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SNL Storage Facility Fire Environment Experiment Data for Model Validation and Development

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Abstract

The development of validated numerical tools to predict the thermal hazard posed by a fuel fire that results from an aircraft or ground transportation accident is a goal of the Fuel Fire Technology Base Program. These validated tools support Defense Threat Reduction Agency (DTRA) probabilistic Weapon System Safety Assessments (WSSA). Two types of tools are being developed to support this type of activity: (1) tools that model the detailed physics of the problem (e.g., fire field models); and (2) tools that model the dominant physical phenomena (e.g., the risk assessment compatible fire models (RACFM)). RACFM are tailored to be compatible with the methodology of a probabilistic WSSA. A large-scale fire testing program has been established to obtain experimental data to (1) develop and calibrate RACFM, (2) validate and further develop fire field models, (3) assess the fire threat to actual systems of interest and, (4) provide archival data for future assessments.

This report describes nine full-scale enclosure pool fire experiments (JP8 fueled) that were conducted at the Sandia National Laboratories (SNL) Lurance Canyon Burn Site in the Building 9830 "Igloo" Facility. Experiment and hardware requirements, the test facility, instrumentation, and a complete description of each experiment are provided herein. The primary purpose of the test series was to furnish experimental data for validating compartment fire models that are being developed to predict the abnormal thermal environment in a storage facility/aircraft accident situation. Fires of interest in the storage and maintenance facilities are primarily hydrocarbon pool fires that could occur as a result of an aircraft engine penetrating the facility during an accident. The models, in turn, are to be used to assess the thermal hazard posed to stored weapons within the facility.

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Executive Summary

This report is essentially a data package that contains temperature, heat flux, vent velocity, and ambient wind data for a series of enclosure fire experiments conducted by Sandia National Laboratories (SNL) for the Defense Threat Reduction Agency (DTRA) (formerly the Defense Special Weapons Agency (DSWA)). The experiment series consisted of nine distinct compartment fire scenarios. The purpose of the experiment series was to furnish experimental data for validating compartment fire models that are being developed to predict the abnormal thermal environment in a storage facility/aircraft accident situation. The models, in turn, are to be used to assess the thermal hazard posed to stored weapons within the facility.

The nine full-scale enclosure pool fire experiments (JP8 fueled) were conducted at SNL's Lurance Canyon Burn Site in the Building 9830 "Igloo" Facility. These experiments were conducted over a period from August 7, 1997, to October 6, 1998. Experiment and hardware requirements, the test facility, instrumentation, and a complete description of each "Storage Facility Fire Environment Model Validation Experiment" are provided herein.

This report was written specifically with the end-user, the fire analyst, in mind. All of the experiment data is included on a CD ROM in two formats. First, an Excel program with embedded Visual Basic macros provides a convenient interface for navigating the IGLOO experiment data sets. The user can either view pre-defined plots of thermocouple, heat flux, or velocity data sets plotted for the full time range or create customized plots for user selected parameters. Most of the figures in the appendices were made using this Excel program.

The CD ROM also contains a PC compatible LabView executable program that allows the analyst to review multiple data fields simultaneously as if participating in the actual experiment. Many of the movies taken with the video cameras were digitized and can be viewed while simultaneously accessing the LabView data playback program. The Excel and LabView programs are intended to provide a user-friendly archival database in support of model validation efforts.

1. Introduction

The Department of Defense (DoD) requested the Defense Threat Reduction Agency (DTRA) to continue the development of capabilities for performing probabilistic Weapon System Safety Assessments (WSSA). In response, DTRA established a Fuel Fire Technology Base Program, the goal of which is to develop validated numerical tools to predict the thermal hazard posed by a fuel fire that results from an aircraft or ground transportation accident. Two types of tools are being developed to support this type of activity: (1) tools that model the detailed physics of the problem (e.g., fire field models); and (2) tools that model the dominant physical phenomena (e.g., the risk assessment compatible fire models (RACFMs)). RACFMs are tailored to be compatible with the methodology of a probabilistic WSSA.

To further support WSSA, DTRA also established a large-scale fire testing program to obtain experimental data to (1) develop and calibrate RACFMs, (2) validate and further develop fire field models, (3) assess the fire threat to actual systems of interest and, (4) provide archival data for future assessments. As part of the program, an extensive test series involving outdoor pool fires has long been underway fulfilling the goals of the experiment program by investigating factors that influence the fire environment, such as wind interaction with large objects.

For the experiments described in this report, however, attention was focused on the thermal environment found in enclosed fires, in particular, those fuel fires that could result from an aircraft crash into a storage or maintenance facility. There are three general types of facilities that could be involved in an aircraft crash fire. They are (1) standard igloos that contain warheads and bombs, (2) J-row igloos that contain air-launched cruise missiles (ALCM), and (3) maintenance facilities (IMF or ASI) that contain both bombs and ALCMs. A description of these facilities is given in Chapter 2, excerpted from Nicolette and Gill (1997).

Fires of interest in the storage and maintenance facilities are primarily hydrocarbon pool fires. While fire scenarios caused by fuel spills associated with servicing activities are certainly credible, this report focused on fires that could occur as a result of an aircraft engine penetrating the facility during an accident. These fires are different from what is normally found in the compartment fire literature in three major ways. First, the fires in the J-row facilities would involve large quantities of aviation fuel (>200 gallons) that come from either the ALCMs (JP10) or the aircraft fuel tank (JP8). Such fuel loads lead to possible fire heat release rates (HRR) well beyond those treated in conventional compartment fire experiments. Second, within the enclosure, ventilation to the fire may be severely limited, perhaps from a single small hole in the facility roof that resulted from the aircraft engine impact. This situation has not been fully explored in the available literature. Third, the curved shape (semi-circular) of the storage igloo ceiling presents a geometry in which significantly different fire environments can occur compared to flat ceilings in other types of enclosures. Because of this unique set of characteristics, a test series was established to obtain relevant data for validation of the fire models that will be used for weapon safety assessment in enclosures of interest.

2. Description of Facilities

2.1 Standard Igloos

"Standard igloos" or "igloos" as used herein refers to storage and mounded igloos that do not house ALCMs. These igloos typically house W80 warheads and/or B83 and B61 bombs. There are no ALCMs stored in these igloos. There is some difference in design from base to base, so the following is understood to be a "typical" description.

Standard igloos are 18.3 m (60 ft) long by 8.2 m (27 ft) wide. They have a curved ceiling that is approximately semi-circular. At its highest point, the ceiling is 4.1 m (13.5 ft) high. They are constructed of reinforced concrete, with an earth overburden. The doors to the igloo are steel. The total door area is 2.44 m (8 ft) wide and 2.9 m (9.5 ft) high. In order to understand fuel dispersion issues, it is necessary to know the floor characteristics. The floor in a standard igloo has a back to front pitch of 0.15 m (6 inches). There are two gutters (one on each side of the igloo) that lead to outlets through the front wall of the igloo. These relatively small openings can easily be blocked by debris, which would prevent any fuel from exiting the igloo through them.

Since there are no ALCMs present in these igloos, there is virtually zero fuel inside them. However, fuel can enter the igloo if an aircraft carrying fuel crashes into it. Generally, only the aircraft engine carries sufficient momentum to penetrate the igloo. Typical holes from aircraft engine impact can range from 0.72 m to 2.24 m (2.36 ft to 7.36 ft) effective diameter. The amount of fuel that enters the igloo through this hole can be estimated from the fuel load in the wing directly behind the engine. It will depend on the type of aircraft that impacts the igloo, and whether a take-off or landing was being attempted, as well as on the effective hole size. The situation is somewhat different if the aircraft engine strikes the igloo doors. It is believed that the igloo doors will be completely destroyed in such an event.

Ventilation to feed a fire in an igloo will come through the hole created by the aircraft engine in the wall or ceiling (or from the doors being destroyed). Additionally, there are two vents in the front wall with grills that are 0.38 m (1.25 ft) high by 1.37 m (4.5 ft) wide. They are located 0.4 m (1.33 ft) above the floor. In some designs, these vents are smaller and located in the doors of the igloo. There is also a ventilator shaft (chimney) along the rear wall at the ceiling, with an approximate cross-sectional area for flow of 0.38 m by 0.38 m (1.25 ft by 1.25 ft). This shaft contains a fusible link damper that actuates at 82 C (180 F). If it operates properly, this damper would effectively close off the shaft from supplying ventilation to the igloo in the event of a fire.

2.2 ALCM Storage Igloos: J-Rows

"J-rows" as used herein refers to ALCM storage igloos. This includes what are commonly referred to as J-row igloos and ALCM Support Phase 2 munitions storage igloos. J-rows typically house ALCMs, either on pylons or on rotary launchers. Both may be present in any given J-row.

J-rows are typically 34.1 m (112 ft) long by 12.2 m (40 ft) wide. The ceiling is arched, but relatively flat compared to the standard igloos, with a height of approximately 5.6 m (18.5 ft). J-rows are constructed of reinforced concrete, with some earth overburden. They have loosely hung steel doors (2 each), that are each 3 m (10 ft) wide by 3.66 m (12 ft) high. The floors have a pitch of 0.15 m (6 inches) from the center to the front and back walls. There is also a slight center to side pitch of 0.05 m (2 inches). There are gutters along both side walls, and outlets in both the front and back walls.

An aircraft engine penetrating the wall, door, or ceiling could provide an external fuel load to the J-row. The previous discussion concerning standard igloo fuel loads and effective hole diameters applies here as well. The doors are only loosely hung, and will undoubtedly be destroyed if impacted. Additionally, since ALCMs are present, the ALCM itself can supply fuel for a fire. The ALCM fuel (200 gallons of JP10) may provide either the primary source of fuel for a fire, or the secondary source. If fuel enters the J-row via an engine impact, without any damage to the ALCMs, then an ensuing fire may eventually breach the aluminum skin on the ALCM fuel tank and release additional (secondary) fuel. It is also possible that the engine impact does not deposit much fuel in the J-row, or perhaps does not penetrate completely through the J-row wall or ceiling. In such cases, spalling concrete and debris may act as projectiles that rupture an ALCM fuel tank, and the ALCM fuel is then the primary fuel source.

Ventilation in a J-row is very limited. There is some leakage around the door frames (a gap of 0.025-0.05 m (1 to 2 inches)), but no other ventilation supply. The hole resulting from an aircraft engine impact (or if the doors are blown away) would be the major ventilation source to a J-row fire.

2.3 Maintenance Facilities: IMF and ASI

"Maintenance facilities" as used herein include both the IMF (Integrated Maintenance Facility) and ASI (Assembly, Surveillance, and Inspection) buildings. These two buildings are different from each other, although both can house ALCMs, W80s, and/or B83s at any given time.

The IMF is a very large, single story facility. The main bay is typically 79.3 m (260 ft) long by 30.5 m (100 ft) wide. There are a number of adjacent rooms/bays. These are typically 18.3 m (60 ft) long by 18.3 m (60 ft) wide. There are various ceiling heights. The main bay is a high bay which is 7.3 - 9.1 m (24-30 ft) high. The walls of the building are concrete, but the roof is constructed of sheet metal. Some rooms have floor drains in them.

