceiling at heights above the floor of 7.3 and 9.1 m (Cary, 1991).

The steel racks were double-row with a length of 7.6 m and a depth of 0.66 m. The trusses were spaced at 2.5 m, with six bays per level. The racks were spaced 203 mm apart (Cary, 1991).

Ceiling only (Test 1) and a combination of ceiling and in-rack (Tests 2 and 3) foam sprinkler systems were tested. Test 2 used staggered sprinkler spacing. Test 3 consisted of in-rack sprinklers positioned adjacent the vertical upright rack supports (Cary, 1991).

The ceiling sprinkler system used in testing was a closed-head foam-water with a design density of 16.3 mm/min in a looped design with 50 mm diameter pipe. Sixteen large orifice pendent sprinklers, with a 141ºC temperature rating, were installed using 3.0 x 3.0 m spacing. Test 1 used quick response elements, whereas standard response elements were used in Tests 2 and 3 (Cary, 1991).

The in-rack system was separate system to the ceiling sprinkler system. The in-rack sprinkler system consisted of large orifice pendent sprinklers, with a 68ºC temperature rating on a looped system using 38 mm diameter pipe. The sprinkler heads were installed in the 203 mm flue space between the double-row racks using 2.5 m spacing (Cary, 1991).

The foam used in testing was alcohol-resistant AFFF foam liquid concentrate. A 3% concentration was recommended for hydrocarbon fire and 6% for polar solvent fires. The actual concentration was measured during each test. In-line balanced pressure foam proportioning systems were used to incorporate the foam into the sprinkler water supply (Cary, 1991).

The flammable liquid used in the tests was Heptane. Four metal 3.8 L containers filled with Heptane were place in a corrugated cardboard carton. Ten cartons were positioned on a pallet, providing 151.4 L of Heptane per layer of cartons. A full pallet consisted of four layers of cartons, with a total of 605.6 L of Heptane. Eight 18.9 L metal containers were placed on a pallet, providing 151.4 L of Heptane per layer of containers. A full pallet consisted of three layers of containers, with a total fuel loading of 454.2 L of Heptane (Cary, 1991).

The remainder of the racks were loaded with Class II packages, as previously described. Schematics for the ceiling height, rack and fuel configurations tested are shown for Tests 1 to 3 in Figure 69, Figure 70 and Figure 71 respectively (Cary, 1991).

The ignition source was a 37.8 L Heptane spill. This was simulated by nine 3.8 L plastic bags filled with Heptane with an additional 3.8 L of Heptane poured over the top of the bags to assist in a simultaneous ignition of all of the bags. The bags of Heptane were located in the longitudinal and transverse flue space formed between the four pallets in the bottom centre storage bay.

Thermocouples were located adjacent to each sprinkler and around the perimeter of the adjustable ceiling, as shown in the schematic of Figure 72. The time to activation of each sprinkler was reported. The concentration of foam incorporated into the sprinkler water supply was also reported. Duration of sprinkler system operation and the total water and foam used were reported. A visual assessment of damage was recorded, including a summary of the quantity of fuel consumed. The external weather conditions during the testing were also included in the reporting (Cary, 1991).

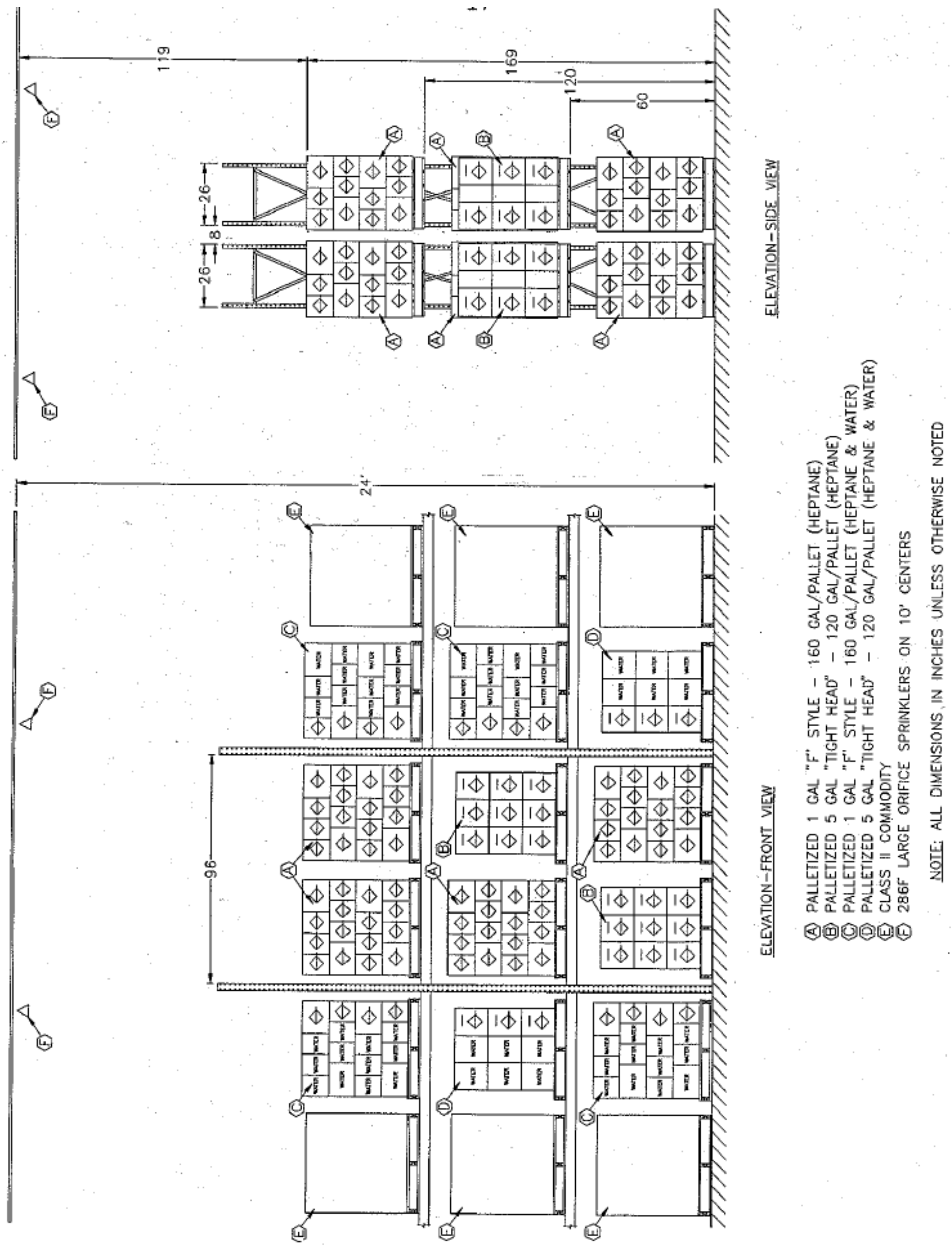


Figure 69: Schematic of the rack and fuel configuration for Test 1 of flammable liquid rack storage tests (Cary, 1991)

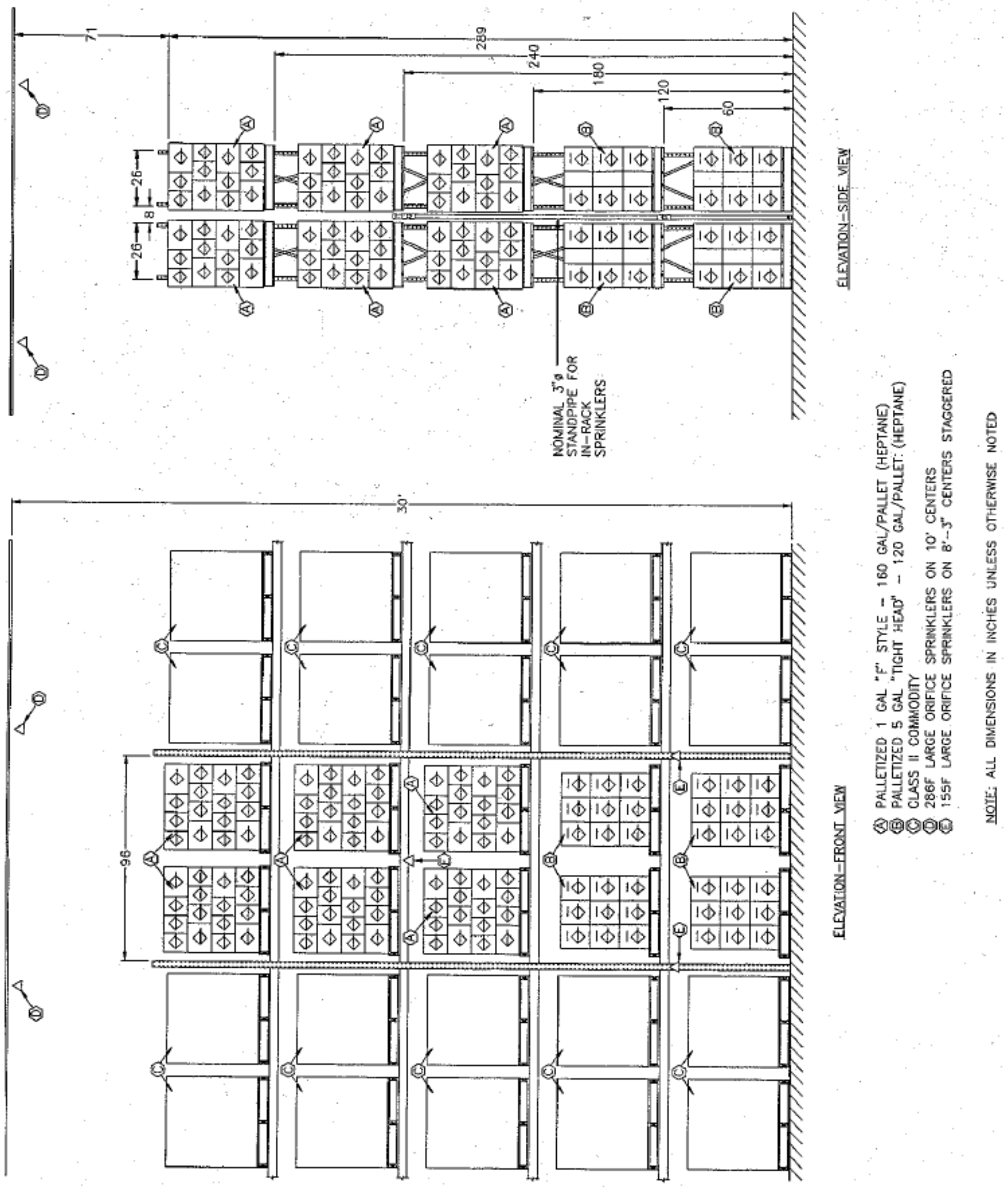


Figure 70: Schematic of the rack and fuel configuration for Test 2 of flammable liquid rack storage tests (Cary, 1991)

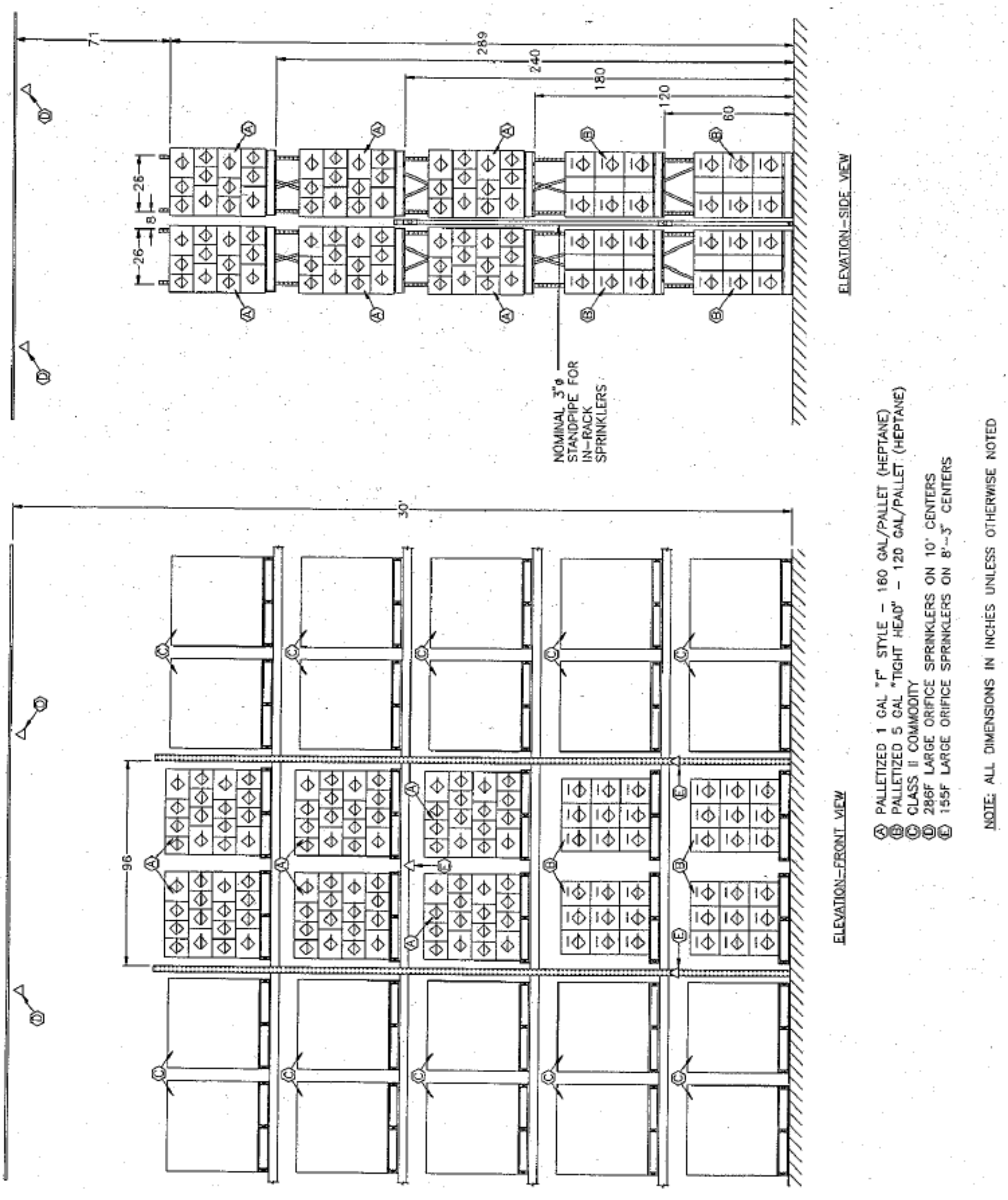


Figure 71: Schematic of the rack and fuel configuration for Test 3 of flammable liquid rack storage tests (Cary, 1991)