The fuel load inside the IMF consists of either JP8 or JP10 (or both). If an aircraft impacts a side wall, JP8 can be introduced into the IMF in a similar manner to the igloos and J-rows. Similarly, JP10 may be released from an ALCM according to the same scenarios discussed for the J-rows. If an aircraft impacts the roof of the IMF, it is expected that the roof of the facility will collapse, since it is sheet metal construction. This could allow for a substantially greater fuel load from the aircraft entering the facility than would otherwise enter through a hole resulting from an engine impact.

There is a complex ventilation system in the IMF. However, the sheet metal roof is likely to collapse upon an aircraft impacting the facility, even if the aircraft impacts a side wall. Therefore the ventilation system is not of consequence for a resulting fire. It should also be noted that the IMF has wet pipe sprinklers and rate of rise detectors for detection and suppression. These may very well collapse upon impact along with the roof, and will not be considered further.

The ASI building is a very large, two-story facility. It is roughly 79.3 m (260 ft) long by 38 m (128 ft) wide, with a mixture of large bays and office size rooms. There are various ceiling heights, with the highest point being 11.3 m (37 ft) high. The walls of the building are concrete, and unlike the IMF, the roof is sturdy (i.e., not constructed of corrugated sheet metal). Some rooms have floor drains in them.

The fuel load inside the ASI can be similar to the IMF building. However, total structural collapse of the ASI roof upon aircraft impact is not likely. The ventilation inside the ASI is complex, with the multi-level layout of the building leading to additional considerations in the event of a fire. Additionally, there are a variety of sprinkler types employed in the ASI with various actuation settings. As a result, modeling fires that occur in the ASI cannot be generalized, and must be evaluated on a case by case basis.

3. Experiment Objectives and Data Requirements

The objective of the test series was to provide appropriate data for model validation of an enclosure fire that results from a postulated aircraft crash into a weapons storage facility. While the aircraft crash was the focus, other accident scenarios associated with weapon handling and fueling could also result in an enclosure fire within the weapon storage facility. Control parameters known to affect the thermal environment in the enclosure fire were identified and a parameter space of interest was formed for investigation *via* computational models (Nicolette and Gill 1997; Nicolette 1996). The strategy for obtaining appropriate data for validation was to conduct experiments at the extremes of the parameter space thereby exercising the model at points spanning the full range of interest.

To define the data requirements, response parameters were identified that characterized the thermal environment. Instrumentation was selected for observation of the response parameters (both directly and indirectly) to allow direct comparison between observations and predictions.

3.1 Control Parameters

The enclosure fire scenario involves a fuel fire provoked by the penetration of the facility by a large massive object, such as a jet engine. The source of the fuel is either from stores within the enclosure or the aircraft wing tank section associated with the engine. It is assumed the only ventilation available to the facility enclosure is the opening created by the penetrating engine. If the engine penetrates the facility roof, a hole approximately 1-2 m in diameter is expected. If the engine penetrates through the door, the entire door area would be opened. The parameters of interest that could control the resulting fire are listed in Table 1. The effect each parameter has on the thermal environment is also indicated. Each of the effects listed ultimately define the thermal hazard presented to stored weapons. The range of parameter variation is also shown to define the limits of the parameter space.

In the postulated scenario, fire products and combustion air share the penetration opening. In a normal mode of operation, bi-directional flow is present in the penetration. Fire products flow out of the enclosure in one region of the opening while combustion air flows in through another region of the opening and the fire progresses in a stable quasi-steady manner. However, it is also possible for the product out flow and combustion air in flow to become unstable producing a "puffing" or breathing mode of operation. The single vent can alternately flow combustion air or products as the facility volume alternately fills with fire products or fresh combustion air. In this regime, the fire progresses in a cyclical manner producing a time varying thermal environment within the enclosure. A stable mode fire would likely yield a short duration, severe thermal environment. A less severe thermal environment, but of longer duration, would likely occur with a breathing mode fire. Conditions that lead to the stable or unstable mode depend both on the penetration size and the location. A large vertical vent in the wall or ceiling is likely to produce a stable bi-directional flow while a small horizontal vent in the wall or ceiling can provoke the unstable flow.

In the present scenario, liquid fuel collects in a pool on the facility floor, ignites and creates a pool fire. The average temperature in the enclosure that develops during the fire depends upon

the heat release rate (HRR) from the fire. The HRR from a pool fire correlates with a number of factors and, in particular, is known to be sensitive to the pool area to pool air-wetted perimeter ratio. The pool area and perimeter are determined by the total quantity of fuel and geometric factors of the facility floor. The minimum quantity of fuel expected is 200 gallons resulting from the rupture of a single ALCM fuel tank. A much larger quantity (1000 gallons or more) could accumulate from aircraft fuel leaking from the wing section associated with the penetrating jet engine. The fuel will collect in the front corner or along one wall since the floors of both the J-row and standard igloos are crowned and slope toward the door. These two pool configurations can be expected to produce different thermal environments. For example, a correlation developed at Sandia predicts an order of magnitude difference in HRR for a 40 ft² pool configured as a quarter circle in a compartment corner (50 MW) compared to a pool with the same surface area configured along a compartment wall with a 27 ft air-wetted perimeter (5 MW). Thus the pool configuration in the enclosure and quantity of fuel are major players in establishing the fire environment.

During an enclosure fire, hot products collect in the upper regions creating a thermally radiating smoke layer that is a major contributor to the average heat flux level in the room. The thermal radiation from the smoke layer is determined by the thickness of the layer and the spatial distribution of temperature within it. Factors which control the smoke layer thickness and temperature distribution, besides the HRR, include the ceiling shape and the presence of clutter in the room. Preliminary runs with the Sandia fire field model, VULCAN, (Nicolette and Gill 1997; Nicolette 1996) indicate that the presence of the curved ceiling shape affects the thermal stratification in the room, ultimately affecting thermal radiation from the upper regions to the rest of the enclosure volume. Clutter in the room can interact with the fire environment by 1) enhancing the mixing of the fuel, air, and combustion products, 2) either blocking or enhancing the thermal radiation to the fuel pool, and 3) providing a local heat sink.

An enclosure fire develops in a predictable manner passing through three distinct phases. In the growth phase, the fire is localized in the vicinity of its origin and the average temperature throughout the enclosure is low. In the fully developed phase that follows, most or all of the combustible material in the enclosure is involved and the HRR is at a maximum. The fire then passes through a decay phase as fuel is consumed and average temperatures begin to fall. The time for the growth phase is typically 2 or 3 minutes, while the duration of the fully developed phase is dependent on the quantity of fuel and pool configuration. The decay phase is typically 1 minute or less for a pool fire, although this can vary if the pool exhibits a variable depth due to geometric factors of the enclosure floor. The possibility of floor cratering due to engine impact could result in unusual recession shape characteristics. The transient cool down period following the fire can be of importance to weapon response. The pool configuration and quantity of fuel therefore establish the fire duration and thus the exposure time of stores in the facility.

There are obviously other parameters that control the behavior of a fire within the enclosure. A high wind condition blowing through an open door could result in an intense high temperature thermal environment due to enhanced mixing within the enclosure. Also, extreme ambient temperatures are known to affect the ignition and progression of pool fires. These parameters are difficult to control and were not included as control parameters in a preliminary test series designed for model validation. However, both wind velocity and ambient temperature were

recorded during the experiments to aid in comparison of the data to model predictions. Furthermore, testing during periods of obvious high wind conditions was avoided.

3.2 The Response Parameters

The relevant response parameters that characterize the thermal environment in an enclosure fire are listed in Table 2. These parameters were selected on the assumption that facility stores are susceptible only to direct thermal attack *via* heat flux and temperature, and are not sensitive to chemical phenomena such as high temperature reduction or oxidation reactions, the production of toxic gases, or the consumption of ambient oxygen. Overpressure of weapon cases due to temperature rise may be of concern, but was not addressed in this study. The parameters are seen to be of three general types; they either describe the thermal environment, directly define the thermal threat, or are involved in a basic process. Each parameter type has its place in model validation.

Thermal radiation from the fire plume and the smoke layer is important in that it is the major heat transfer mechanism both in propagation of the fire from the original source and in defining the threat to any stores within the enclosure. Due to the smoke layer's location in the enclosure, the walls, floor, ceiling, and any object in the enclosure are directly impinged by radiation from the layer. The smoke layer is characterized by both measuring the temperature versus height in the enclosure, and observing the thermal radiation to any point from the half space above. The radiation to the floor level is of particular interest because measurements there respond to the entire layer, if the layer is not optically thick. Instrumentation required for these measurements include thermocouples mounted on towers (or trees) placed about the enclosure and hemispherical heat flux gauges (HFGs) (Gritzo et al. 1995) mounted on the towers and arrayed on the floor.

Stores in the enclosure respond to the radiant heat flux level in the room, which can be both spatial and time dependent (Nakos and Keltner 1989). Convection from the smoke layer can also be an important consideration and further augments the temporal and spatial effect. Characterization of the thermal environment from the stores point of view was accomplished by observing the heat flux absorbed through the surface of a representative calorimeter. For proper interpretation of the response, the calorimeter needed to be of representative size and shape, be in a specified location within the enclosure, and exhibit thermal inertia properties that typify facility stores. Externally mounted HFGs registered the time-temperature response of the object. These signals can be converted to absorbed heat flux *via* post-test data processing (Blackwell et al. 1985).

In the present situation, the fire products and the combustion air share the same opening. The flow in the penetration becomes a significant factor in the progression of the fire. As discussed above, the flow can either alternate as the enclosure volume breathes, or two opposing flows can be set up in the same opening. In either event, proper modeling of the flow in this area is paramount to obtaining valid predictions. The flow in the penetration therefore is an important measurement point for model validation. Flow information was gathered with an array of bi-directional velocity probes (Kent and Schneider 1987).

The fuel consumption rate is also fundamental in determining the HRR and hence the fire environment. The vaporization process from a pool of fuel is not yet fully understood as pointed out in the ongoing work with outdoor pool fires. As such, this process is likely to be the weak point in enclosure fire modeling. Various sub-models ranging from empirical correlations to detailed heat transfer calculations exist. Fuel consumption data, heat flux to the pool, and pool temperatures from this test series may be used to evaluate the different sub-models and contribute to the empirical correlation database. Fuel consumption can be deduced from the time history response of a pool thermocouple comb array deployed to sense fuel level.

3.3 Proposed Test Conditions

A test series should fully exercise the model computational capabilities. A way to accomplish this is to perform experiments at the extremes of the parameter space. The extremes of the parameter space are determined by different combinations of each parameter limit. Bracketing the parameter space identified in Table 1 requires 64 different combinations of parameter limits as shown in Table 3. In Table 3, the minus (-) sign corresponds to the first limit listed in Table 1, and the plus (+) sign is for the second limit. For example, configuration 1 in Table 3 identifies the parameter space extreme at the conditions where: 1) the penetration is located in the ceiling (-), 2) the penetration size is the ceiling hole (-), 3) the pool is configured along the wall (-), 4) the ceiling is curved (-), 5) no clutter is present (-) and, 6) there is 200 gallons of fuel (-).