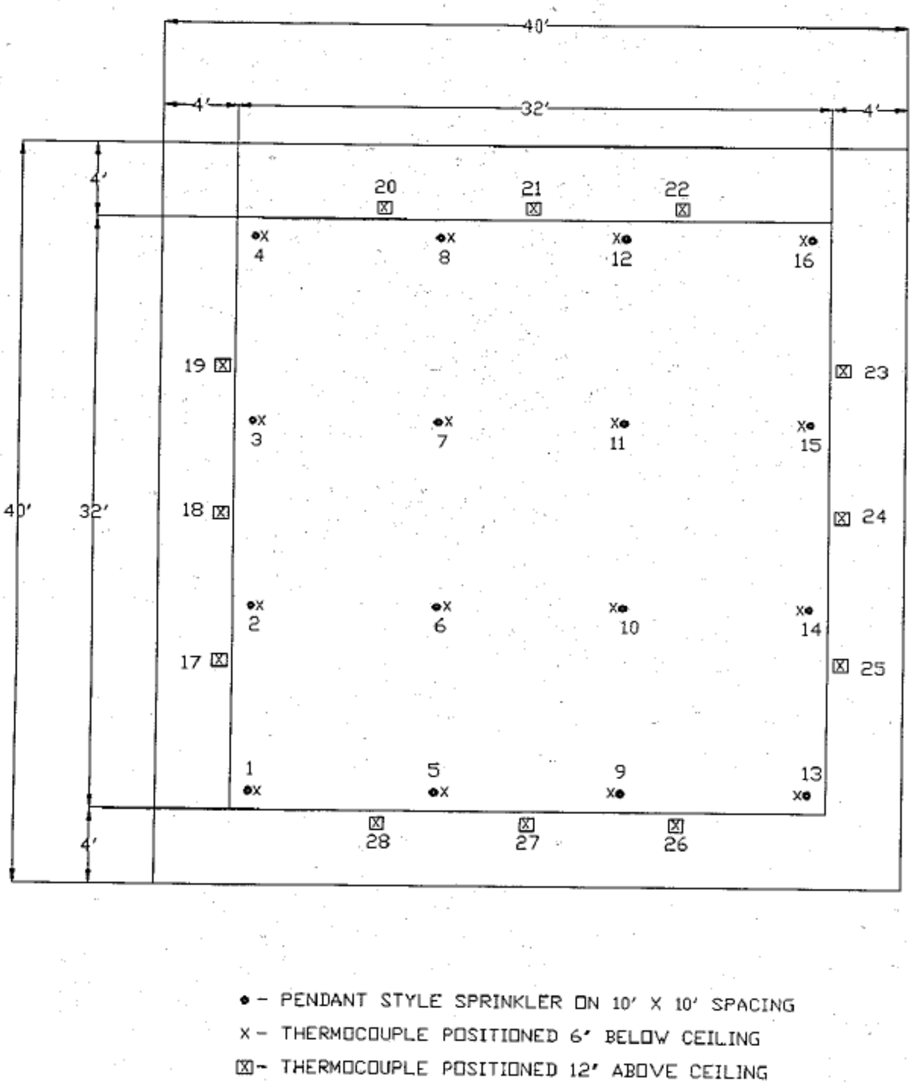


Figure 72: Schematic of instrument layout for flammable liquid rack storage tests (Cary, 1991)

2.2.9.7.3 Test G.19

Fourteen full-scale tests of single pallets of 3.8 L metal F-style and 18.9 L polyethylene or metal containers of Heptane were conducted at Underwriters Laboratories as part of the International Foam-Water Sprinkler Research Project initiated by The National Fire Protection Research Foundation. The tests were performed under the 9.8 x 9.8 m adjustable ceiling at a height of 8.2 m above the floor (Cary, 1992).

A ceiling foam-water sprinkler was used in the testing. Sixteen closed-head foam-water 12.7 mm orifice pendent sprinklers, with a temperature rating of 141ºC and RTI of 220 $(m.s)^{1/2}$, were installed using 3.0 x 3.0 m spacing (Figure 75). The design density of the system was 12.2 to 16.3 mm/min (Cary, 1992).

The foam liquid concentrate was an alcohol compatible aqueous film forming foam (AFFF). Three types of AFFF foam were tested. An in-line balanced pressure foam proportioning system was used to incorporate the foam into the sprinkler water supply. The concentration of foam during the tests was recorded (Cary, 1992).

Each pallet consisted of only one type of container. Four F-style 3.8 L containers were placed in a corrugated cardboard carton. Ten cartons were positioned on a 0.76 x 1.07 m wide by 0.28 m high wood pallet. Three layers cartons made a full pallet, with a total of 454.2 L of Heptane (Figure 73a). Eight 18.9 L containers were loaded onto the 1.07 x 1.07 m wide by 0.13 m high wood pallet to form each layer, with 151.4 L of fuel per layer. The pallets of 18.9 L metal containers were stacked three layers high, with a total of 454.2 L of Heptane (Figure 73b) (Cary, 1992).

The configurations of containers on pallets tested were (Cary, 1992):

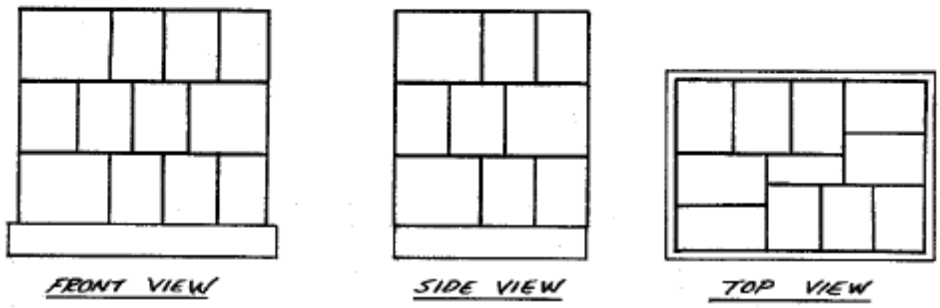
- One layer of containers per pallet in a 2 pallet x 2 pallet arrangement
- Two layers of containers per pallet in a 2 x 2 pallet arrangement
- Full pallets (three layers of containers per pallet) in a 2 x 2 pallet arrangement
- Eight full pallets in a 2 x 2 pallet by 2 pallet high arrangement
- Twelve full pallets in a 2 x 2 pallet by 3 pallet high arrangement.

An example of the plan view of the 2 x 2 pallet arrangement is shown in Figure 74 for 18.9 L containers (Cary, 1992).

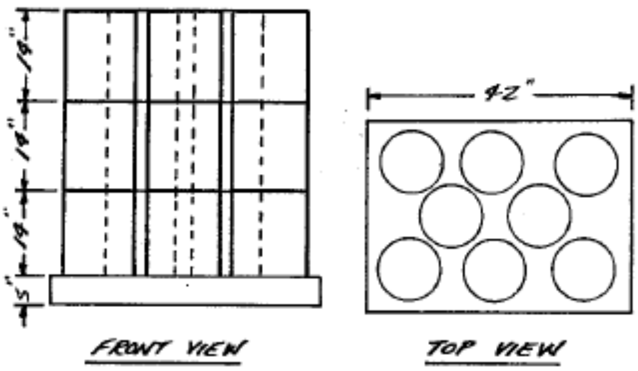
The ignition source was a simulated Heptane spill fire. Nine plastic bags were filled with 3.8 L of Heptane each and evenly spaced in the 152 mm flue space formed between the pallets in the 2 x 2 pallet arrangement, as shown in Figure 74 (Cary, 1992).

Sixteen thermocouples were located adjacent to each sprinkler head, 152 mm below the ceiling. Twelve thermocouples were located 305 mm above the ceiling at the ceiling perimeter. Two bi-directional probes were located 1.52 m from the centre of the ceiling perpendicular to each other 152 mm below the ceiling. A schematic of the layout of the instrumentation is shown in Figure 75 (Cary, 1992).

The sprinkler system was not sufficient to control the fires involving the plastic containers (Cary, 1992).



(a)



(b)

Figure 73: Schematics of the front and top view of a fully loaded pallet of (a) 3.8 L containers, and (b) 18.9 L containers for the flammable liquid pallet tests (Cary, 1992)

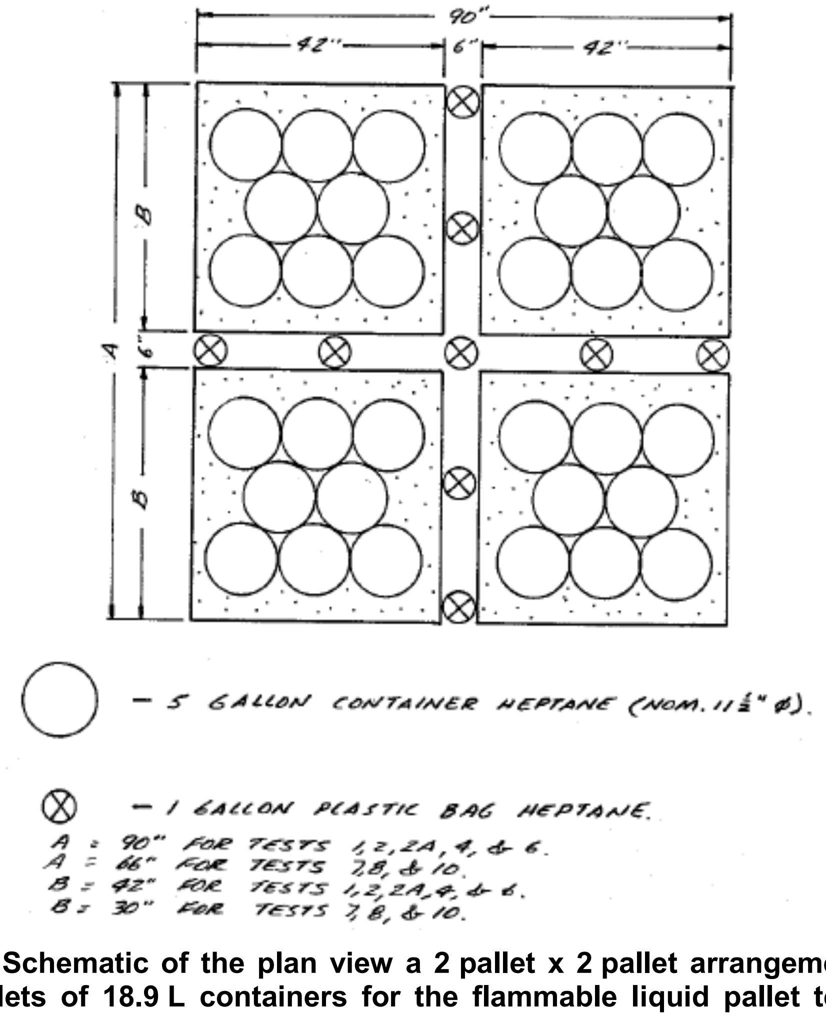


Figure 74: Schematic of the plan view a 2 pallet x 2 pallet arrangement of fully loaded pallets of 18.9 L containers for the flammable liquid pallet tests (Cary, 1992)

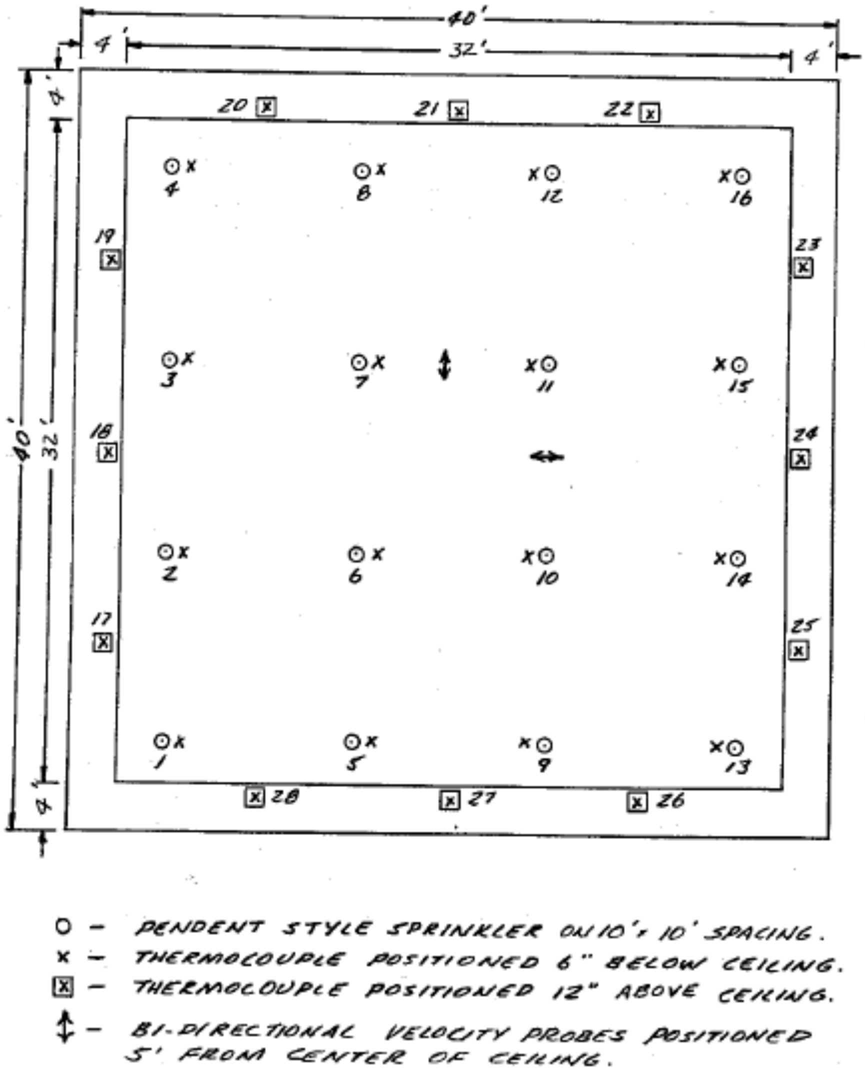


Figure 75: Schematic of instrument layout for the flammable liquid pallet tests (Cary, 1992)

2.2.9.8 Nozzle configuration

2.2.9.8.1 Test G.20

Tests conducted by Back (1995) investigated the influence of nozzle configuration for fire scenarios tested using five commercially-available water mist systems and two generic systems used in a 3.0 x 3.0 x 2.4 m compartment (Figure 67) to simulate a flammable liquid storeroom (Back, 1995; Back et al., 1995). Along with a number of other variables (such as nozzle type, pressure and flow rate), two nozzle configurations were also investigated. One configuration with a single nozzle located in the centre of the room and a second configuration consisting of four nozzles, with a nominal spacing of 1.5 m (Back, 1995; Back et al., 1995).

Results for temperature, radiant and total heat flux, optical density, oxygen, carbon monoxide and carbon dioxide gas species, and time to extinguishment were reported for locations within the test compartment (Figure 68). Extinguishment was determined based on the measured temperature directly above the fire and visual observations (Back, 1995).

2.2.9.8.2 Test G.21

Increasing nozzle numbers of water mist systems for ventilated fires was reported to increase the system performance (Dyer, 1997). However limits were reported for challenging compartment fire scenarios involving lubrication oil (~1.5 MW) or aviation jet spray fires, or (~1.5 MW) pool fires located under the engine. After this, increasing the numbers of nozzles no longer increased the suppression performance of the systems.

The suppression effectiveness of the systems was not reported to increase with an increase of nozzles past 11 for the flooding method (where the results from 11 to 22 nozzles were compared), or past seven nozzles for the localised application method (where results from seven to 14 nozzles were compared). System performance was reported in terms of time to extinguishment (Dyer, 1997).

2.2.9.8.3 Test G.22

In another set of experiments (Hansen, 1998), the impact of the location of the nozzle below the ceiling (i.e. directly below and 2 m below the ceiling) was investigated for potential localised water mist system applications. The nozzle closer to the ceiling was associated with more effective extinguishment performance. This was suggested to be caused by the application of more water mist into the hot upper layer, compared to the amount of water mist that could be introduced to the hot upper layer by the nozzle located 2 m below the ceiling (Hansen, 1998).

The location of the nozzle(s) relative to the fire has also been shown to be influential in the resulting extinguishment performance. For example, experiments were conducted to investigate the performance of localised use of a water mist system (Hansen, 1998). That is, one nozzle protecting a specific area within a compartment. The application of these experiments was the protection of machinery. Results for nozzles located above the fires and beside the fires were compared. A significant difference was reported for the two relative nozzle locations, approximately 90% to 5% successful extinguishments for the nozzle located directly above the fire and beside the fire respectively (Hansen, 1998).

2.2.9.8.4 Test G.23

The impact of increasing the number of doorway nozzles on the extinguishing performance was investigated by Pepi (1998) for a ventilated compartment fire. Results were reported for experiments where the number of nozzles in the doorway was increased from two to four. The water mist effectiveness against ventilated fires was reported to increase for the larger number of nozzles tested, due to the increase in the density of water mist around the opening (Pepi, 1998).

2.2.9.8.5 Test G.24

Flashover fire suppression experiments using water mist systems have been successfully conducted on mock-ups of Navy ship cabin and corridor sections (6.7 x 3.65 m wide x 2.44 m high, Figure 59a). Flashover suppression was defined as the ability of water mist to keep compartment ceiling temperatures below 400ºC (Mawhinney et al., 1999a).

A wood crib in a corner lined with panels was used to bring the compartment to near-flashover conditions before the suppression system was manually activated. Several variations of the locations of nozzles relative to the ventilation openings were tested, including: (a) two nozzles located 3.35 m apart on the centreline, equidistance from each sidewall; (b) one nozzle in front of the door; and (c) one nozzle at the mid-point of the ceiling (Mawhinney et al., 1999a, 1999b).

Compartment temperatures (using four eight-point thermocouple trees), oxygen, carbon dioxide and carbon monoxide concentrations, and smoke obscuration measurements (Figure 59) for both suppressed and unsuppressed compartment conditions were reported (Mawhinney et al., 1999a, 1999b).

2.2.9.9 Continuous vs cycling application

2.2.9.9.1 Test G.25

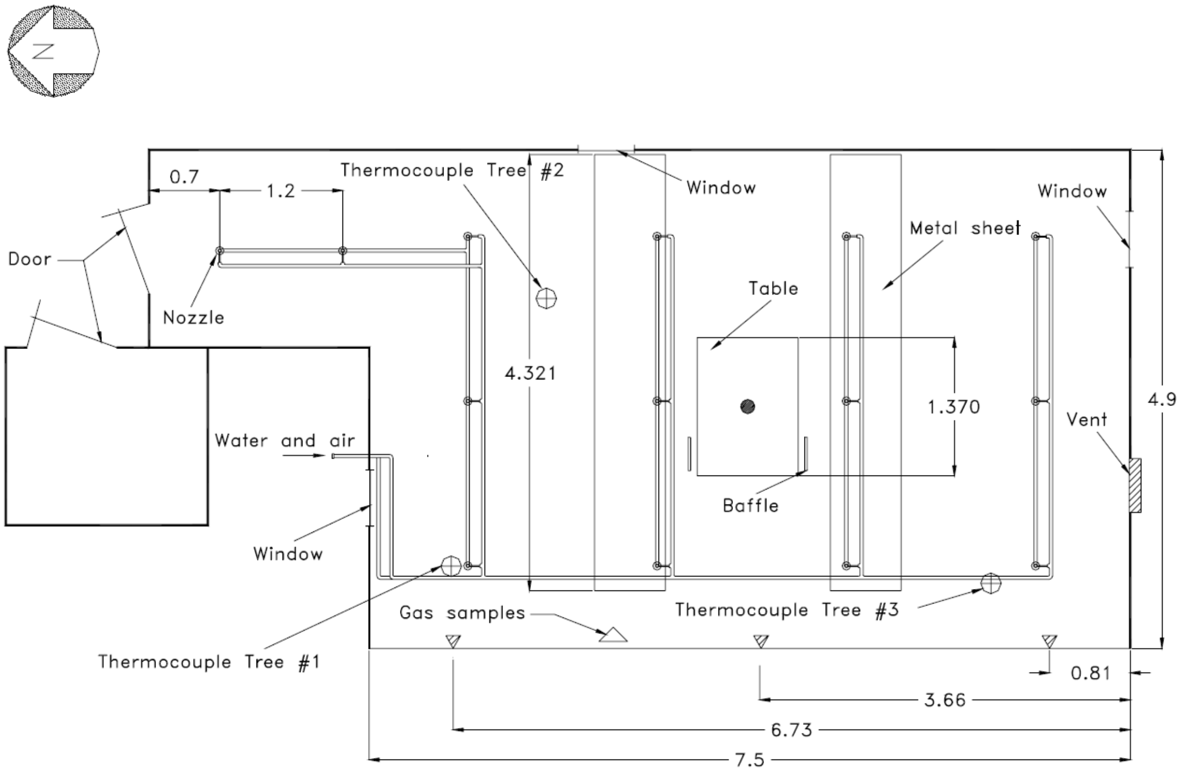
Tests conducted at NRCC compared continuous to cyclic discharge application of a twin-fluid, low-pressure water mist system to a range of fire challenges in a compartment with a mock-up engine. The test room was an irregular shape; a rectangular room (9.7 x 4.9 m wide by 2.9 m high) with a corner (2.9 x 2.2 m removed) (Figure 76). The compartment had a 0.9 x 2.0 m high door and three 0.56 x 0.56 m viewing windows. During forced ventilation conditions, the pressure relief vent (0.5 x 0.5 m) close to the floor, in the west wall, was also open.

Fire tests were also conducted in a mock-up machinery space. The mock-up engine was based on a diesel engine that was represented by a 0.85 mm thick sheet of galvanised sheet steel that topped a table and was installed at a 45º angle to the top of the table (as shown in Figure 76). The sides below the metal plate were shielded using tow 0.3 x 0.3 m sheet metal baffles (Liu et al., 1999).

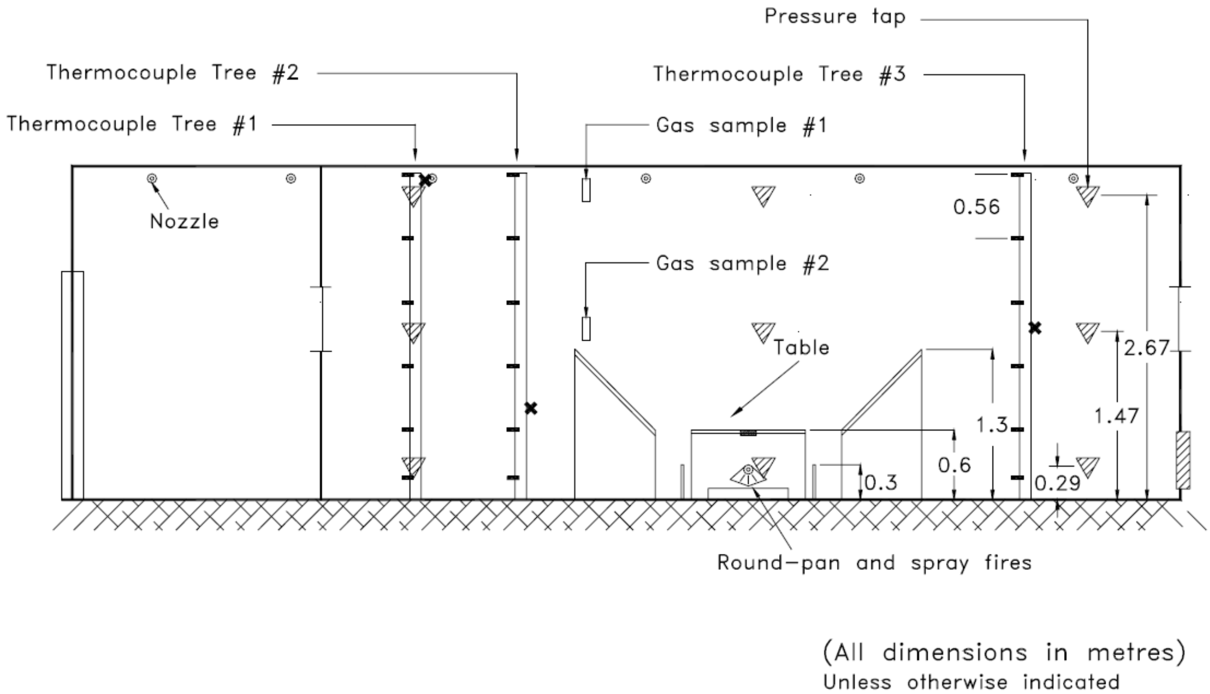
The influences of various fire sizes (~150 to 520 kW), types (a range of pool fire sizes and spray fires) and locations, and different ventilation conditions (natural and forced, up to 0.727 m³/s) on the performance of a water mist system using either continuous or cycling discharge applications were investigated. Shielded fires were also tested for comparison. Various sided pool fires were placed in a mesh sided and topped metal box (0.80 x 0.84 by 0.94 m high) (Liu et al., 1999).

HRR (at 1 Hz), estimated from oxygen consumption calorimetry, was reported for each test. Time to extinguishment was also reported. Thermocouple measurements were reported for three thermocouple trees (each consisting of six thermocouples) in the room. The thermocouples were 30-gauge, chromel-alumel type K, and stainless steel sheathed and recorded at 1 Hz. Carbon dioxide and carbon monoxide concentrations (at 1 Hz) were reported for two locations within the room.

Oxygen concentrations were also reported for the higher location where the carbon monoxide and carbon dioxide measurements were taken. Nine pressure measurements were also reported for locations on the west wall. Two video cameras were used to record the water mist activation and behaviour of the fires during control and suppression (Liu et al., 1999; Kim and Zhigang, 2002).



(a)



(b)

Figure 76: Schematic of the (a) top view, and (b) side view of the irregular compartment test setup for mock-up engine experiments (Liu et al., 1999)

2.2.9.9.2 Test G.26

The influence of cycling application of the spray was also investigated as part of the flashover fire suppression experiments using water mist systems have been successfully conducted on mock-ups of Navy ship cabin and corridor sections (6.7 x 3.65 m wide by 2.44 m high, Figure 59a). Flashover suppression was defined as the ability of water mist to keep compartment ceiling temperatures below 400ºC (Mawhinney et al., 1999b).

The fuel packages tested were (508 x 508 mm wide by 380 mm high) wood cribs (made from 10 layers of five 38 x 38 mm by 508 mm long dried pine sticks) in a corner with wall panels (1.2 x 2.4 m x 3 mm thick Georgia Pacific medium-density fibreboard). The wood crib (ignited by a 100 ml 100 x 100 mm Heptane pan fire) and wall panel fire heated the compartment to the point where an array of cardboard boxes ignited. This was considered near-flashover conditions and the suppression system was manually activated (Mawhinney et al., 1999b).

Water mist characteristics were reported for flow and pressure, water density distributions, spray velocity and drop size distributions was reported for the nozzles tested (Mawhinney et al., 1999b).

Compartment temperatures for both suppressed and unsuppressed compartment conditions were reported, for thermocouple trees, with eight thermocouples each, located within the compartment (Figure 59). Oxygen, carbon dioxide and carbon monoxide concentrations were also reported. Several variations of the locations of nozzles relative to the ventilation openings were also tested (Mawhinney et al., 1999b).