For validation purposes, configurations 1, 4, 5, 8, 12, 16, 28, and 32 of the control parameters listed (and highlighted) in Table 3 were selected as being the test cases of interest. Configurations 1, 4, 5, and 8 were chosen as being significantly different from any other enclosures found in the literature. They contrast the ventilation and pool configuration for the curved ceiling geometry. Configurations 12 and 16 were chosen to investigate the effect of HRR in conventional flat ceiling geometry with large door openings. The 50 MW HRR in configuration 16 was well beyond any condition found in the literature. Combinations 28 and 32 were selected to contrast the effect of clutter and HRR in the flat ceiling/large door opening configurations.

The other configurations were not considered for validation purposes for the following reasons. The high fuel quantity cases 36 through 64 were discarded as it is believed sufficient data can be generated for validation purposes with a minimum fuel loading.

The pool size and configuration were chosen based on the heat release rate (HRR), after realizing that the fuel quantity was not an issue for validation purposes. The following empirical correlation for HRR (in MW units) as a function of pool dimensional characteristics has been developed from historical open pool fire test data taken at the SNL Lurance Canyon Burn Site (Gill 2000)

$$HRR = 1.73 \left(\frac{A}{P} \right)^{2.63} MW$$

where

A = pool area (ft²)
P = pool air wetted perimeter (ft).

The range of the correlation is from $1 < (A/P) < 10.0$.

For the fires of interest,

A/P = 1.5 ft for a HRR = 5 MW

A/P = 3.6 ft for a HRR = 50 MW.

For a circular pool of diameter D and air available along the full circumference, $A/P = D/4$. For a circular quarter pool lying in a corner of radius R, $A/P = R/2$. For a rectangular pool lying along a wall of dimension L x W and air available only along the length L, $A/P = W$, where W is the pool width. Thus, the possible pool configurations and associated HRRs are:

Configuration	A/P	5 MW	50 MW
Circular Pool	D/4	D = 6.0 ft	D = 14.4 ft
Rectangular Pool	W	W = 1.5 ft	W = 3.6 ft
Corner Pool	R/2	R = 3.0 ft	R = 7.2 ft

The configurations chosen for the experiments were 5 MW and 50 MW using the circular pool, 50 MW using the rectangular pool, and 5 MW using the quarter corner pool.

Certain combinations of penetration location and size were not part of scenarios of interest. Door size penetrations in the ceiling and small diameter penetrations in the wall are not likely to occur, thus eliminating combinations 2, 3, 6, 7, 10, 11, 14, 15, 18, 19, 22, 23, 26, 27, 30 and 31.

Table 4 summarizes the eight proposed experiments as matched to a particular configuration (in parentheses) given in Table 3. The proposed experiments address the three issues discussed at the end of section 2.0. Experiments 1 through 4 represent fires occurring in the standard igloo and provide needed data for the curved ceiling geometry and limited ventilation cases. Experiments 5 through 8 are focused on fires in the J-row facilities and provide needed data for high HRR fires in enclosures.

Table 5 summarizes the nine actual enclosure fire experiments performed in the Igloo building and also shows the relationship to the proposed experiments (in parentheses) given in Table 4. Note that of the eleven tests listed in Table 5, only nine were actually performed and documented.

4. Experiment Hardware and Instrumentation

In Table 2 and Section 3.2, the hardware and instrumentation required to measure the response parameters were presented and discussed. These included thermocouples, HFGs, representative objects and clutter, velocity gauges for vent flows, pool instrumentation, and video cameras. The following sections discuss these items in detail as well as the test facility.

4.1 The Test Facility

These experiments were performed in SNL's Building 9830, a buried igloo structure originally constructed in 1968 as a high explosive test facility and modified in 1978 as a fire test enclosure. The structure interior is approximately 24 ft wide by 54 ft long with an 18.5 ft high arched roof. As can be seen in Figure 1, the building is composed of two rooms of about equal size, an equipment room and a burn room. The rooms are separated by a fireproof wall fitted with a 6 x 8 ft door. The equipment room opens to the outside *via* a 12 wide x 14.6 ft high door. The igloo ceiling is a 12.5 ft radius arch constructed of 10 gage multi-plate galvanized steel arch (~3/16-inch thick with 6 inch by 2 inch corrugation) that is surfaced with a ceramic insulation for thermal protection.

The Building 9830 rests on a reinforced, 6 inch thick concrete slab, has a concrete front wall (with steel doors and jams) and a concrete back wall. The 180° corrugated steel roof sections attach to six foot tall concrete side walls. The front, back, and side wall concrete thickness is 16 inches. A soil berm surrounds and covers the igloo on all sides (except the front wall) with the minimum soil thickness (three feet) found at the roof. The center wall dividing the burn room and the equipment room is constructed using a steel frame, with dry wall on the west side and ceramic plaster on wire mesh facing the east side. The interior wall surfaces and round ceiling were insulated with 1-inch thick Kaowool® Firemaster insulation blanket (6-8 lb/ft³).

The burn room occupies an ~24 ft wide by 26 ft long floor space and features a centrally located vent in the curved ceiling. The original 4-ft diameter circular vent was modified to a 2.8-ft square configuration, with a depth of 4-ft (see Figures 1, 16-18). The burn room was used for those test configurations specifying a ceiling vent. Note that the ceiling vent was modified to a square geometry. The burn room floor was modified in 1978 with the addition of a 0.25 inch thick steel plate placed on a few inch thick compacted sand base. Figure 2 shows the location and configuration of the pools in the burn room experiments. The location of instrumentation such as thermocouple trees, floor HFGs, and representative calorimeters are also indicated. The instrumentation is discussed in the following sections.

The equipment room (~24 ft wide by 28 ft long floor space) was used for the experiment configurations with the full door wall opening and either curved or flat ceilings. Figure 3 shows the location and configuration of the pools as well as the instrumentation. The location of thermocouple trees, the floor HFGs, and two representative objects are also indicated. Table 4 shows that two of the proposed experiments in the equipment room (proposed experiments 2 and 4) utilized the curved ceiling. Figure 4 shows the equipment room layout with a false flat ceiling installed at a height consistent with J-row igloo geometry for the proposed experiments 5

through 8. For the experiments with clutter, objects reminiscent of pylon mounted ALCMs in storage were placed in the center of the room.

Some of the later experiments conducted in the burn room used a flat ceiling. The false flat ceiling was constructed using 0.03-inch thick 304 stainless steel sheets overlapped and spot welded to a 2-inch angle carbon steel frame. Kaowool® Firemaster insulation blanket or board (2-inch thick) was attached to the underside of the steel panels.

4.2 Thermocouples and Thermocouple Trees

All temperature measurements utilized type K thermocouples, 0.063 inch diameter, Inconel sheathed, ultra-pure MgO insulated, with ungrounded junctions. The type K thermocouple has an operating range from 0°C to 1250°C that encompassed expected temperature levels. The 0.063 inch diameter has proven best for field use. Smaller diameters are too fragile and larger diameters are too unwieldy. The Inconel sheath has been found to withstand the fire environment where other materials such as 304 stainless steel have not. Ultra-pure MgO insulation is required to avoid thermal shunting, an insidious problem that appears in long thermocouples routed through multiple zones of high and low temperature (Reed 1982) (Acton et al. 1996). The use of ungrounded junctions with grounded sheathing minimizes electrical noise prevalent in thermocouple circuitry. The response time of these thermocouples in a fire is expected to be on the order of a few seconds. A detailed description of the devices can be found in the Omega Catalog (1992), however, equivalent thermocouples are available from several manufacturers including Thermoelectric, Watlow Gordon, and Omega.

Thermocouples were deployed on trees as depicted in Figure 5. The trees extended from the floor to the ceiling. A thermocouple was placed about every 2 ft, starting from 2 ft off the floor, up to the ceiling. The trees were constructed of steel pipe and covered with thermal insulation blanket.

Data from thermocouples in the smoke layer provide important validation data for the fire models. However, data from the thermocouples are not directly equivalent to media temperatures, which are typically the output of fire models (Gritzo et al. 1996 and Nakos et al. 1991). A thermocouple submodel is being developed for Sandia fire field models that will provide an estimate of the temperature of a thermocouple in a specified location.

4.3 Heat Flux Gauges

The HFG is primarily a thin metal plate with one side facing the fire environment and the other side insulated. The metal plate responds to the heat flux from the half space in front of the exposed face. If it is assumed the plate is in thermal equilibrium with a radiation dominated environment, the plate temperature can: 1) be converted to an incident flux characteristic of the half space, or 2) be interpreted as an effective temperature of the half space. The plate temperature is measured using a thermocouple attached to the insulated face of the metal plate. The response time of the HFG has been experimentally determined to be on the order of about 60 seconds. Details of the construction and the performance of the gauge can be found in Gritzo et al. (1995).

The HFGs were deployed on the thermocouple trees (facing up), the enclosure floor (facing up), and the enclosure walls (facing out). The tree installation is shown in Figure 5, while the arrangement on the walls and floor are shown in Figures 2, 3, and 4. The HFGs were attached to the walls at the 8 ft level at the positions indicated. The data from these gauges can be directly compared with predictions from the fire models. The instruments are arrayed throughout the enclosure so as to allow mapping of heat flux distribution from the floor level up to the near ceiling level.

All HFG temperature data were processed posttest (see Experiment Appendices) to provide an estimate of the instantaneous incident heat flux. The thermal response model used to reduce the HFG data is documented in "Sandia Heat Flux Gauge Thermal Response and Uncertainty Models" (Blanchat et al. 2000). This report, SAND2000-1111, also provides an uncertainty analysis of the thermal response model.

4.4 Representative Calorimeters and Clutter

Two types of representative calorimeters were used. The first was intended to thermally simulate a weapon found in the standard igloo. The weapon calorimeter was constructed of two 10 ft sections of 18 inch nominal diameter, 0.25 inch wall thickness, rolled carbon steel pipe, as shown in Figure 6. The sections, with the ends blocked off with "jelly-rolls" of 12-inch wide Kaowool® Firemaster insulation blanket, were mounted one above the other (6-inches apart) on a metal frame in an orientation mindful of a tandem handling cart. The pipe section appearance was generally an oxidized, sooted, dirty, dark flat color.

HFGs were attached such that the face of the HFG was flush with the outer side of the wall at the midpoint of the pipe sections. Only the HFG faces were mounted on the pipe sections, "jelly-rolls" of 12-inch wide insulation blanket were placed inside the pipe sections behind the gauges faces (the back of the gauges were not used, in contrast to the clutter calorimeter HFG setup discussed below (see Figures 45-48). The remaining interior of each pipe section was empty. The HFGs were oriented at 3 angular positions; top, and two sides of WP-1/WP-3 and bottom and two sides of WP-2/WP-4 as shown in Figure 6.

The second type of representative calorimeter was intended to serve as clutter likely to be found in J-row facilities. The clutter calorimeter was constructed of two sets of 10 ft sections of 18 inch nominal diameter, 0.25 inch wall thickness, rolled carbon steel pipe, (butted together) as shown in Figure 7. The assembly was meant to interact with flow in the enclosure and respond thermally much like ALCMs in storage. However, the physical arrangement was not a precise copy of either the pylon or rotary launcher configurations. This is because it is doubtful a pylon or rotary launcher would be found in any predictable order or state in an actual accident scenario. The clutter calorimeter was to be deployed in the proposed experiments 5 and 6 as shown in Figure 4. The clutter calorimeter was instrumented with thirty-six HFGs which were installed with the back cylinder sections (see Figures 45-48). Note that only the North clutter section was instrumented (see Figures 4 and 7).