2.2.9.10 Repeatability

2.2.9.10.1 Test G.27

Five tests were carried out at the Upinniemi, Finland in a purpose-built room for use in simulated engine fire tests. A preheated steel plate was used to simulate a hot engine, or part thereof. When the steel plate reached approximately 600°C, oil was sprayed over the hot steel plate at 10 L/min and 13 MPa. The oil ignited and flowed into the bilges.

A water mist system, using a combination of low-pressure and high-pressure nozzles, was manually activated after a prescribed number of minutes. Thermocouple temperatures in the room, the amount of water used and the time to extinguishment were reported (Turner, 1993).

The full test report is: Tuomissari M. 1992. *Fire Suppression Tests in Simulated Ship's Engine Room with a Hi-fog Fire Protection System, PAL 2210/92.* VTT Fire Technology Laboratory. Helsinki, Finland (Turner, 1993).

2.2.10 Generic test compartment space

2.2.10.1 Compartment size

2.2.10.1.1 Test H.1

Seventy-two (7.3 x 5.5 m) compartment tests were performed for six configurations of ceiling slope and beam tests. Slopes of 0º, 13º and 24º and with and without two up-slope beams (0.2 m wide x 0.25 m deep) were tested. The compartment had one opening of 1 x 2.1 m at the front (Figure 77). The walls and ceiling were constructed with a wood frame covered with 12.7 mm thick gypsum board. The floor consisted of 12.7 mm thick plywood. The initial ceiling height was 2.4 m. The ceiling was sloped by raising the front portion. When the beams were present, they ran the full depth of the room, dividing the room into three equal bays (Vettori, 2003).

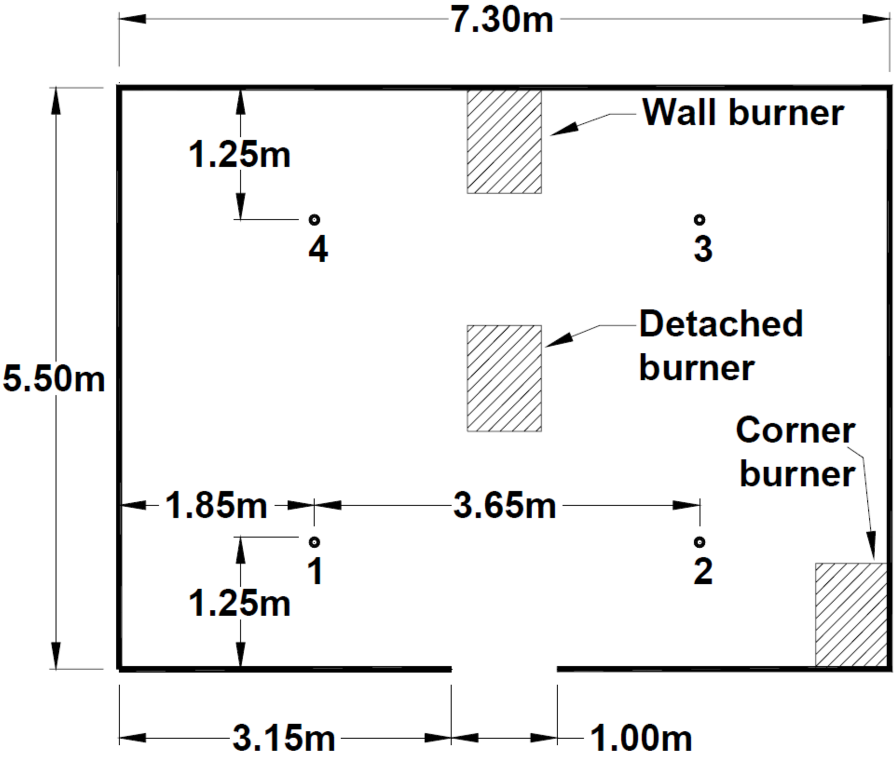
Four quick response pendent sprinklers were installed, in accordance with NFPA 13D, for all tests (Vettori, 2003).

The fire source was a methane gas burner. Two t^2 fires (with alpha values of 0.0468 and 0.00293) were tested. Three fire locations (wall, corner and centre) were tested (Vettori, 2003).

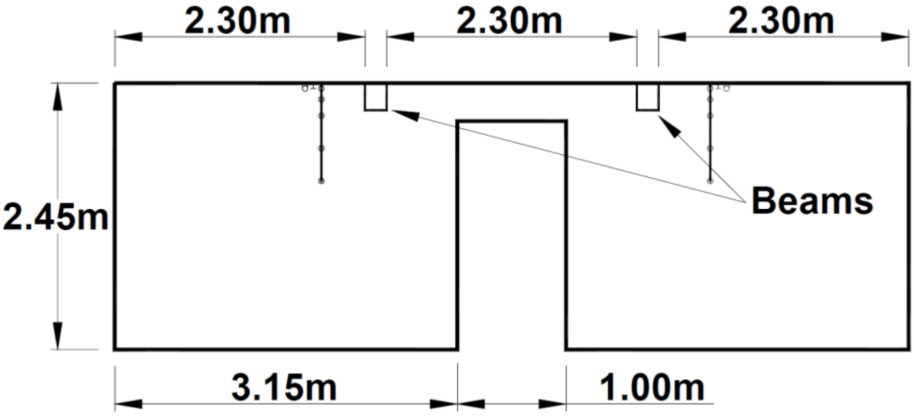
Each test slope, beam, fire size and fire location configuration was tested twice (Vettori, 2003).

Type K 0.51 mm diameter thermocouples were used throughout. Four vertical arrays of were used for all tests. The arrays were located in each quadrant of the compartment, adjacent to each of the sprinkler heads, as shown in Figure 77a. Each array consisted of five thermocouples; four of them were always located 25, 150, 300 and 600 mm below the ceiling. The fifth thermocouple was always located 1.5 m above the floor.

A bi-directional probe was also used to measure gas velocities near each sprinkler head. The openings of the bi-directional probe faced the front and rear of the room. The probe was located 25 mm below the ceiling. A schematic of the instrument array adjacent to a sprinkler head is shown in Figure 78. Time to sprinkler activation was also reported (Vettori, 2003).



(a)



(b)

Figure 77: Schematics of the (a) plan view and (b) front view of the slope and beam compartment tests

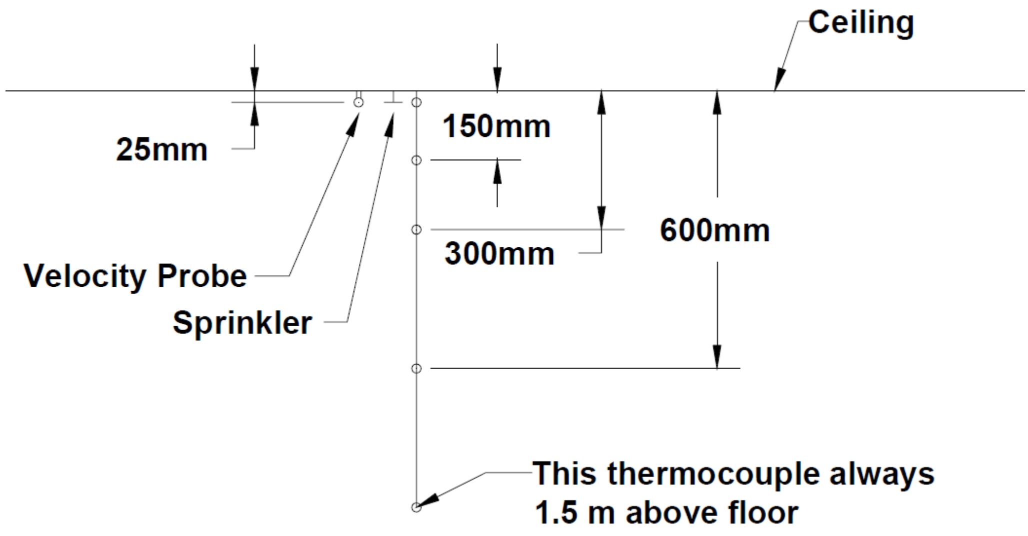


Figure 78: Schematic of the instrumentation for the slope and beam compartment tests

2.2.10.1.2 Atriums and balconies

2.2.10.1.3 Test H.2

Eighty-five spill plume tests were conducted for mass flow rates produced by steady fires in a 13.8 x 5 m wide by 5 m high compartment with an attached balcony (Figure 79). The compartment size was kept constant for the tests, but the intermediate floor shape, with and without a balcony, etc, were varied (Lougheed and McCartney, 2008a; 2008b).

The front wall of the compartment was modular, allowing for openings of different widths. A 1.6 m removable downstand could be installed on top of the opening. A 4 m deep sheet steel balcony was located over the full width of the compartment. The underside of the balcony was flush with the ceiling of the compartment. The height of the balcony was 5 m above the compartment floor and 7.2 m below the ceiling of the simulated atrium (Lougheed and McCartney, 2008a).

The experiments conducted with the widest compartment opening and no compartment opening downstand represent cases of a fire under a balcony. For these experiments, the compartment ceiling acted as a balcony section to give a total balcony depth of 5 m for tests without the balcony section and 9 m with the balcony (Lougheed and McCartney, 2008a).

The compartment ceiling, back wall and end walls were lined with 25 mm thick ceramic fibre insulation to provide protection for multiple fire tests. This material was selected because of its low thermal conductivity, therefore minimising heat losses to compartment boundaries and maximising the temperature and flow velocity of the smoke exiting the compartment. The panels used to change the opening width and downstand were made from uninsulated galvanised steel. All openings were aligned with the centreline of the compartment (Lougheed and McCartney, 2008a).

A propane burner was centrally located at the centre of the compartment for all tests, 0.4 m above the floor. The burner was assembled from pipes to from 1, 2 or 3 m square shapes. The mass flow rate to the burner was controlled within ±10% (Lougheed and McCartney, 2008a).

A smoke exhaust system was used to extract smoke from near the ceiling of the 16.8 x 30.5 m wide by 12.2 m high facility in which the compartment with the simulated atrium was located (Lougheed and McCartney, 2008a).

The varied parameters included (Lougheed and McCartney, 2008a):

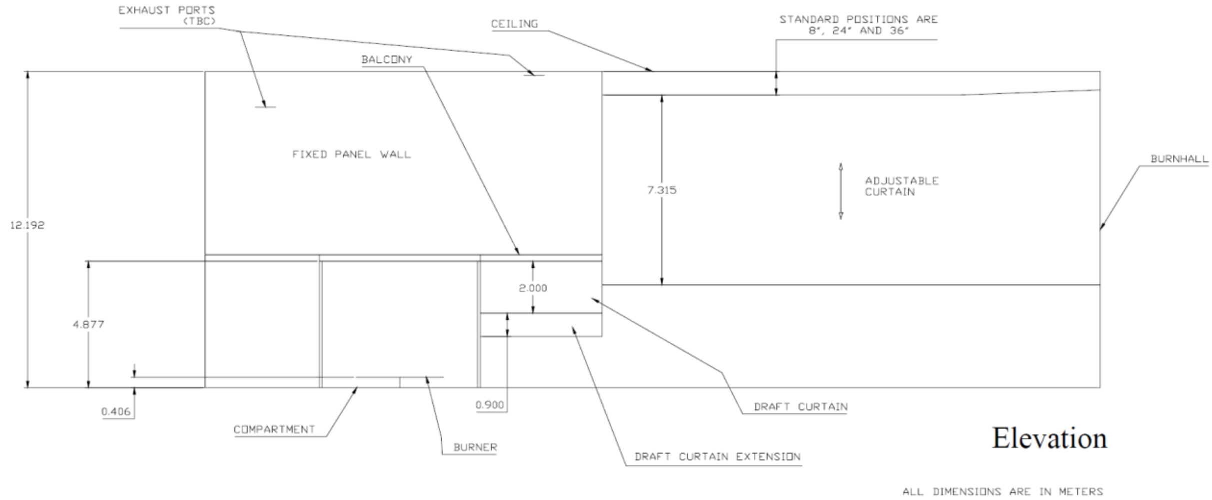
- Fire size: 500 to 5000 kW, and 1 x 1 m, 2 x 2 m or 3 x 3 m
- Fire density: 250 to 750 kW/m² (intended to relate to retail-sized fires and cover sprinklered office buildings (Lougheed, 1997)
- Ventilation openings: widths of 5.0, 7.5, 10 and 12 m
- Extraction rate: six different fan speeds were tested
- Downstand depth: compartment opening downstand depths of 0.0 and 1.6 m
- Balcony: with and without the balcony attached to the compartment
- Draught curtains: with and without draft curtains attached to the balcony.

All thermocouples used in testing were Type K without shielding or other types of radiation compensation. Data was collected at 2 s intervals (Lougheed and McCartney, 2008a, 2008b).

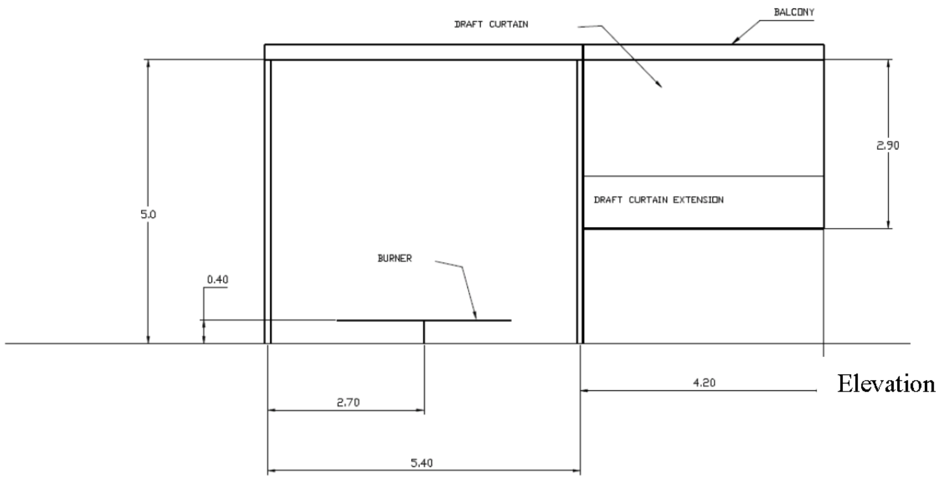
Three thermocouple trees were located along the centreline of the compartment. One was centred in the compartment, above the burner. The other two were located 3.5 m either side of the first tree. Each tree consisted of six thermocouples spaced 500 mm apart, with the highest thermocouple located at the ceiling (Lougheed and McCartney, 2008a).