4.5 Velocity Gauges and Vent Flow Instrumentation

An approximately 3 x 3 ft square duct was installed in the ceiling vent and instrumented with a square array of bi-directional velocity gauges. The layout of the ceiling gauges is shown in Figure 8. The square geometry was chosen to facilitate comparisons with VULCAN predictions that utilize a Cartesian grid. Preliminary runs with VULCAN indicated that any bi-directional flow mode in the ceiling duct is likely to involve the corners, with the inflowing air confined to a single corner with the outflowing fire products occupying the rest of the channel. A similar rectangular array of the 25 door velocity gauges was deployed in the facility door opening (12' wide by 14' tall) since VULCAN simulations indicated significant variation in incoming air velocity across the opening. The layout of the door velocity gauges is shown in Figure 9.

The bi-directional velocity gauge is composed of a 2-inch long, 1-inch OD, cylindrical metal body fitted with a differential pressure gauge and a thermocouple. The axis of the cylindrical body was oriented normal to the facility door penetration. The probes are relatively insensitive to wind angle within 45 degrees orientation of the probe axis. The pressure gauge sensed the difference in pressure on the upstream and downstream ends (flow direction was not measured). The 1/16-inch sheathed ungrounded thermocouple, suspended inside two cylindrical radiation shields with an axis also oriented along the direction of flow, was located close to the differential pressure gauge body and was used to determine the gas density. The thermocouple radiation shield was fabricated using 0.01-inch thick 304 stainless steel (outer cylinder 2.75 inch OD, inner cylinder 1.0 inch OD, 6-inch length). The pressure gauge voltage and the thermocouple readings were processed posttest to give gas velocity (units of m/s) as a function of time following the procedures and calibrations given in Kent and Schneider (1987)

$$Velocity = \frac{1}{1.05} \sqrt{2 \frac{\Delta P}{\rho}} \quad (1)$$

where

$$\begin{aligned} \Delta P &= \text{gauge constant x voltage reading} = 2.403 \times \text{volts} \\ \rho &= \text{air density (kg/m}^3\text{)} \\ 1.05 &= \text{probe calibration constant.} \end{aligned}$$

Details for the bi-directional velocity gauge data reduction scheme including an error analysis is given in Appendix A. The error analysis determined large errors are expected for computed velocities less than 1 m/s, mostly due to the uncertainty of measuring a very small differential pressure. These errors reduce to about 15% of the calculated velocity when the velocity increases to about 5 m/s. The velocity data from the ceiling duct and full door can be directly compared with modeling predictions. Video data taken of the duct exit and door can be used to corroborate the velocity direction information and the presence of the stable or unstable flow modes.

4.6 Fuel Pool Instrumentation

The fuel pools were fitted with thermocouple combs at the geometric center of the pools to measure in-depth temperatures in the fuel during the burn. The response of the in-depth thermocouples can be used to deduce the fuel consumption rate. The data from the in-depth thermocouples can be incorporated into the data base for the fuel recession submodel that is under development. Figure 10 shows a schematic of the thermocouple comb.

4.7 Video Cameras

Video cameras were used to record the smoke layer level as the fires progressed. For the experiments in the burn room, cameras were placed in the equipment room viewing the fire through a quartz window in the wall between the burn room and equipment room. For the fires in the equipment room, cameras were placed outside looking in the door. The arms on the thermocouple trees were used as stadia indicators for level determination. Two cameras were placed facing opposite corners on the ceiling duct exit to record the flow regime mode in the ceiling vent fires. For the fires in the equipment room, the main door was viewed with a camera to determine the height of the point separating the inflow and outflow. The sides of the door were marked to facilitate the measurement. Still photos were also taken to record these fires and also to record the instrumentation setup. Figures 11 through 53 show these instrumentation setups and fires.

4.8 Data Acquisition

The data acquisition system had the capability to acquire type K thermocouple signals as well as high level voltage signals from devices such as pressure gauges, weather monitors and the like. A summary of the data channels is shown in Table 6. The data was sampled at 10 second intervals beginning at least 2 minutes before ignition of the fuel and continuing for up to 30 minutes after the fire burned out. The data was stored in ASCII format on a 3.5 inch floppy disk suitable for importing into a PC or UNIX-based machine software application.

The integrity of all thermocouple channels was evaluated prior to each experiment with an Ectron thermocouple simulator. The simulator inputs a controlled signal into each channel at the thermocouple device connection point and provides a check on the integrity of the channel hardware and software from that point to the final magnetic storage location. The thermocouple simulators are calibrated yearly in the SNL Standards Lab that ties back to a National Institute of Standards Technology (NIST) standard.

The data acquisition system was protected from power failure by an uninterruptible power supply (UPS). The UPS is capable of sustaining data acquisition for up to 17 hours without commercial power.

4.9 Measurement Error and Uncertainty

The maximum type-K thermocouple error using the manufacturer's calibration is $\pm 9.4^{\circ}\text{C}$ at 1250°C . It is possible in some cases for considerable temperature measurement error to occur

(Gill 1999). This error is caused by thermal shunting (the creation of false junctions due to TC insulation breakdown) in overheated sheath and insulation sections in the assembly. Large TC errors are noticeable near the end of Igloo Experiment #10; a very intense fire yielding room and structure temperatures well in excess of 1200°C.

An experiment was performed to determine the temperature response SNL's heat flux gage (HFG) used extensively in fire experiments (Blanchat and Verner 1998). The experimental setup was essentially a heat flux measurement at the exit of a cylindrical steel shroud that was heated to 1000°C. Four Hy-Cal Gardon gages measured the heat flux at the same location as the Sandia HFG. The experimental analyses determined that applying a simple thermal response model to the SNL HFG data yields calculated incident heat fluxes within about 5% of measured values, provided the input flux is steady. However, the early time results may be in considerable error. A report (SAND2000-1111) entitled "Sandia Heat Flux Gauge Thermal Response and Uncertainty Models" describes the SNL HFG data reduction scheme and the associated error analysis.

The door and ceiling vent velocity probe array utilized a bi-directional velocity pitot-tube probe designed for measurement in large fires (Kent and Schneider 1987) attached to a Micro Differential Pressure (DP) Sensor. These sensors, manufactured by Cambridge Accusense, Inc., were specified to measure a differential pressure up to 0.05 inches of water column, with a $\pm 4\%$ of full scale accuracy and a 100 msec response time. They were not capable at distinguishing flow direction. The DP sensors were attached to the velocity probes with long runs of tubing. The smallest tube ID was 0.17-inch and the tubing length varied, 17 ft to 44 ft depending on the probe location. The pressure sensors were found to be extremely sensitive to ambient temperature change (causing output baseline voltage drift). Therefore, they were housed in an air-conditioned box after Igloo experiment #2.

According to Kent and Schneider (1987), small fluctuations in the measured pressure differences caused a large uncertainty in the probe calibration constant (see Equation 4) at low Reynolds numbers (~ 600 or less). A Reynolds number of 600 corresponds to an air velocity of about 0.6 m/s at 100°C or about 1.1 m/s at 1000°C. Large measurement errors were expected in those experiments that produced small velocities. Temperatures measured near the flame boundary are expected to be biased by radiation effects. Well within the flames the thermocouples will not be affected by radiation losses to the ambient. These effects should be noted since the density used in the calculation of velocities is based on the measured temperatures. Another assumption is that the combustion products have the same density as air. Another consideration is that the thermocouples have time constants on the order of 1 to 5 seconds, depending on the local gas velocities and temperatures. This is slow in comparison to the response of the pitot tubes. See Appendix A detailing the bi-directional velocity gauge data reduction scheme and the associated error analysis.

5. Experiment Conduct and Results

As anticipated, minor variations in configuration occurred between those experiments proposed in Table 4 and the actual experiments that were conducted and summarized in Table 5. Note that a test having the conditions of proposed Experiment 6 was not performed, after seeing the extensive damage that occurred in Experiment 10 (proposed Experiment 8). All of the experiment data are plotted in separate appendices (B-J). Note that no data is provided for experiment 4 and experiment 8. Experiment 4 was a brief demonstration test and experiment 8 was not performed; however, the test numbers (and separate appendices) are maintained for historical and archival purposes. Each appendix includes time-temperature plots of the tower thermocouples, the pool thermocouples, the weapon or clutter calorimeter thermocouples, the tower HFGs, the floor HFGs, the wall HFGs, and the velocity probe thermocouples. Note that ambient temperature conditions can be obtained from the first few minutes of each temperature plot. The HFG data were reduced to provide time-heat flux plots of the tower, floor, wall, and the weapon or clutter calorimeter. The differential pressure gauge data were reduced to provide time-velocity plots of the flow at the ceiling or door openings. Ambient wind speed and direction plots are also given.

All of the experiment data is provided to DTRA on the included CD ROM as an Excel program with embedded Visual Basic macros. The Excel Workbook provides a convenient interface for navigating the IGLOO experiment data sets. The raw data is stored and organized on each "DATA" worksheet in collapsible outline form. There is a convenient dialog macro called AUTOPLOT that can be accessed from the IGLOO drop-down menu. This Macro allows the user to either view pre-defined plots of thermocouple or velocity data sets plotted for the full time range or to create customized plots for user selected parameters. Most of the figures in the appendices were made using this Excel Workbook.

The CD ROM also contains a PC compatible LabView executable program. This program will "playback" each experiment at either real-time or some scaled time speed. This allows the user to review multiple data fields simultaneously as if participating in the actual experiment. Figure 54 provides a sample preview of the playback from Igloo experiment #3. Some of the movies taken with the video camera were digitized and can be viewed while simultaneously accessing the LabView data playback program. The Excel and LabView programs are intended to provide a user-friendly archival database in support of model validation efforts.

The digitized movies can also be viewed with a standalone MPEG viewer, such as Windows Media Player. Table 7 lists the movies on the CD. The label convention for each movie file is test name, followed by camera view, followed by start of video correlated to the start of the fire.

The average heat release rate (HRR) for the experiments is given in Table 8. First, the fuel recession rate was calculated by dividing the fuel pool thermocouple spacing (1.28 mm) by the flame arrival time (determined when the thermocouple first reached 180°C) between successive thermocouples. Fuel consumption rate was then calculated by multiplying the fuel recession by the pan area and the fuel density (808 kg/m³). The heat release rate was finally calculated by multiplying the fuel consumption rate by the JP-8 heat of combustion (43.2 MJ/kg). An average

was computed if the successive thermocouple results were similar. The HRR for the fires in the air-starved burn room were quite small, on the order of a few tenths of a MW. In the equipment room with the fully open front door, the HRR was clearly a function of the pan area; the small and large pans yielded HRRs on the order of 5 MW and 50 MW, respectively. Note that two averages are calculated for Test 5 and Test 6, since the fuel consumption at the beginning of those tests was much greater than near the end. It is suspected that boiling of the underlying water layer decreased the HRR in those tests.

The following sections briefly describe the conduct and results of each enclosure fire.

5.1 Experiment 1

Experiment 1 (Configuration 1) was performed in the burn room on June 2, 1997. The door between the equipment room and the burn room was closed; the only intentional room ventilation was *via* the ceiling exit hole. Two weapon calorimeters were placed in the burn room. The 1-m radius corner pool (1/4 of a circle) contained about 3 inches of JP-8 fuel (~16 gallons) on 1 inch of water. The fuel was ignited at about $t = 75$ minutes and the fire burned out at about $t = 210$ minutes. The fire was relatively small and cool, indicated by a long burn time and room temperatures no greater than 250°C. The fire burned hotter during the first 40 minutes as compared to the later 90 minutes. Opening the door at about $t = 210$ minutes increased the fire intensity near the completion of the burn. Ambient wind speed and direction were not recorded in Experiment 1. All experiment data and reduced data for Experiment 1 are attached in Appendix B. The equipment room filled quickly with smoke during Experiments 1 through 3; the videos taken through the quartz windows yielded little information. Light smoke issued from the ceiling vent and was not captured well with the video camera.

The ceiling vent provided the only intentional room ventilation. However, there were other potential leak paths. These included ceiling to wall joints, the walk through door jams, plumbing and instrument wall feed-throughs, and window seals. Sealing of all potential leak paths was addressed; however, it is certain that some leakage existed.

The ambient wind velocity and direction anemometer was mounted on a 5-ft tall pole located on top of the burn room for Experiments 1, 2, and 3. The burn room ceiling vent extends about 1-ft above ground, shown in Figure 16. The 2-ft wide by 3-ft tall insulated box containing the vent velocity probe array differential pressure transducers may have presented a possible obstruction to the ambient wind flow over the vent. This box, located on the west side of the vent, is also shown in Figure 16.

5.2 Experiment 2

Experiment 2 (Configuration 1) was performed in the burn room on June 17, 1997. This experiment was essentially a replicate of Experiment 1. The door between the equipment room and the burn room was closed; the only intentional room ventilation was *via* the ceiling exit hole. Two weapon calorimeters were placed in the burn room. The 1-m radius corner pool (1/4 of a circle) contained about 3 inches of JP-8 fuel (~16 gallons) on 1 inch of water. The fuel was ignited at about $t = 114$ minutes. Even though the camera view was obscured (either due to

smoke or sooting of the window), the fire behavior could be determined somewhat by the change in "orange glow" at the window. The following is a brief synopsis of the video. At $t = 114$ min., all preparations were completed and the door was shut. The fire was fully developed at $t = 116$ min. but either smoke filled the room or the fire died down at $t = 118$ min. Between 144 and 152 min. there was visual evidence of a flare-up. This was repeated at $t = 159$ -162 min. and $t = 176$ -178 min. At $t = 189$ min., the fire appeared to get stronger and then settled to a low, steady flame. The fire burned out at about $t = 318$ minutes.

As in Experiment 1, the fire was relatively small and cool, indicated by a long burn time and room temperatures no greater than 250°C . All experiment data and reduced data for Experiment 2 are attached in Appendix C.

Oxygen concentration in the burn room was measured by dropping a probe into the exhaust vent (see Figure 16). The probe extended a few feet below the ceiling. Data logged by hand is presented at the end of Appendix C as plots of oxygen concentration (taken every 5 minutes) versus temperatures (taken every 10 s). Note that the oxygen plots assume a constant value until the next data point (this made more sense, just connecting the dots seemed to skew the data due to the virtual time response, i.e., manual data logger). The data shows that the oxygen concentration gradually decreased during the initial burn but rose quite dramatically when the fire died down during each room breath-in period (at 138, 153, and 168 minutes).

5.3 Experiment 3

Experiment 3 (Configuration 5) was performed in the burn room on July 9, 1997. This was the last experiment performed in the burn room. The door between the equipment room and the burn room was closed; the only intentional room ventilation was *via* the ceiling exit hole. Two weapon calorimeters were placed in the burn room. The long pool was placed along the entire south wall. The long pool (24 ft x 43 in) contained about 1 inch of JP-8 fuel (53.6 gallons) on 2 inches of water. The fuel was ignited at about $t = 140$ minutes and the fire burned out at $t = 540$ minutes. A very distinct "puffing" mode developed in Experiment 3. The fire appeared to burn strong and consume most of the oxygen in the room in a few minutes; this was followed by a long period where the fire would die down. The puffing occurred regularly at about 29 minute intervals. Many of the top tower thermocouples near the fire reached 500°C during the momentary puffs.

The following is a brief synopsis of the video. At $t = 135$ min., all preparations were completed and the door was shut. The fire was fully developed at $t = 145$ min. but either smoke filled the room or the fire died down at $t = 147$ min. Visual evidence of flare-ups occurred at $t = 165$ -168 min., $t = 190$ -193 min., $t = 215$ -217 min., and $t = 243$ -344 min.

All experiment data and reduced data for Experiment 3 are attached in Appendix D. Observers stationed at the ceiling vent exhaust stated that outward hot-air (with little visible smoke) flow was evident during the puffs; however, they could not determine where inward flow (if any) occurred during the quiescent intervals.

5.4 Experiment 4

Experiment 4 was for demonstration purposes only and did not match any proposed test configuration.

5.5 Experiment 5

Experiment 5 (Configuration 8) was performed in the equipment room on September 30, 1997. This was the first experiment performed in the equipment room. The door between the equipment room and the burn room was closed; the only room ventilation was *via* the equipment room doors (wide open). Two weapon calorimeters were placed in the equipment burn room. The 1-m radius corner pool (southwest corner, 1/4 of a circle) contained about 2.5-3 inches of JP-8 fuel (13-16 gallons) on 1 inch of water. The fuel was ignited at about $t = 24$ minutes and the fire burned out at $t = 78$ minutes. This fire yielded a strong burn during the initial 15 minutes, followed by a quiescent period with a strong burn at the end. The increase in fire intensity near the completion of the burn may be caused by water boiling and interacting vigorously with the remaining thin film of burning fuel. The following is a brief synopsis of the videos. Fuel ignition occurred at $t = 24.2$ min. and fire was fully developed at $t = 26$ min., with smoke exiting the front door. A fairly steady column of pulsating flame licked the room corner from above the pan to the ceiling. The fire became less intense at about $t = 40$ min and remained very small. Just before the fire died out, a vigorous flame column initiated at about $t = 72$ min. and lasted about 5 min. All experiment data and reduced data for Experiment 5 are attached in Appendix E.

For Experiment 5 and the remainder of the experiments, the ambient wind velocity and direction anemometer was mounted on top of the instrument trailer (50-ft out, 26-ft south, and 18-ft high from the outside bottom center of the igloo front door, see Figure 51).

5.6 Experiment 6

Experiment 6 (Configuration 4) was performed in the equipment room on September 30, 1997. The door between the equipment room and the burn room was closed; the only room ventilation was *via* the equipment room doors (wide open). Two weapon calorimeters were placed in the equipment burn room. The long pool (24 ft x 43 in) contained about 3 inches of JP-8 fuel (161 gallons) on 1 inch of water. The fuel was ignited at about $t = 15$ minutes and the fire burned out at $t = 50$ minutes. The fire became quite hot; temperature near the ceiling approached 1200°C. This fire also showed behavior similar to Experiment 5; a strong burning during the initial 15 minutes, followed by a quiescent period with a strong burn at the end.

The following is a brief synopsis of the videos. Fuel ignition occurred at $t = 15$ min. and a very large fire was fully developed at $t = 16$ min. The entire ceiling area (not just above the pan) appeared to fill with flame, possibly due to ignition of vaporized fuel and/or combustion gases. Flames and smoke filled the upper half of the room and vigorously exited from the upper half of the door opening. Loud crackling noises due to concrete spallation were heard. At $t = 26$ min., the fire became somewhat calmer, with flames heights of about six feet (above the pan) and generating lighter smoke levels. Combustion of gases near the ceiling ceased. The fire became

much stronger at $t = 42$ min. (possibly due to water interactions), generating lots of smoke and reigniting ceiling gases at $t = 48$ min. The fire started to die down at $t = 50$ min. and was completely out at $t = 54$ min. A visual inspection of the pan revealed a dry pan (no water) immediately after the experiment. Note that at the completion of all previous experiments, water was found remaining in the pans. All experiment data and reduced data for Experiment 6 are attached in Appendix F.

5.7 Experiment 7

Experiment 7 (Configuration 8) was performed in the equipment room on October 7, 1997. This experiment was a replicate of Experiment 5 except that no water was used in the fuel pan (note that no water was used in any of the following experiments). The door between the equipment room and the burn room was closed; the only room ventilation was *via* the equipment room doors (wide open). Two weapon calorimeters were placed in the equipment burn room. The 1-m radius corner pool (southwest corner, 1/4 of a circle) contained 4 inches of JP-8 fuel (21 gallons) utilizing no water with the fuel resting directly on the steel surface of the pan. The fuel was ignited at about $t = 16$ minutes and the fire burned out at $t = 40$ minutes. The behavior was quite different from Experiment 5. The fire burned faster, and there was no quiescent period followed by a strong end burn. This suggests that the water can affect the fire behavior.

The following is a brief synopsis of the videos. Fuel ignition occurred at $t = 16.3$ min. and fire was fully developed at $t = 17$ min., with smoke exiting the front door. A fairly steady column of pulsating flame licked the room corner from above the pan to the ceiling between $t = 18$ -28 min. The wind was quite strong into the door, appearing to momentarily cause smoke holdup at the door. In this experiment, a camera was also located inside the room, setup near the NE corner floor. This camera had a good view of the pan, showing a steady fire with flames about 6 feet above the pan. Also, the smoke layer inside the room appeared very steady and attached to the ceiling (the view was very clear from the floor to within a few ft. of the ceiling). All experiment data and reduced data for Experiment 7 are attached in Appendix G.

5.8 Experiment 8

Experiment 8 (Configuration 32) was not performed, based on the experiences of Test 10 (Configuration 12). Test 10 produced a very severe fire that damaged the facility (destroyed the false flat ceiling and much instrumentation). The only difference between the two tests would have been the inclusion of the clutter calorimeter in experiment 8, believed to have little effect on this size of fire.

5.9 Experiment 9

Experiment 9 (Configuration 16) was performed in the equipment room on November 26, 1997. A flat ceiling was used. All previous experiments utilized the curved ceiling geometry. The door between the equipment room and the burn room was closed; the only room ventilation was *via* the equipment room doors (wide open). No calorimeters were utilized. The 5 MW pool (6-foot diameter) was located near the middle and back of the equipment room, resting inside the larger 15-foot diameter pan. The circular pool (full circle) contained 3.6 inches of JP-8 fuel (63

gallons) utilizing no water with the fuel resting directly on the steel surface of the pan. The fuel was ignited at about $t = 41$ minutes and the fire burned out at $t = 66$ minutes. Temperatures near the ceiling averaged 700-800°C. There was no quiescent period followed by a strong end burn.