An additional three thermocouple trees were located in the compartment opening: one located at the midway of the opening; and the other two evenly spaced between the first thermocouple tree and the sides of the opening. Depending on the details of the test, the thermocouple tree located at the midway of the openings consisted of either 11 or 12 thermocouples starting at 1 m above the floor up to either 4.75 m or 5 m. The other two thermocouple trees consisted of either seven or eight evenly spaced thermocouples starting at the ceiling (Lougheed and McCartney, 2008a).

Estimates of compartment layer height, based on the thermocouple tree results, were also reported (Lougheed and McCartney, 2008a, 2008b).



(a)



(b)

Figure 79: Schematic of the test setup for balcony spill plume tests (Lougheed and McCartney, 2008a)

2.2.10.2 Ventilation

2.2.10.2.1 Test H.3

A series of compartment fires were conducted to investigate the interaction of sprinklers and fire vents at the Swedish National Testing and Research Institute. One of the intents of the experimental program was to provide test data for use in modelling applications (O'Grady and Novozhilov, 2009).

For investigating wall vents, the compartment was 15 x 7.5 m wide by 6 m high, with large ventilation openings in the short length walls. The walls were constructed from 13 mm thick gypsum boards and the ceiling was constructed from 9.5 mm thick Navilite N boards. The wall opposite the burner was fully open. The short wall closest to the fire was open from the floor to approximately half the ceiling height, as shown in Figure 80 (O'Grady and Novozhilov, 2009).

A 1 x 1 m propane burner was used located centrally in the width of the compartment, 6 m from the sprinkler head and 1 m from the short wall (O'Grady and Novozhilov, 2009). The sprinkler head was centrally located in the compartment (O'Grady and Novozhilov, 2009).

Thermocouple tree temperatures and gas velocity measurements were reported for three locations within the compartment. Each tree consisted of six thermocouples and five bi-directional probes (O'Grady and Novozhilov, 2009).

The full report is: Ingasson H & Olsson S. 1992*. Interaction Between Sprinklers and Fire Vents, Full Scale Experiments, BRANDFORSK Project 406-902, SP REPORT 1992:11.* Swedish National Testing and Research Institute, Boras, Sweden. (O'Grady and Novozhilov, 2009)

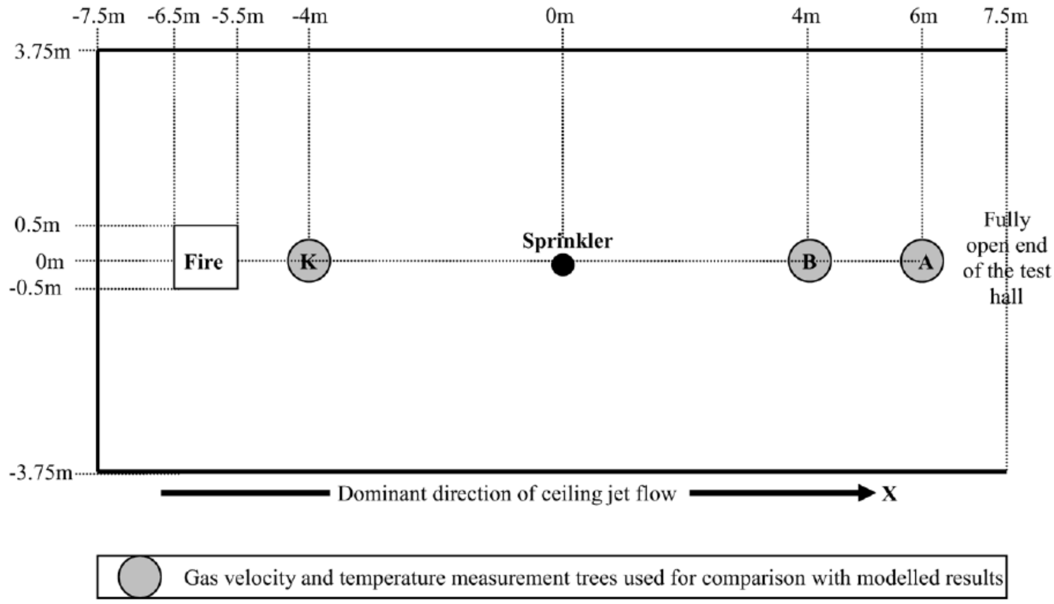


Figure 80: Schematic of compartment and layout for the burner, sprinkler head and instrumentation for the sprinkler and wall vent interaction fires

2.2.10.2.2 Test H.4

Displacement water mist system tests were conducted in a 3 x 2.4 m wide by 2.4 m high compartment with a 0.6 m deep plenum at the from of the chamber, as shown in the schematic of Figure 81. The plenum was used to mix and condition the air before it was supplied to the compartment via a diffuser. The water mist nozzles were located in the compartment supply vent. An air-conditioning unit and duct heater were also installed in the compartment (Hume, 2003).

Two fire types were tested: a 20 kW Heptane pool fire and a 20 kW crib fire (Hume, 2003).

The test results were reported for detection time for two thermocouple trees within the compartment (Figure 82), two smoke detectors (one ionisation and one optical sensor), and visual observations. As part of the study were compared to model output for a numerical package, FDS (McGrattan et al., 2010; Hume, 2003).

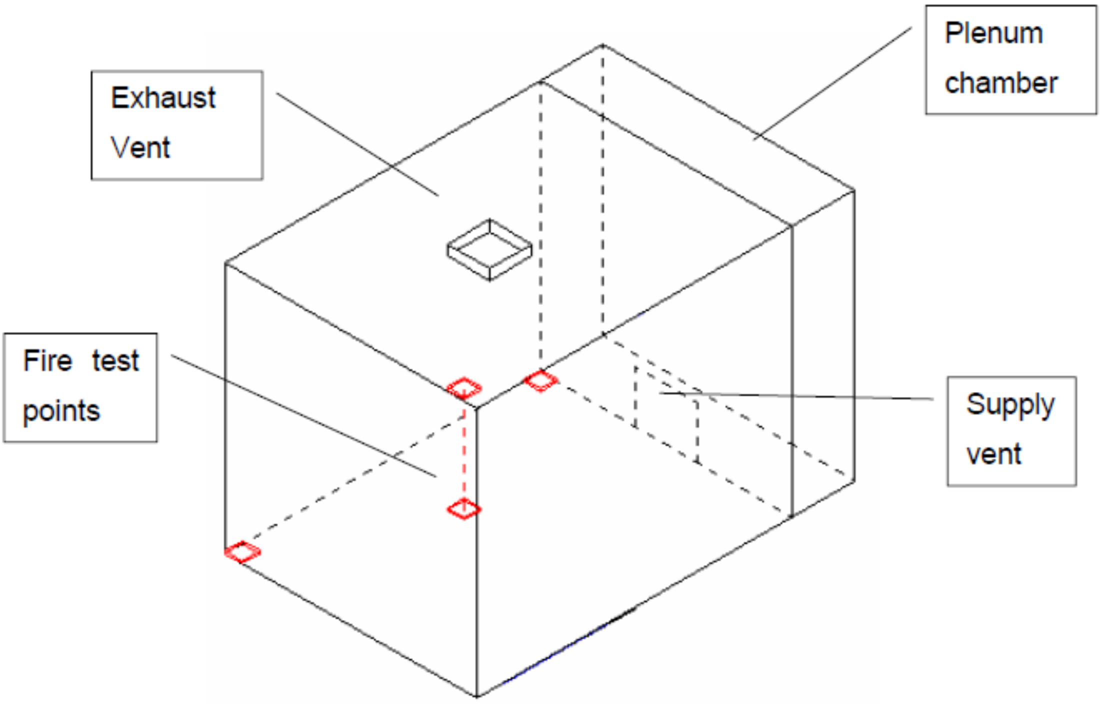


Figure 81: Schematic of the compartment used for displacement water mist testing (Hume, 2003)

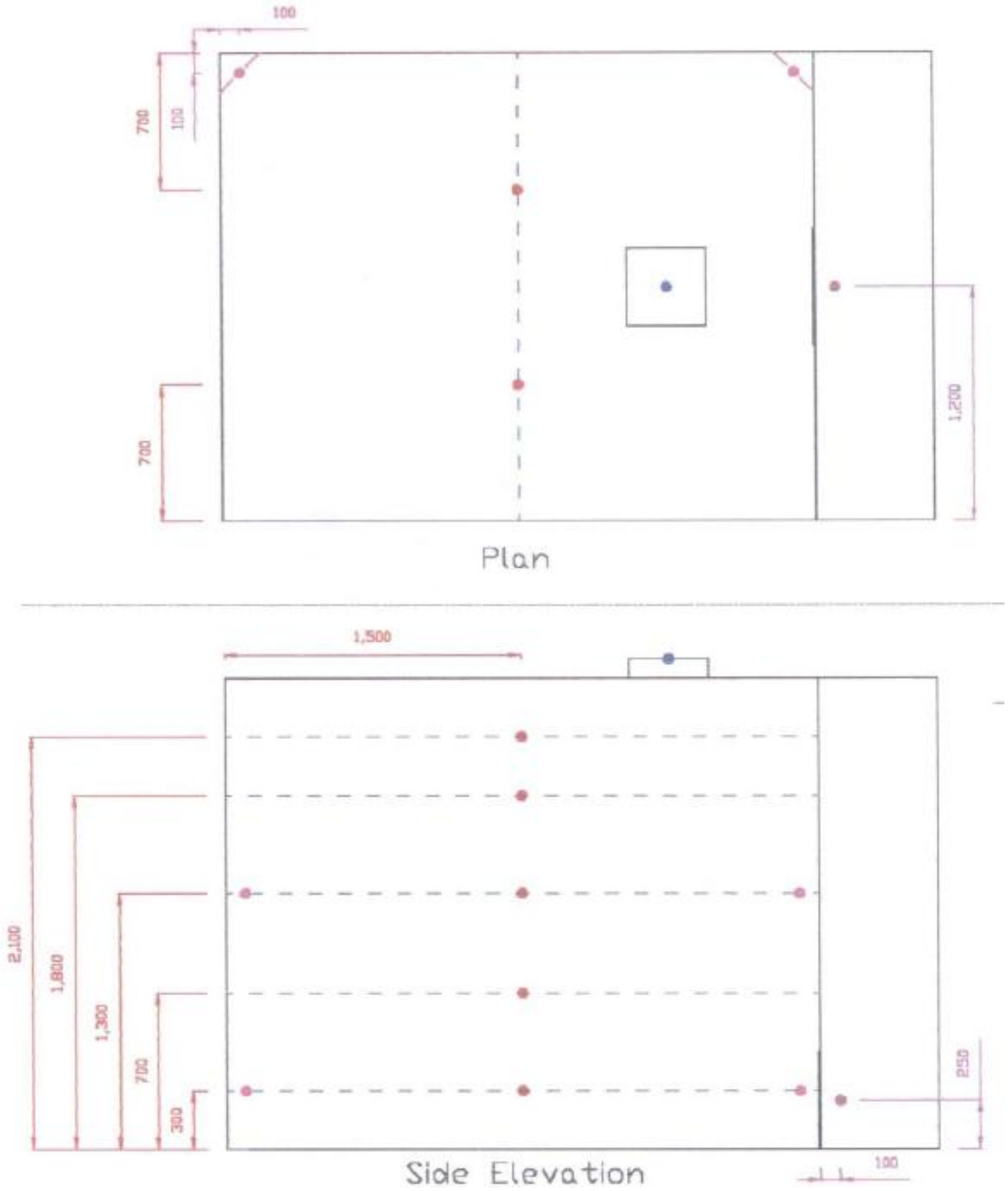


Figure 82: Thermocouple layout of the compartment used for displacement water mist testing – dimensions in mm (Hume, 2003)

2.2.10.2.3 Test H.5

Twenty-four tests were conducted to investigate the flow in the 1.04 x 2.24 m doorway of a 9.75 x 4.88 m wide by 2.44 m high compartment with a fire and one sprinkler head, as shown in the schematic of Figure 83. The walls were constructed of plywood with a black fire-resistant coating, the ceiling with gypsum board, and the floor was uncovered concrete. Other than the doorway, all seams and cracks were sealed (Crocker et al., 2010).

One pendent residential sprinkler head was installed in the compartment (Figure 83), 2.44 m from each wall in the corner closest to the burner, with a design flow rate of 49.2 L/min used for testing (Crocker et al., 2010).

A 0.46 x 0.46 m premixed air-propane burner was located in the corner of the room, opposite the doorway (Figure 83). Steady-state fires were used to try to reduce the variability between tests. Three fire sizes were tested: 42 ±5, 75 ±5, and 96 ±5 kW. The burner was controlled by the mass flow rate of the fuel. These three levels were selected to give a range of sprinkler activation times. It was intended that the smallest fire was insufficient to activate the sprinkler (Crocker et al., 2010).

All thermocouples used during the tests were Type K 24 gauge. Thirty-six thermocouples were located within the compartment, as shown in Figure 83. However the focus was the doorway flow. A thermocouple tree of bare bead thermocouples and bi-directional velocity probes were located in the doorway. The thermocouple tree covered half of the doorway height and the location within the doorway was varied between similar HRR tests. The bi-directional velocity probes were aligned with an assumed horizontal flow at the doorway.

The six repeated tests at each HRR were associated with a different location of the instrumentation in the doorway, as indicated in Figure 84. Data was collected 30 minutes after ignition of the burner, allowing the compartment to have reached a quasi-steady-state (Crocker et al., 2010).