The following is a brief synopsis of the videos. Fuel ignition occurred at $t = 40.2$ min. and fire was fully developed at $t = 42$ min. The wind was quite strong from a direction out of the door. At $t = 54$ min., the fire appeared to spread into the large pan. It was noted that the large pan became warped and lifted off the ground on one side, possibly dumping liquid fuel or vaporized fuel from the small pan into the larger pan, this yielding a larger fire. The timing coincides with an increase in the LP-P6 fuel thermocouple temperature (to be expected if the thermocouple becomes uncovered) and various tower thermocouple temperatures. The fire started to die down at $t = 63$ min. All experiment data and reduced data for Experiment 9 are attached in Appendix H.

5.10 Experiment 10

Experiment 10 (Configuration 12) was performed in the equipment room on December 9, 1997. A flat ceiling was used. The door between the equipment room and the burn room was closed; the only room ventilation was *via* the equipment room doors (wide open). No calorimeters were utilized. The 50 MW pool (15-foot diameter) was located near the middle and back of the equipment room. The circular pool (full circle) contained 2.75 inches of JP-8 fuel (303 gallons) utilizing no water with the fuel resting directly on the steel surface of the pan. The fuel was ignited at about $t = 24$ minutes and the fire burned out at $t = 38$ minutes. This configuration produced the most intense fire of all the experiments. Temperatures near the ceiling averaged 1300°C. Some of the tower thermocouples, HFGs, and velocity probes were damaged.

The following is a brief synopsis of the videos. The wind was from 270° and strong, almost directly into the door opening (note that Figure 1 shows the door opening facing 245°). Fuel ignition occurred at $t = 16$ min. and fire became fully developed at $t = 24$ min. Immediately, the entire ceiling area (not just above the pan) appeared to fill with flame, possibly due to ignition of vaporized fuel and/or combustion gases (as in Experiment 6). Flames and smoke filled the upper part of the room and vigorously exited from the upper half of the door opening. Loud crackling noises due to concrete spallation were heard. Some of the thermocouple radiation shields (on the door velocity probe array) moved downward due to failure of their supporting wires. The flat ceiling failed between $t = 34$ -36 min. There are indications that the fire became more intense after the ceiling failed, numerous tower thermocouples failed at this time and also increased temperatures were seen on the floor HFGs. At $t = 39$ min., the height of the fire above the pan reduced and ignition of ceiling gases ceased. The fire burned low above the pan until about $t = 54$ min, when it died. All experiment data and reduced data for Experiment 10 are attached in Appendix I.

5.11 Experiment 11

Experiment 11 (Configuration 28) was performed in the equipment room on October 6, 1998. A flat ceiling was used. The door between the equipment room and the burn room was closed; the only room ventilation was *via* the equipment room doors (wide open). The clutter calorimeter

was used for the first time, located between the open door and the fire pan. The 5 MW pool (6-foot diameter) was located near the middle of the equipment room. The circular pool (full circle) contained about 2.5 inches of JP-8 fuel (54 gallons) utilizing no water with the fuel resting directly on the steel surface of the pan. Note that about 11 gallons of fuel was needed to level and fully wet the pan surface. The final fuel surface was just below the P3 pool thermocouple.

The following is a brief synopsis of the videos. The wind was light and variable from 120°, almost directly away from the door opening. Fuel ignition occurred at $t = 2$ min. and the fire became fully developed at $t = 4$ min. The fire rose straight above the pan and did not come forward and touch the clutter calorimeter. Thick black smoke filled the room from about mid-height to the ceiling. The top four pipes on the clutter became heavily sooted. Prior to the experiment, string was hung on each velocity probe to provide a visual telltale of the air direction. It was clearly evident that a steady air flow occurred into the room at the third and fourth probe levels (Probes 11-20). Little flow occurred on the bottom level except for a small in-flow seen near the north corner (Probe 21). The telltales on the top two levels were mostly obscured by the strong outflow of turbulent puffing smoke. The fire started to die down at about $t = 23$ min., indicated by reduced flame height, a lessening of the smoke leaving the door opening, and little or no flow seen on the velocity probe telltales.

All experiment data and reduced data for Experiment 11 are attached in Appendix J. Also, a combustible gas analyzer was used for the first time in Experiment 11. The gas sample was continuously taken throughout the experiment, close to the top tower T8-3 thermocouple, near the ceiling and door opening (see Figure 43). Appendix J shows that oxygen concentration decreased and carbon monoxide and carbon dioxide concentrations increased during the fire.

6. Conclusions

Nine full-scale enclosure fire experiments were conducted at SNL's Lurance Canyon Burn Site in the Building 9830 "Igloo" Facility by SNL for DTRA. These experiments were conducted over a period from August 7, 1997 to October 6, 1998. The purpose of the test series was to provide data to validate compartment fire models that are being developed to predict the abnormal thermal environment in a storage facility/aircraft accident situation. The models, in turn, are to be used to assess the thermal hazard posed to stored weapons within the facility. This report provides a complete description of the nine enclosure fire experiments and includes plots of temperature, heat flux, exit velocity, and ambient wind data.

This report was written specifically with the end-user, the fire analyst, in mind. All of the experiment data is available on a CD ROM in two formats. First, an Excel program with embedded Visual Basic macros provides a convenient interface for navigating the IGLOO experiment data sets. The user can either view pre-defined plots of thermocouple, heat flux, or velocity data sets plotted for the full time range or create customized plots for user selected parameters. Most of the figures in the appendices were made using this Excel program.

The CD ROM also contains a PC compatible LabView executable program that allows the analyst to review multiple data fields simultaneously as if participating in the actual experiment. Some of the movies taken with the video camera were digitized and can be viewed while simultaneously accessing the LabView data playback program. The Excel and LabView programs are intended to provide a user-friendly archival database in support of model validation efforts.

7. References

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Table 1. Control Parameters.

Control Parameter	Major Effect	(-) Limits (+)
Penetration location	Stability	Ceiling - Side
Penetration size	Ventilation	Hole - Full door
Fuel pool configuration	Heat release rate (HRR)	Along wall - Corner
Enclosure ceiling geometry	Average heat flux level	Curved - Flat
Clutter	Temperature distribution	Not present - Present
Fuel quantity	Burn time	200 gal - 1000 gal

Table 2. Response Parameters.

Response Parameter	Parameter Type	Expected Level	Instrumentation
Smoke layer temperature distribution	Characteristic of the environment	800°C within 1 m of the floor	Thermocouple tree with thermocouples and Hemispherical Heat Flux Gauges (HFG)
Heat flux to floor and walls	Characteristic of the environment	70 kW/m ²	HFG array on floor
Heat flux to an object	Defines threat to facility stores	30 to 150 kW/m ²	Thick wall calorimeters integrated into the representative object
Flow in penetration	Basic process that ties to the model	1 m/sec in 3 m/sec out	Bi-directional velocity gauges
Fuel Consumption Rate	Basic process that ties to the model	0.12 to 1.16 kg/sec 5 MW to 50 MW	Thermocouple comb gauge for pool level

Table 3. Test Configurations and Control Parameter Space Extremes.

Configuration	Penetration Location	Penetration Size	Pool Configuration	Ceiling Geometry	Clutter	Fuel Quantity
1	-	-	-	-	-	-
2	+	-	-	-	-	-
3	-	+	-	-	-	-
4	+	+	-	-	-	-
5	-	-	+	-	-	-
6	+	-	+	-	-	-
7	-	+	+	-	-	-
8	+	+	+	-	-	-
9	-	-	-	+	-	-
10	+	-	-	+	-	-
11	-	+	-	+	-	-
12	+	+	-	+	-	-
13	-	-	+	+	-	-
14	+	-	+	+	-	-
15	-	+	+	+	-	-
16	+	+	+	+	-	-
17	-	-	-	-	+	-
18	+	-	-	-	+	-
19	-	+	-	-	+	-
20	+	+	-	-	+	-
21	-	-	+	-	+	-
22	+	-	+	-	+	-
23	-	+	+	-	+	-
24	+	+	+	-	+	-
25	-	-	-	+	+	-
26	+	-	-	+	+	-
27	-	+	-	+	+	-
28	+	+	-	+	+	-
29	-	-	+	+	+	-
30	+	-	+	+	+	-
31	-	+	+	+	+	-
32	+	+	+	+	+	-
	- = ceiling + = side	- = hole + = door	- = wall + = corner	- = curved + = flat	- = no + = yes	- = 200 + = 1000

Table 3. Test Configurations and Control Parameter Space Extremes (concluded).

Configuration	Penetration Location	Penetration Size	Pool Configuration	Ceiling Geometry	Clutter	Fuel Quantity
33	-	-	-	-	-	+
34	+	-	-	-	-	+
35	-	+	-	-	-	+
36	+	+	-	-	-	+
37	-	-	+	-	-	+
38	+	-	+	-	-	+
39	-	+	+	-	-	+
40	+	+	+	-	-	+
41	-	-	-	+	-	+
42	+	-	-	+	-	+
43	-	+	-	+	-	+
44	+	+	-	+	-	+
45	-	-	+	+	-	+
46	+	-	+	+	-	+
47	-	+	+	+	-	+
48	+	+	+	+	-	+
49	-	-	-	-	+	+
50	+	-	-	-	+	+
51	-	+	-	-	+	+
52	+	+	-	-	+	+
53	-	-	+	-	+	+
54	+	-	+	-	+	+
55	-	+	+	-	+	+
56	+	+	+	-	+	+
57	-	-	-	+	+	+
58	+	-	-	+	+	+
59	-	+	-	+	+	+
60	+	+	-	+	+	+
61	-	-	+	+	+	+
62	+	-	+	+	+	+
63	-	+	+	+	+	+
64	+	+	+	+	+	+
	- = ceiling + = side	- = hole + = door	- = wall + = corner	- = curved + = flat	- = no + = yes	- = 200 + = 1000

Table 4. Proposed Experiment Conditions.

Proposed Experiment (Configuration)	Penetration Location and Size	Ceiling Geometry	Fuel Pool Configuration	Clutter Calorimeter
1 (1)	Ceiling-Hole	Curved	Along Wall	No
2 (4)	Wall-Open Door	Curved	Along Wall	No
3 (5)	Ceiling-Hole	Curved	Corner	No
4 (8)	Wall-Open Door	Curved	Corner	No
5 (28)	Wall-Open Door	Flat	5 MW	Yes
6 (32)	Wall-Open Door	Flat	50 MW	Yes
7 (16)	Wall-Open Door	Flat	5 MW	No
8 (12)	Wall-Open Door	Flat	50 MW	No

Table 5. Actual Experiment Conditions.