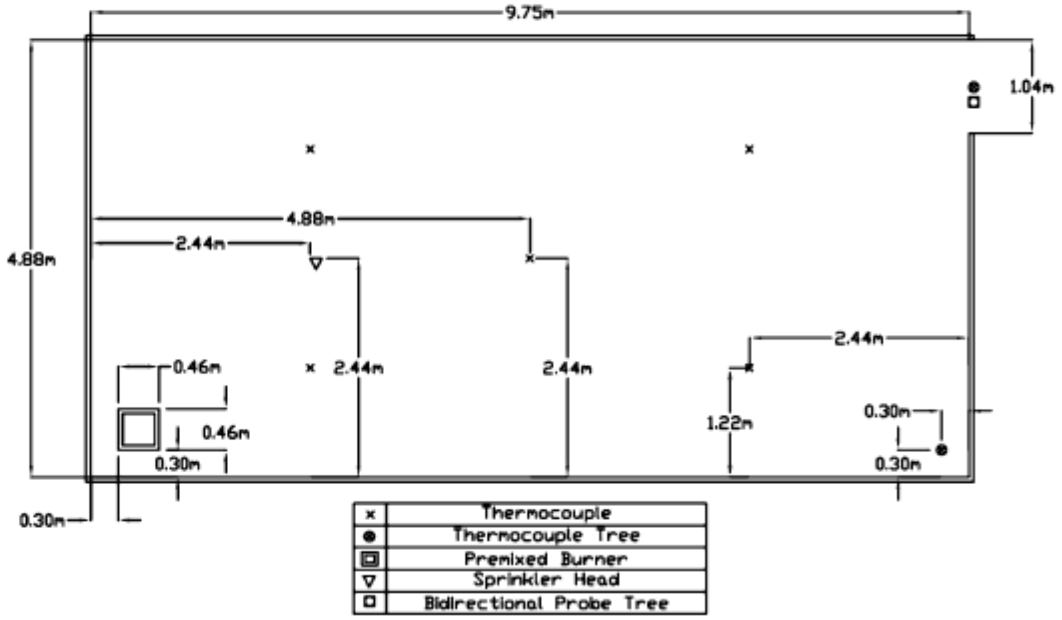


Figure 83: Schematic of the compartment and instrumentation for the tests used in the investigation of induced doorway flows (Crocker et al., 2010)

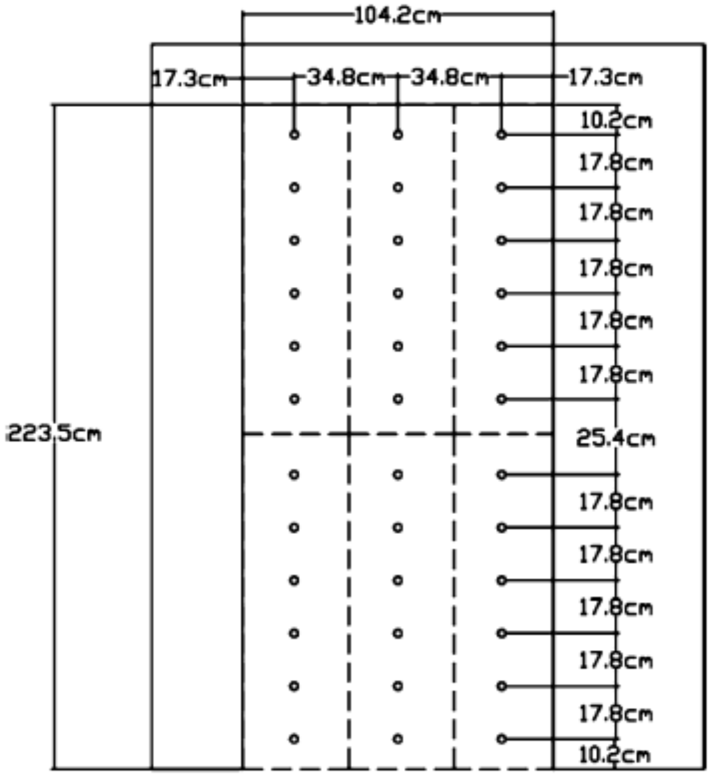


Figure 84: Schematic of the doorway instrumentation locations for both thermocouples and bi-directional velocity probes (Crocker et al., 2010)

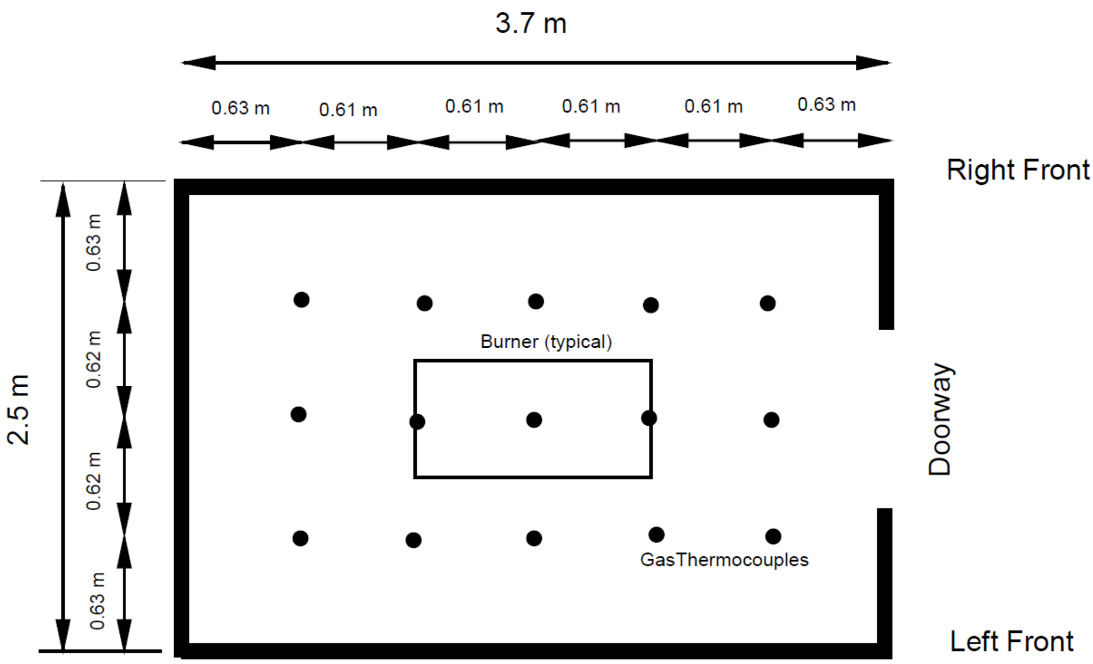
2.2.10.3 Fire type and size

2.2.10.3.1 Test H.6

A set of full-scale compartment fire experiments was conducted, designed to be suitable for model comparison (Dembsey et al., 1995). The experiments were conducted in a fire test compartment that was 2.5 x 3.7 m with a height of 2.5 m (Figure 85). The compartment was similar in size, geometry and construction to the standard fire test compartment specified in Uniform Building Code Standard 8-2.

The fire challenge consisted of a 0.61 x 1.22 m porous surface burner placed in the centre of the compartment. The porous surface of the burner was 0.61 m above the floor of the compartment. Propane fuel was supplied at a steady rate to obtain either a 330 kW or 980 kW fire for the duration of each experiment (Dembsey et al., 1995).

The ceiling gas temperature distribution was measured using 15 thermocouples arranged in a uniform grid centred in the compartment, 0.10 m below the ceiling (as shown in Figure 85). The compartment had a single doorway, 0.76 m wide by 2.0 m high centred on one of the shorter sides (Dembsey et al., 1995).



Compartment Height = 2.5m. Doorway Height = 2.0m
Burner Height = 0.61 m. Burner porous surface 0.61 m x 1.22 m
Thermocouples 0.10 m below ceiling.

Figure 85: Schematic of the fire test compartment used in the full-scale compartment tests (Dembsey et al., 1995)

2.2.10.3.2 Test H.7

Methanol and Hexane pan fire tests were conducted in a 4 x 4 m wide by 2.3 m high compartment with and without the application of water mist. The intent of the use of the test results was model validation evaluation. The ceiling of the test compartment was formed by the hood of the calorimeter, as shown in Figure 86 (Kim and Ryou, 2003).

The fuel pan was located in the centre of the floor. Two sizes of square pan (0.3 m and 0.4 m) were tested with each of the two fuels (Kim and Ryou, 2003). Five nozzles were located in the compartment, 1.8 m above the floor (Kim and Ryou, 2003).

Sheathed Type K thermocouples were located within the room. Two thermocouple trees were installed with six thermocouples each. The thermocouple trees were used to estimate the location between the hot upper and cool lower layer during each test. Four thermocouples were located on the ceiling (Kim and Ryou, 2003).

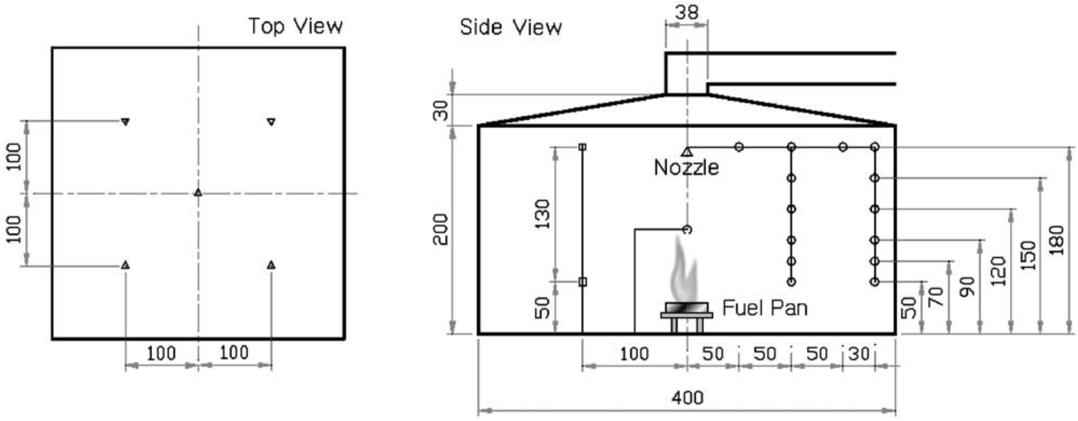


Figure 86: Schematic of the test setup for the compartmented hood fires (Kim and Ryou, 2003)

2.2.10.4 Suppression system characteristics

2.2.10.4.1 Test H.8

A test series of 15 wood crib fires with and without sprinkler activation were reported for a 3.8 x 3.6 m wide by 2.4 m high cement board compartment with a sliding door that was intended to represent a living room (Sekizawa et al., 1997).

Various wood crib locations (Figure 88) and door opening proportions were tested. Three sprinkler heads were located at either point A, or points F and G of Figure 87. Three tests were performed with no sprinkler activation (Sekizawa et al., 1997).

Response time of several types of smoke detectors and activation of a residential sprinkler system were reported. Thermocouple trees were located in the compartment as well as carbon monoxide concentration sample ports, and these measurements were reported for both before and after sprinkler activation. The locations of these instruments are shown in Figure 87 and Figure 88. (Sekizawa et al., 1997)

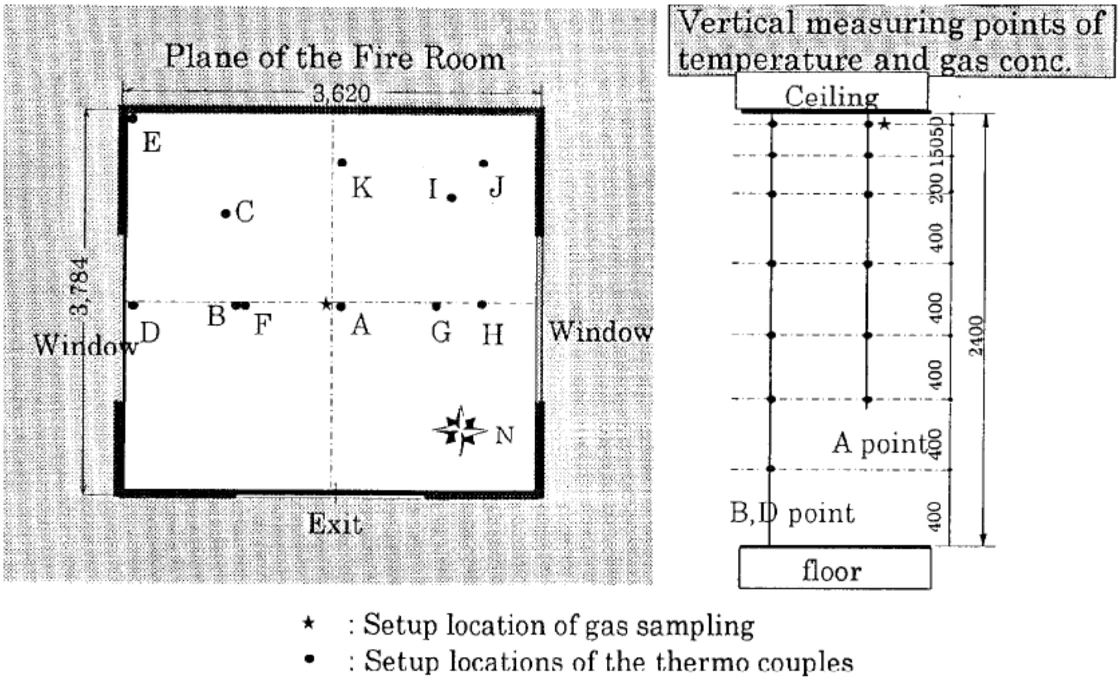


Figure 87: Schematic of the thermocouple and gas sampling locations for the wood crib compartment tests (Sekizawa et al., 1997)