Actual Experiment (Proposed)	Room, Penetration Location and Size	Ceiling Geometry	Fuel Location and Quantity	Weapon Calorimeter	Clutter Calorimeter
1 (1)	Burn Ceiling-Hole	Curved	Corner 16 gal with H ₂ O	Yes	No
2 (1)	Burn Ceiling-Hole	Curved	Corner 16 gal with H ₂ O	Yes	No
3 (3)	Burn Ceiling-Hole	Curved	Long Pool 53.6 gal with H ₂ O	Yes	No
4	DEMONSTRATION EXPERIMENT, NOT DOCUMENTED				
5 (4)	Equipment Wall-Open Door	Curved	Corner 16 gal with H ₂ O	Yes	No
6 (2)	Equipment Wall-Open Door	Curved	Long Pool 161 gal with H ₂ O	Yes	No
7 (4)	Equipment Wall-Open Door	Curved	Corner 21 gal without H ₂ O	Yes	No
8 (6)	EXPERIMENT NOT CONDUCTED				
9 (7)	Equipment Wall-Open Door	Flat	Circle Pool (6 ft dia.) 5 MW 63 gal without H ₂ O	No	No
10 (8)	Equipment Wall-Open Door	Flat	Circle Pool (15 ft dia.) 50 MW 303 gal without H ₂ O	No	No
11 (5)	Equipment Wall-Open Door	Flat	Circle Pool (6 ft dia.) 5 MW 54 gal without H ₂ O	No	Yes

Table 6. Instrument Summary.

DAS1 #	ID	Instrument Name	DAS1 #	ID	Instrument Name
1	T1-1	tower flame temp	41	T5-8	tower flame temp
2	T1-2	tower flame temp	42	T5-9	tower flame temp
3	T1-3	tower flame temp	43	T6-1	tower flame temp
4	T1-4	tower flame temp	44	T6-2	tower flame temp
5	T1-5	tower flame temp	45	T6-3	tower flame temp
6	T1-6	tower flame temp	46	T6-4	tower flame temp
7	T1-7	tower flame temp	47	T6-5	tower flame temp
8	T1-8	tower flame temp	48	T6-6	tower flame temp
9	T2-1	tower flame temp	49	T6-7	tower flame temp
10	T2-2	tower flame temp	50	T6-8	tower flame temp
11	T2-3	tower flame temp	51	T7-1	tower flame temp
12	T2-4	tower flame temp	52	T7-2	tower flame temp
13	T2-5	tower flame temp	53	T7-3	tower flame temp
14	T2-6	tower flame temp	54	T7-4	tower flame temp
15	T2-7	tower flame temp	55	T7-5	tower flame temp
16	T2-8	tower flame temp	56	T7-6	tower flame temp
17	T2-9	tower flame temp	57	T7-7	tower flame temp
18	T3-1	tower flame temp	58	T7-8	tower flame temp
19	T3-2	tower flame temp	59	T8-1	tower flame temp
20	T3-3	tower flame temp	60	T8-2	tower flame temp
21	T3-4	tower flame temp	61	T8-3	tower flame temp
22	T3-5	tower flame temp	62	T8-4	tower flame temp
23	T3-6	tower flame temp	63	T8-5	tower flame temp
24	T3-7	tower flame temp	64	T8-6	tower flame temp
25	T3-8	tower flame temp	65	T8-7	tower flame temp
26	T4-1	tower flame temp	66	T8-8	tower flame temp
27	T4-2	tower flame temp	67	T8-9	tower flame temp
28	T4-3	tower flame temp	68	T9-1	tower flame temp
29	T4-4	tower flame temp	69	T9-2	tower flame temp
30	T4-5	tower flame temp	70	T9-3	tower flame temp
31	T4-6	tower flame temp	71	T9-4	tower flame temp
32	T4-7	tower flame temp	72	T9-5	tower flame temp
33	T4-8	tower flame temp	73	T9-6	tower flame temp
34	T5-1	tower flame temp	74	T9-7	tower flame temp
35	T5-2	tower flame temp	75	T9-8	tower flame temp
36	T5-3	tower flame temp			
37	T5-4	tower flame temp			
38	T5-5	tower flame temp			
39	T5-6	tower flame temp			
40	T5-7	tower flame temp			

Table 6. Instrument Summary (continued).

DASI #	ID	Instrument Name	DASI #	ID	Instrument Name
76	T1-HFG-1	tower heat flux	117	HFG-W1	wall heat flux
77	T1-HFG-2	tower heat flux	118	HFG-W2	wall heat flux
78	T2-HFG-1	tower heat flux	119	HFG-W3	wall heat flux
79	T2-HFG-2	tower heat flux	120	HFG-W4	wall heat flux
80	T3-HFG-1	tower heat flux	121	HFG-W5	wall heat flux
81	T3-HFG-2	tower heat flux	122	HFG-W6	wall heat flux
82	T4-HFG-1	tower heat flux	123	HFG-W7	wall heat flux
83	T4-HFG-2	tower heat flux	124	HFG-W8	wall heat flux
84	T5-HFG-1	tower heat flux	125	HFG-W9	wall heat flux
85	T5-HFG-2	tower heat flux	126	HFG-W10	wall heat flux
86	T6-HFG-1	tower heat flux	127	HFG-W11	wall heat flux
87	T6-HFG-2	tower heat flux	128	HFG-W12	wall heat flux
88	T7-HFG-1	tower heat flux			
89	T7-HFG-2	tower heat flux	129	QP-P1	quarter pool temp
90	T8-HFG-1	tower heat flux	130	QP-P2	quarter pool temp
91	T8-HFG-2	tower heat flux	131	QP-P3	quarter pool temp
92	T9-HFG-1	tower heat flux	132	QP-P4	quarter pool temp
93	T9-HFG-2	tower heat flux	133	QP-P5	quarter pool temp
			134	QP-P6	quarter pool temp
94	HFG-F1	floor heat flux	135	LP-P1	long pool temp
95	HFG-F2	floor heat flux	136	LP-P2	long pool temp
96	HFG-F3	floor heat flux	137	LP-P3	long pool temp
97	HFG-F4	floor heat flux	138	LP-P4	long pool temp
98	HFG-F5	floor heat flux	139	LP-P5	long pool temp
99	HFG-F6	floor heat flux	140	LP-P6	long pool temp
100	HFG-F7	floor heat flux			
101	HFG-F8	floor heat flux	166	WP-1-A	weapon temp
102	HFG-F9	floor heat flux	167	WP-1-B	weapon temp
103	HFG-F10	floor heat flux	168	WP-1-F	weapon temp
104	HFG-F11	floor heat flux	169	WP-2-C	weapon temp
105	HFG-F12	floor heat flux	170	WP-2-D	weapon temp
106	HFG-F13	floor heat flux	171	WP-2-E	weapon temp
107	HFG-F14	floor heat flux	172	WP-3-A	weapon temp
108	HFG-F15	floor heat flux	173	WP-3-B	weapon temp
109	HFG-F16	floor heat flux	174	WP-3-F	weapon temp
110	HFG-F17	floor heat flux	175	WP-4-C	weapon temp
111	HFG-F18	floor heat flux	176	WP-4-D	weapon temp
112	HFG-F19	floor heat flux	177	WP-4-E	weapon temp
113	HFG-F20	floor heat flux			
114	HFG-F21	floor heat flux	178		Wind speed
115	HFG-F22	floor heat flux	179		Wind direction
116	HFG-F23	floor heat flux			

Table 6. Instrument Summary (concluded).

DAS1 #	ID	Instrument Name	DAS2 #	ID	Instrument Name
141	VP-1	velocity probe temp	1	VP-1	velocity probe DP
142	VP-2	velocity probe temp	2	VP-2	velocity probe DP
143	VP-3	velocity probe temp	3	VP-3	velocity probe DP
144	VP-4	velocity probe temp	4	VP-4	velocity probe DP
145	VP-5	velocity probe temp	5	VP-5	velocity probe DP
146	VP-6	velocity probe temp	6	VP-6	velocity probe DP
147	VP-7	velocity probe temp	7	VP-7	velocity probe DP
148	VP-8	velocity probe temp	8	VP-8	velocity probe DP
149	VP-9	velocity probe temp	9	VP-9	velocity probe DP
150	VP-10	velocity probe temp	10	VP-10	velocity probe DP
151	VP-11	velocity probe temp	11	VP-11	velocity probe DP
152	VP-12	velocity probe temp	12	VP-12	velocity probe DP
153	VP-13	velocity probe temp	13	VP-13	velocity probe DP
154	VP-14	velocity probe temp	14	VP-14	velocity probe DP
155	VP-15	velocity probe temp	15	VP-15	velocity probe DP
156	VP-16	velocity probe temp	16	VP-16	velocity probe DP
157	VP-17	velocity probe temp	17	VP-17	velocity probe DP
158	VP-18	velocity probe temp	18	VP-18	velocity probe DP
159	VP-19	velocity probe temp	19	VP-19	velocity probe DP
160	VP-20	velocity probe temp	20	VP-20	velocity probe DP
161	VP-21	velocity probe temp	21	VP-21	velocity probe DP
162	VP-22	velocity probe temp	22	VP-22	velocity probe DP
163	VP-23	velocity probe temp	23	VP-23	velocity probe DP
164	VP-24	velocity probe temp	24	VP-24	velocity probe DP
165	VP-25	velocity probe temp	25	VP-25	velocity probe DP

Table 7. Experiment Movies.

Movie Name	Experiment Name	View	Movie Time Start-End (min)	Movie Duration (min)
igloo5_door_24.mpg	5	Door	24-40	16
igloo5_pan_24.mpg	5	Pan	24-40	16
igloo6_pan_15.mpg	6	Pan	15-52	37
igloo6_door_31.mpg	6	Door	31-52 ¹	21
igloo6_profile_15.mpg	6	Profile	15-52	37
igloo7_door_16.mpg	7	Door	16-40	24
igloo7_inside_16.mpg	7	Inside	16-40	24
igloo9_door_40.mpg	9	Door	40-70	30
igloo9_pan_40.mpg	9	Pan	40-70	30
igloo9_profile_40.mpg	9	Profile	40-70	30
igloo10_door_16.mpg	10	Door	16-54	38
igloo10_pan_16.mpg	10	Pan	16-54	38
igloo10_pan_16.mpg	10	Profile	16-54	38
igloo11_door_1.mpg	11	Door	1-3 ²	2
igloo11_door_13.mpg	11	Door	13.2-34	21
igloo11_inside_2.mpg	11	Inside	2-18.9 ³	17
igloo11_profile_2.mpg	11	Profile	2-34	32

Igloo fire experiment movies, digitized at 10fps, 240x180 pixels mpg compression.
Label convention: test name_view_test time start

- ¹ tape starts, then stops at about 19 min while camera is moved
- ² lost video between 3 min and 13 min
- ³ camera failed at about 19 min

Table 8. Summary of Experiment Heat Release Rates (HRR).

Experiment Name	Pan Area (m²)	Time (min)	Fuel Recession (mm/min)	Fuel Consumption (kg/s)	HRR (MW)
1	0.785	86-98	1.12	0.012	0.51
		98-188	0.44	0.005	0.20
2	0.785	145-245	0.57	0.006	0.26
3	7.989	145-321 ¹	0.07	0.008	0.34
5	0.785	28-34	4.24	0.045	1.94
		34-66	1.42	0.015	0.65
6	7.989	17-24	5.28	0.553	23.90
		24-44	1.50	0.161	6.96
7	0.785	19-31	5.24	0.055	2.39
9	2.626	41-52	6.13	0.217	9.36
10	16.417	24-29	5.17	1.143	49.37
11	2.626	4-11	5.09	0.180	7.77

¹ Determination of the time that the thermocouples became uncovered is uncertain, data may be unreliable.