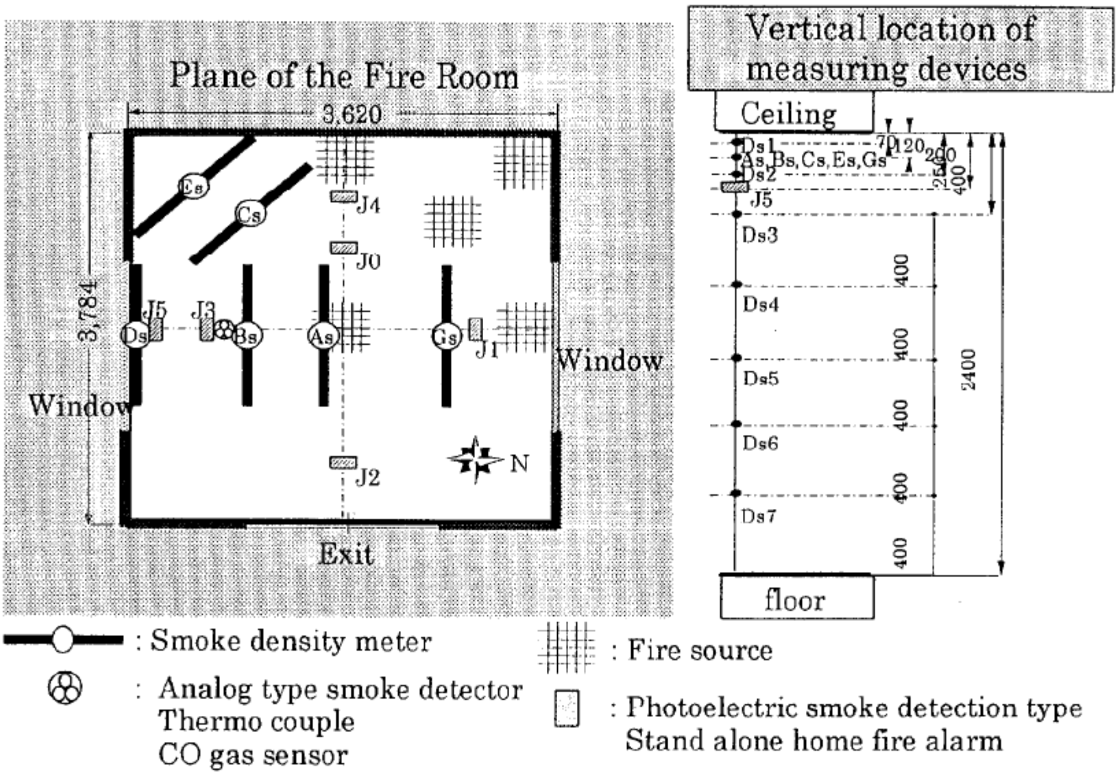


Figure 88: Schematic of the smoke density meters, various detectors and wood crib locations for the wood crib compartment tests (Sekizawa et al., 1997)

2.2.10.4.2 Test H.9

A series of small (130 and 200 mm diameter) pool fires in a large (4.5 x 10 m) test compartment were investigated. The fuel used in testing was kerosene. Various sized nozzles and operation pressures were also tested. A set of four water mist nozzles was located equidistant from the centre of the fuel pan for each test. Time to extinguishment, and temperatures of thermocouples in a tree located over the centre of the fuel pool, were reported. (Wang et al., 2002)

2.2.10.5 Additives

2.2.10.5.1 Test H.10

Pool fire tests were conducted under a furniture calorimeter hood. The pool fires subjected to a water mist fire suppression system with various fire fighting additives. The pool fires were either run in the open under the hood or placed within a 3.5 x 3.1 m wide by 3.3 m high perforated steel enclosure. A 0.9 m diameter, 0.1 m deep pan was used for both the Heptane and diesel pool fires. Wood cribs (0.6 x 0.6 m wide by 0.3 m high using 40 x 40 mm pine) were also tested. Perforated steel was used to break up the convective air currents without limiting the ventilation rate (Kim, 2001).

A water mist nozzle and a standard pendent sprinkler nozzle were used in the testing. Drop size distributions were reported for each of the types of nozzles tested. One or two low-pressure nozzles were used during each test. When one nozzle was used, it was centrally located over the fuel at the ceiling of the enclosure (3 m above the enclosure floor). When two nozzles were used, they were located 2 m apart, equidistant from the fuel, at the ceiling of the enclosure.

The water mist systems were manually activated, to allow each fire to develop for approximately 2 min from ignition for the crib fires and diesel pool fires and approximately 1 min from the ignition of the Heptane pool fires (Kim, 2001).

Two types of additives were used in testing: a foam-forming (Silvex) concentrate; and a film forming (Aqueous Film Forming Foam) concentrate. Concentrations of 0.3% for the foam-forming additive and 1% and 3% for the film-forming additive were tested. (Kim, 2001)

HRR, estimated from oxygen consumption during each test, was reported. The concentrations of carbon dioxide, carbon monoxide and unburned hydrocarbons and the amount of water vapour collected using the furniture calorimeter hood were recorded. Thermocouple and heat flux meter measurements were also recorded for locations within the enclosure. (Kim, 2001)

2.2.10.6 Continuous vs cycling application

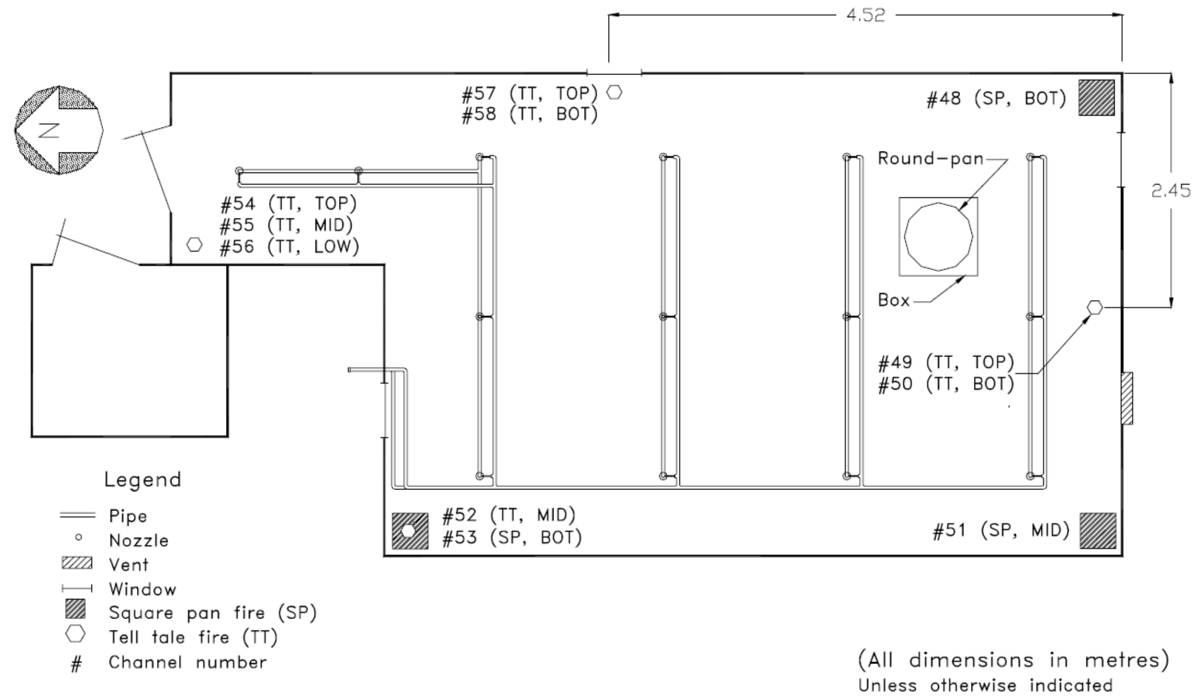
2.2.10.6.1 Test H.11

Tests conducted at NRCC compared continuous to cyclic discharge application of a twin-fluid, low-pressure water mist system to a range of fire challenges in an empty compartment. The test room was an irregular shape; a rectangular room (9.7 x 4.9 m wide by 2.9 m high) with a corner (2.9 x 2.2 m removed) (Figure 89). The compartment had a 0.9 x 2.0 m high door and three 0.56 x 0.56 m viewing windows. Fire tests were also conducted in a mock-up machinery space. (Liu et al., 1999)

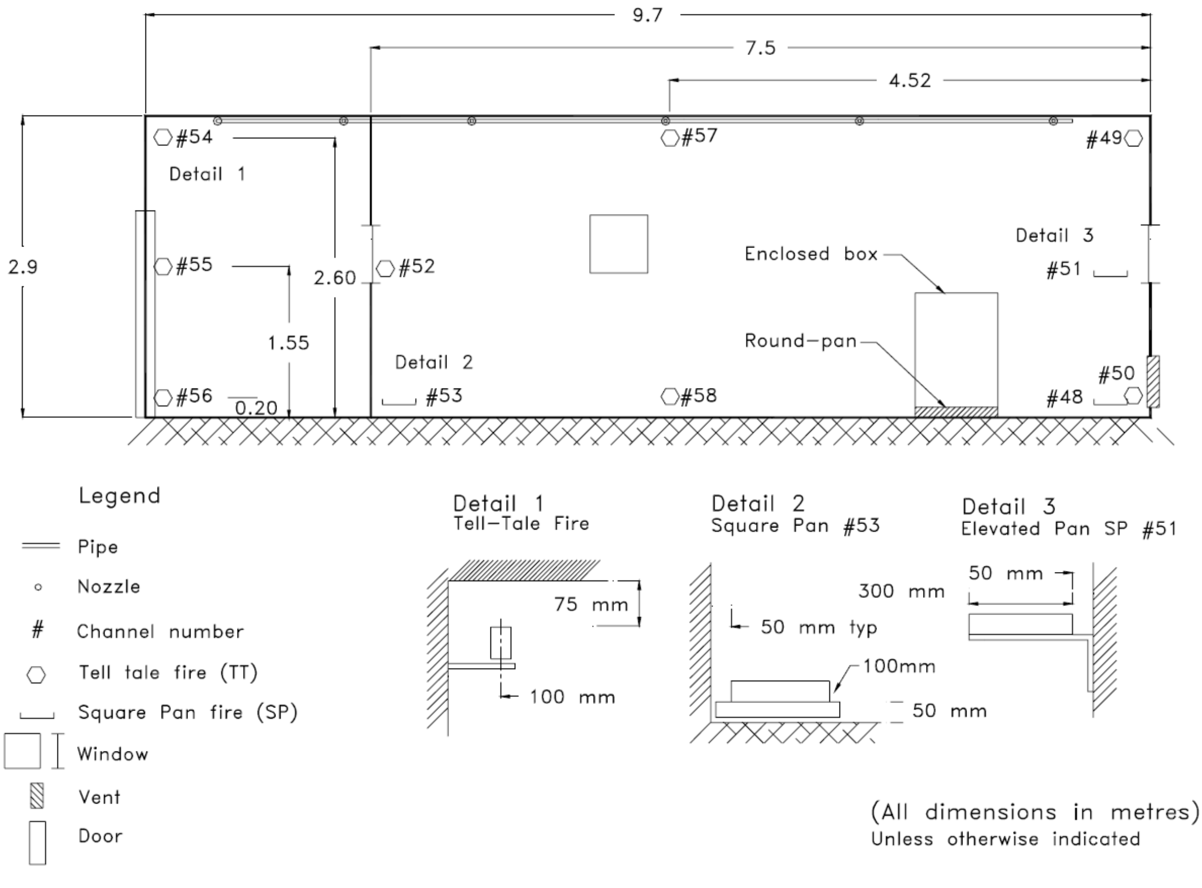
The influences of various fire sizes (~50 to 520 kW), types (a range of pool fire sizes and spray fires) and locations on the performance of a water mist system using either continuous or cycling discharge applications were investigated. Shielded fires were also tested for comparison. Various sided pool fires were placed in a mesh sided and topped metal box (0.80 x 0.84 by 0.94 m high). (Liu et al., 1999)

HRR (at 1 Hz), estimated from oxygen consumption calorimetry, was reported for each test. Time to extinguishment was also reported. Thermocouple measurements (at 1 Hz) were reported for three thermocouple trees (each consisting of six thermocouples) in the room. Four thermocouples were also placed above the surface of the fuel to monitor when the fire progress and extinguishment.

The thermocouples were 30-gauge, chromel-alumel Type K and stainless steel sheathed. Carbon dioxide and carbon monoxide concentrations (1 Hz) were reported for two locations within the room. Oxygen concentration was also reported at the higher location for which the carbon monoxide and carbon dioxide concentration measurements were taken. Nine pressure measurements (1 Hz) were also reported for locations on the west wall. Two video cameras were used to record the water mist activation and behaviour of the fires during control and suppression. (Liu et al., 1999; Kim and Zhigang, 2002)



(a)



(b)

Figure 89: Schematic of the (a) top view, and (b) side view of the irregular compartment test setup for empty compartment experiments (Liu et al., 1999)

2.3 Other experimental programs of interest

An experimental case study was setup to test the FireGrid system. A small, 2 x 2 m wide by 2 m high, compartment was used. The test fire was a Heptane pool fire. Forty thermocouples were used throughout the compartment. These were arranged in four thermocouple racks and used to estimate the smoke layer height. (Upadhyay et al., 2009)

Although the details of these tests were not reported, since the focus of the study was the evaluation of the appropriateness of the FireGrid system for the scenario, the results for this type of experiment with either successful or partial or total failure of an automatic fire suppression system would be useful for validation purposes of fire modelling packages. (Upadhyay et al., 2009)

A series of 12 2 m diameter pool fire water mist suppression experiments with controlled boundary conditions were performed in the FLAME/Radiant Heat test cell at the Thermal Test Complex at Sandia National Laboratories. The test cell is cylindrical, with an 18.3 m diameter and height of 12.2 m. The ceiling of the test cell slopes upward, so that the centre of the ceiling is 14.6 m above the floor, as shown in Figure 90.

There is a circular vent (4.9 m diameter) in the ceiling that transitions to a duct that calorimetry instrumentation is attached to. Make-up air is introduced to the test cell via ducts at the bottom of the test cell. The outer walls of the test cell are filled with water to help maintain a constant wall temperature during tests. (Yoon et al., 2009)

The nozzles tested had 30° spray angles and were full-solid-cone type with a uniform, round, fully dense spray of medium to large-sized drops. The pressure, flow rate and drop size were characterised. Two nozzle configurations were tested (90° and 45° attack angle) relative to the centre of the pool fire. (Yoon et al., 2009)

The fuel used during this series of tests was JP8, a kerosene-based hydrocarbon (Yoon et al., 2009).

Time to extinguishment, visual observations and temperatures of thermocouples located on the centreline above the pool fire were reported (Yoon et al., 2009).

Figure 90: A representation of the constant boundary temperature test cell used in a series of pool fires (Yoon et al., 2009)

2.4 Unsuccessful fire suppression

It may be useful to compare experiment results, where the suppression system has not been successful in controlling or suppressing the fire, to a model of a similar initial condition. For example, tests of under-designed water mist systems have been conducted. The results were that the systems were not successful in extinguishing liquid pool fires. (Jones and Thomas, 1993)

In another example, a prototype single-fluid/high-pressure water mist system was investigated for applications involving fixed library shelves. The test setup was based on the geometry of the rare book vaults of the Library of Congress in Washington, DC. Fire scenarios tested were involving ignition of archival materials on shelves, and another involving the ignition of materials on a work cart in the centre of an aisle.

Flooding and localised application of the water mist system were investigated. The suppression system was manually activated at various times. The time to ignition after activation of the suppression system and the amount of water was reported. (Mawhinney, 1997; Liu and Kim, 2001)

For flooding application tests, the fire was controlled when the mist system was activated 50 s after ignition. However, the system was unsuccessful at controlling the fire when the system was activated 100 s after ignition. (Mawhinney, 1997; Liu and Kim, 2001)

Other examples of fires that could not be controlled for an experiment were various fires sizes, from 1 to 6 MW, which were investigated for shielded and unshielded spray fires, and a wood crib fire and a 2 m² pan fire. The experiments were conducted in a compartment area of 2800 m² with a height of 18 m. A high-pressure (6.9 MPa) and a low-pressure (1.2 to 1.5 MPa) water mist system were used in various tests. The number of the nozzles was increased from 30 to 100. In each case, the suppression system was unable to control the fire. The reported oxygen concentration in the compartment was not reduced significantly during the tests. (Bill et al., 1997)

3. SUMMARY OF COLLATED EXPERIMENT PARAMETERS AND VARIABLES

To assist in the identification of a useful set of experiment results when considering validation assessments of a model, a tabular format of the experiments that have been summarised here was created. An example of the types of experiment parameters and variables that may be reported on for a water mist fire suppression system test is included in Table 1.

The collation of reported experiments summarised in this document are tabled for speed of access in Table 2.

Table 1: An example a summary of experiment parameters and variables for a water mist system (Mawhinney, 1996; Liu and Kim, 2001)

	Water Mist System
Experiment Variables Associated with System	Directionality of the system Drop size Flow rate Nozzle pressure Spray cone angle Four combinations of spray characteristics were considered: • very fine drops, low momentum mist • small drops, moderate momentum • coarse drops, high flow rate • coarser drops, super-heated water generation System activation method (zoned activation by detection system)
Experiment Variables Associated with Scenario	Compartment size Ventilation conditions Fire size Fire location (including degree of shielding of fire from system)
Scenario	Electronic equipment protection from: • fires (in kW vs time) in electronic cabinets (with geometry and ventilation rates) • fires in underfloor segments of cable plenums • fires in overhead segments of cable trays (locations and geometry) Zone vs total flooding operation of system Grouped cables
Experiment Parameters	• Efficacy of system protection • Fire size • Spread of humidity (H_2O vapour measurements) • O_2, CO and CO_2 measurements

Table 2: Summary of collated experiments in this report

Type of Space	Test Parameter Varied	Test No.	Experimental Data Reported															
				Thermo-couples		Gas Species Concen-trations												
			HHR	Individual	Trees	O_2	CO	CO_2	HCN	Air Velocities	Smoke	Pressure Differences	Heat Flux	Sprinkler Activation	Detector Activation	Visual Observations	Post-fire Damage	Non-Sprinklered Test
Accommodation	Compartment	A.1	✓	✓	✓									✓				
		A.2		✓	✓			✓			✓			✓	✓			✓
		A.3		✓	✓	✓	✓	✓								✓		
		A.4		✓	✓	✓	✓	✓			✓			✓				
	Ventilation	A.5	✓	✓							✓							
		A.6			✓								✓	✓	✓			
		A.7			✓	✓	✓	✓					✓	✓	✓	✓		
	Fire	A.8\1	✓	✓	✓									✓				
		A.9	✓	✓		✓	✓	✓						✓				
		A.10		✓	✓	✓	✓	✓						✓				
		A.11		✓	✓	✓	✓	✓			✓			✓	✓	✓		✓
		A.12		✓		✓	✓	✓			✓			✓	✓	✓		
	Suppres.Sys.	A.13	✓	✓	✓									✓		✓		
	Head Config.	A.14		✓	✓									✓		✓		
Kitchen/Cooking	Fire	B.1		✓	✓	✓	✓	✓					✓	✓		✓		
		B.2	✓	✓	✓								✓	✓				
	Suppres.Sys.	B.3			✓									✓		✓		
		B.4		✓		✓							✓	✓		✓		
Office	Fire	C.1																✓
		C.2		✓										✓				
		C.3		✓	✓									✓	✓			
	Shielding	C.4	✓	✓	✓	✓	✓	✓					✓		✓	✓		
		C.5	✓				✓						✓					
	Suppres.Sys.	C.6	✓	✓		✓	✓	✓							✓			
Heritage and Libraries	Fire	D.1		✓									✓	✓	✓	✓	✓	
	Shielding	D.2		✓									✓	✓	✓	✓	✓	
		D.3		✓									✓	✓	✓	✓	✓	
		D.4		✓	✓										✓	✓		
	Suppres.Sys.	D.5		✓											✓		✓	
		D.6		✓									✓	✓	✓	✓	✓	
	Head Config.	D.7		✓									✓	✓	✓	✓	✓	
Electronic Equipment	Fire	E.1		✓		✓	✓	✓	✓			✓				✓		
	Suppres.Sys.	E.2		✓										✓		✓		
		E.3		✓			✓		+							✓		
		E.4		✓		✓	✓	✓	✓			✓				✓		
Entertainment		F.1		✓	✓	✓	✓	✓	✓	✓			✓			✓		✓
Factory/ Machinery	Compartment	G.1				✓								✓		✓		
	Ventilation	G.2	✓		✓	✓	✓	✓				✓		✓		✓		
		G.3	✓		✓	✓	✓	✓				✓		✓		✓		
		G.4		✓	✓									✓		✓		
		G.5		✓										✓		✓	✓	
	Fire	G.6														✓		
		G.7														✓		
		G.8														✓		
		G.9				✓								✓		✓		
		G.10		✓	✓	✓	✓	✓										✓

	Shielding	G.11											✓		✓		
		G.12				✓							✓		✓		
		G.13		✓	✓	✓	✓	✓			✓		✓			✓		
	InteractionO	G.14		✓	✓					✓	✓					✓		
	Suppres.Sys.	G.15														✓		
		G.16		✓		✓	✓	✓			✓		✓			✓		
	Additives	G.17														✓		
		G.18		✓											✓	✓	✓	
		G.19		✓						✓						✓		
	Head Config.	G.20		✓		✓	✓	✓					✓			✓		
		G.21														✓		
		G.22														✓		
		G.23														✓		
		G.24			✓	✓	✓	✓			✓					✓		✓
	Application	G.25	✓		✓	✓	✓	✓				✓				✓		
		G.26			✓	✓	✓	✓								✓		✓
	Repeatability	G.27		✓												✓		
Generic Compartment	Compartment	H.1		✓	✓					✓						✓		
		H.2		✓	✓													
	Ventilation	H.3			✓					✓								
		H.4			✓									✓	✓	✓		
		H.5			✓					✓						✓		
	Fire	H.6		✓												✓		
		H.7		✓	✓													
	Suppres.Sys.	H.8			✓		✓							✓	✓			
		H.9			✓											✓		
	Additives	H.10	✓	✓		✓	✓	✓	+				✓					
	Application	H.11	✓	✓	✓	✓	✓	✓				✓		✓		✓		
Unsuccessful Suppression	Various	E.2\ G.5\ G.19\																

Table Notes:

The test parameters varied are abbreviated in the table as:

- Compartment = Compartment Size and Configuration
- Ventilation
- Fire = Fire Type and Size
- Shielding = Shielding of Fires
- InteractionO = Interaction with Other Fire Protection Systems
- Suppres.Sys. = Suppression System Characteristics
- Additives = Fire Fighting Additives
- Head Config. = Nozzle/Head Configuration
- Application = Continuous (e.g. Flooding) vs Cycling Application
- Repeatability = Repeatability

Also + indicates additional gaseous or vaporous species were also reported.

3.1 Discussion of use of data for modelling purposes

3.1.1 Verification vs validation

Model verification is to ensure that the algorithms have been programmed correctly and implemented properly. Verification is to eliminate programming errors. Model validation is to measure the differences between model predictions and real world results for one or more controlled experiments.

A data set used for the development of the theories implemented in the model cannot also be used for model validation. The focus of the experiment results summarised for this project has been on the validation aspects of use of available data sets. Therefore it is important to know the algorithms implemented in the model, and understand what assumptions and experimental data sets were used in the development of the specific algorithms.

For example, if a model utilises a sprinkler fire suppression algorithm based on the GSA engineering fire assessment system to estimate reductions in HRRs, then it would be inappropriate to use any of the experimental data set used in the development of this empirical estimate. For example, in this case various fuel packages tested in large-scale experiments by Madrzykowski and Vettori (1992b) or the wood crib experiments conducted by Walton (1988).

Model validation of various aspects of the Consolidated Fire Growth and Transport model (CFAST) are discussed in relation to applications in the nuclear power plant building design and assessment (USNRC, 2007). Similarly, validation of aspects of BRANZFIRE and application of the model to various situations is discussed elsewhere e.g. (Wade et al., 2004, 2007). Good examples of documented model validation for a field fire modelling approach are presented in Volume 3 of the FDS (Version 5) Technical Users Guide (McGrattan et al., 2010).

3.1.2 Aspects of modelling approaches

General modelling approaches used for the incorporation of fire suppression systems in models are summarised here. Specific modelling approaches used in various models and theories were not the focus of this study, so details of specific theories and programming approaches are not included in the discussion.

Aspects incorporated into modelling of various fire suppression systems may include, but are not limited to, one or more of the following:

- Extinguishment mechanisms:
  - evaporation cooling
  - oxygen displacement
  - radiation blocking
- Use of additives
- Methods of system activation and operation (individual nozzles, zoning or flooding)
- Spray characteristics:

- drop size distribution
- spay angle and cone shape
- velocity distribution
- mass flow rate
- flux density
- spray momentum, etc.

- Spray dynamics:
  - interaction of mist and fire plume
  - interaction of mist and fuel properties
  - ability to extinguish the fire, as related to the burning rate and HRR
  - entrained air velocity and interaction with spray
  - enclosure effects, etc.
- Empirical influence on the fire:
  - reduction in HRR.

It cannot be more highly recommended to understand the reasons and experimental data sets used both directly and indirectly in the development of each aspect of a model, such that the same or too similar data sets are avoided during validation evaluations.

3.1.3 Creation of databases for experiment data

In some cases there is little data available from the tests. In other cases, data sets are only available in a printed form as graphs or tables. Test data that is available in electronic form have been stored in a range of electronic file formats and with various methods of coding for the label of each of the data channels related to each test. This leads to the value of the data being potentially lost in translation because of the storage format or the loss of context of the data labels of data column headers. More recent test series incorporate some aspect of potential comparison with model outputs. A good test plan includes these considerations and others, such as future value and use of the data sets.

Potential standardisation of data labels poses a challenging problem, since there are standard tests that each have a similar range of test setup that have many similarities that would be easier to collate in a standard way. However, divergence from the standard test methods and true ad hoc testing pose a much more complex problem.

Previous attempts, such as FASTdata by NIST (Peacock et al., 1999), can be learnt from and used in the development of future useable and useful databases. Also current databases may provide be the most useful to join and continue the development, such as the experiment data repository at http://code.google.com/p/fds-smv/wiki/Accessing_Subversion_Repository that is part of the FDS-based community. Using this repository as a working example, the style of data sets included in the repository reflects the type of model intended for the application, specifically a field model in this case. Therefore a slightly broader approach to the formatting style of the data sets might be useful for opening the applicability to a wider range of models.

4. OVERALL SUMMARY AND CONCLUSIONS

When assessing the validation of a model for application to a defined scenario it is important to: identify experiments that appropriately represent the scenario of interest and the context of the intended application of the model for design or investigation work; and subsequently identify the types of sets of tests that focus on aspects related to the scenario.

As summarised here, experiment data sets are available for a range of fire tests related to water-based automatic fire suppression systems. However, the extent of the usefulness varies greatly depending on the context of the scenario of interest and the method of information transfer from the experiment program.

For instance, experiments may have been conducted for a particular test series that directly relates to a fire scenario of interest, but some test parameters were recorded but are not reported in available literature, and test parameters are not in desirable locations etc. This is because the focus of the experiments and the modelling are fundamentally different, even though the scenario may be the same or similar, or the value of the data has been lost in translation because of the storage format or the loss of context of the data labels of data column headers.

Potential standardisation of data labels poses a challenging problem, since there are standard tests that each have a similar range of test setup that have many similarities that would be easier to collate in a standard way. However divergence from the standard test methods and true ad hoc testing pose a much more complex problem.

4.1 Recommendations for future research

The primary recommendation for future research based on this review of available experiment literature is:

- Development of a standard for data labelling to enable decoding of available data sets. This may need to be related to the type of testing etc.

Other recommendations for future research based on the experience gained during this project:

- Selection of a structure to use for data storage to ensure future accessibility and ease of upgrading or change of format, in terms of future-proofing as far as practicable.
- Development and implementation of strategies to encourage active sharing of experimental data sets. For example, incentives or contract conditions for researchers to upload data sets to online repositories at the close-out of a project etc.

5. REFERENCES

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