Figure 1. Schematic of Building 9830.

The facility can be operated with either the doors open or the ceiling vent open.

Figure 2. Burn room configuration for actual Experiments 1, 2, and 3.
The corner pool was used in Experiments 1 and 2 and the wall pool was used in Experiment 3.

Figure 4. Equipment room configuration for actual Experiments 9, 10, and 11.
The 5 MW small pool was used in Experiments 9 and 11. The 50 MW large pool was used in Experiment 10. The clutter calorimeter was present only in Experiment 11.

Figure 5. Thermocouple tree with positions of thermocouples (TC #) and HFGs.

Figure 6. Representative calorimeter simulating two weapons in a storage configuration.

Figure 7. The clutter calorimeter.

North

Figure 8. Location of the velocity probes in the ceiling duct of the burn room.
(looking down the stack)

Figure 9. Equipment room door velocity probe array (outside looking in).

Figure 10. Quarter and long fuel pool thermocouple comb.

Figure 11. Looking into the burn room (at the SW corner door) at the long pan fueled for Test 3.

Figure 14. A burn room view from the SE corner of the long pan in Test 3.

Figure 12. A burn room view from the SW corner showing the weapon calorimeters.

Figure 15. A burn room view from the NE corner showing weapon calorimeters WP-1 and WP-2.

Figure 13. The NW corner burn room quarter pool and HFGs used in Tests 1 and 2.

Figure 16. Measuring oxygen concentration at the ceiling stack in Test 2.

Figure 17. The velocity and thermocouple array in the ceiling stack viewed from outside the burn room.

Figure 18. The velocity and thermocouple array in the ceiling stack viewed from inside the burn room.

Figure 19. The equipment room quarter pool used in Tests 5 and 7.

Figure 20. The equipment room (with curved ceiling) and velocity probes used in Tests 5-7.

Figure 21. The Test 5 equipment room quarter pool fuel fire.

Figure 22. The Test 5 quarter pool fire heating the WP-1 and 2 weapon calorimeters.

Figure 23. Smoke venting from the equipment room ceiling in Test 5.

Figure 24. The equipment room velocity probe array in Test 6.

Figure 25. Weapon calorimeters WP-3 and WP-4 in Test 6.

Figure 26. Test 6 viewed from the equipment room NE corner prior to Test 6.

Figure 27. The steady burn during Test 6.

Figure 28. End of burn in Test 6.

Figure 29. The outside view of Test 6.

Figure 30. The equipment room (flat ceiling) and velocity probe array in Test 9.

Figure 31. The 6-ft diameter pan used in Test 9.

Figure 32. The Test 9 fire.

Figure 33. The spiraling smoke plume in Test 9.

Figure 34. The equipment room flat roof in Test 10.

Figure 35. The 15-ft diameter pan used in Test 10.

Figure 36. The start of Test 10.

Figure 37. The middle of Test 10.

Figure 38. The end of Test 10.

Figure 39. The equipment room velocity probe array in Test 11.

Figure 40. South end of the clutter calorimeter from inside the equipment room in Test 11.

Figure 41. North end of the clutter calorimeter from inside the equipment room in Test 11.

Figure 42. HFGs on the clutter calorimeter J and K pipes in Test 11.

Figure 43. The ceiling gas sample line near thermocouple T8-3 in Test 11.

Figure 44. The 6-ft diameter pan used in Test 11.

Figure 45. The clutter calorimeter HFG outer surface.

Figure 46. Installing the HFGs inside the clutter calorimeter in Test 11.

Figure 47. Insulating the clutter calorimeter HFGs.

Figure 48. Installing the clutter calorimeter insulating pipe plugs in Test 11.

Figure 49. Fuel burning in Test 11.

Figure 50. Close-up view of the 6-ft pan fire in Test 11.

Figure 51. Smoke slowly spiraling out of the equipment room in Test 11.

Figure 52. String telltales showing influx at the lower three rows of the velocity array in Test 11.

Figure 53. Soot on the upper three clutter calorimeter pipes in Test 11.

Figure 54 (Monitor 1). A preview of the LabView playback from Igloo Test 11.

Figure 54 (Monitor 2). A preview of the LabView playback from Igloo Test 11

Figure 54 (Monitor 3). A preview of the LabView playback from Igloo Test 11

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Appendix A

Bi-Directional Velocity Probe Velocity Response and Uncertainty Model

Data Reduction for the Bi-Directional Velocity Gauge

The velocity of the gas at the door and ceiling opening was computed using the differential pressure measurements obtained with the bi-directional velocity gauges and also the temperature measurements from thermocouples located near each velocity gauge. The pressure gauge and the thermocouple data were processed posttest to give gas velocity (units of m/s) as a function of time following the procedures and calibrations given in Kent and Schneider (1987)

$$Velocity = \frac{1}{C} \sqrt{2 \frac{\Delta P}{\rho}} \quad (A1)$$

where

C	=	bi-directional probe calibration constant (1.05)
ΔP	=	pressure transducer differential pressure (Pa)
ρ	=	gas density (kg/m^3) = $P/R/T$
P	=	ambient pressure (Pa)
R	=	specific gas constant
T	=	gas temperature (K).

Long lines (~6-15 m) connecting the bi-directional velocity probes to individual pressure transducers were necessary to protect the pressure transducers from the fire environment. The ultrasensitive pressure transducers measured differential pressure (0-12 Pa) based on a thermister monitoring flow through a small orifice. Because of the pressure drop induced by the long line length, the calibration curves supplied by the manufacturer were not appropriate for the enclosure fire test application. In addition, the pressure transducers were found to be sensitive to ambient temperature, indicated by a baseline (no wind) voltage drift. A portable flow calibrator was designed and fabricated that yielded unique calibration data for each bi-directional velocity gauge and its associated pressure transducer. The calibration data was fit using a linear equation to allow compensation of the test data for the baseline voltage drift. Figure A-1 shows the differential pressure at the face of a bi-directional probe as a function of the pressure transducer voltage. The linear fit equation and the fit standard error is shown. The manufacturers calibration curve for the pressure transducer is also shown, clearly indicating the effects of the line loss.

Table A-1 gives the slope (M) and the standard error for the linear fit of each velocity probe. The data reduction for each gauge consisted of first determining the no wind baseline voltage (typically either the first data point or the minimum voltage point in the dataset). After calculating an adjusted intercept value ($BP = -M \times \text{first data point volts}$), the differential pressure (ΔP) was found using $\Delta P = M \times \text{volts} + BP$.

Figure A-1. Differential pressure at the face of the bi-directional probe as a function of the pressure transducer voltage.

Table A-1. Linear fit and fit standard error for the in-situ calibration of the bi-directional velocity probes.

Gauge	Slope/ error	Gauge	Slope/ error	Gauge	Slope/ error	Gauge	Slope/ error	Gauge	Slope/ error
1	5.269/ 0.839	6	4.774/ 0.895	11	5.032/ 0.579	16	4.706/ 0.524	21	4.643/ 0.715
2	6.547/ 0.726	7	5.251/ 1.187	12	6.391/ 1.321	17	5.258/ 0.612	22	4.617/ 0.745
3	6.140/ 0.707	8	5.601/ 1.397	13	6.497/ 0.843	18	7.238/ 0.947	23	4.958/ 0.462
4	8.599/ 0.687	9	7.775/ 0.609	14	6.483/ 1.264	19	6.539/ 1.100	24	5.652/ 0.610
5	8.428/ 0.407	10	6.624/ 1.448	15	6.234/ 0.883	20	6.282/ 1.667	25	5.970/ 0.416

Error Analysis for the Bi-Directional Velocity Gauge

An estimate of the uncertainty in the velocity results, caused by the uncertainties in measuring the independent variables (i.e., C , ΔP , P , R , T) can be written as

$$\frac{\partial V}{V} = \left[\left(\frac{\delta C}{C} \right)^2 + \left(\frac{1}{2} \frac{\delta \Delta P}{\Delta P} \right)^2 + \left(\frac{1}{2} \frac{\delta P}{P} \right)^2 + \left(\frac{1}{2} \frac{\delta R}{R} \right)^2 + \left(\frac{1}{2} \frac{\delta T}{T} \right)^2 \right]^{\frac{1}{2}} \quad (\text{A2})$$

where $\delta(*)$ denotes the uncertainty (or standard deviation) of $(*)$ quantity measurement (note $\delta(*)/(*)$ is the fractional probable error). The standard deviation of the calibration constant C is 0.015 (Kent 1987), yielding a $\delta C/C = 0.015/1.05 = 0.014$. The probable error for ΔP is a function of the fit of the calibration data. For example, using the standard error for the linear fit of gauge #1, $\delta \Delta P/\Delta P = \text{FitStdErr}/\Delta P = 0.839/\Delta P$. Note that the probable error gets large when the calculated ΔP is very small. The density of the gas is a function of the gas pressure, composition, and temperature. The ambient pressure probable error quite small, $\delta P/P = 0.25 \text{ inHg}/23.75 \text{ inHg} = 0.011$. The probable error in the gas constant is due to the uncertainty of exactly what gas is striking the face of the probe. Noting that air has a molar mass of 29 and a gas containing combustion products and unburned hydrocarbons may have a molar mass up to 36, the probable error of $\delta R/R = (36-29)/29 = 0.241$. The radiation shields for the gas temperature thermocouples were specifically designed to minimize the probable error, yielding a $\delta T/T = 0.112$.

Figure A-2 presents the velocity calculated using Equation A1 and the velocity error calculated using Equation A2 for an example data set. Note that the error is quite large for computed velocities less than 1 m/s but reduces to about 15% of the reading with velocities near 5 m/s. The velocity error is sensitive to temperature. Assuming air at about 3 m/s, the probable error ranges from 29% to 49% for temperatures of 573 K and 1273 K, respectively.

Figure A-2. Velocity and uncertainty for a bi-directional velocity probe.

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Appendix B

Igloo Fire Experiment 1

**Igloo Fire Test 1
Tower 1 Thermocouples**

**Igloo Fire Test 1
Tower 3 Thermocouples**

**Igloo Fire Test 1
Tower 2 Thermocouples**

**Igloo Fire Test 1
Tower 4 Thermocouples**

**Igloo Fire Test 1
Tower 5 Thermocouples**

**Igloo Fire Test 1
Tower 7 Thermocouples**

**Igloo Fire Test 1
Tower 6 Thermocouples**

**Igloo Fire Test 1
Tower 8 Thermocouples**

**Igloo Fire Test 1
Tower 9 Thermocouples**

**Igloo Fire Test 1
Tower 2 HFG Thermocouples**

**Igloo Fire Test 1
Tower 1 HFG Thermocouples**

**Igloo Fire Test 1
Tower 3 HFG Thermocouples**

**Igloo Fire Test 1
Tower 4 HFG Thermocouples**

**Igloo Fire Test 1
Tower 6 HFG Thermocouples**

**Igloo Fire Test 1
Tower 5 HFG Thermocouples**

**Igloo Fire Test 1
Tower 7 HFG Thermocouples**

Igloo Fire Test 1
Tower 8 HFG Thermocouples

Igloo Fire Test 1
Wall HFG (1-3) Thermocouples

Igloo Fire Test 1
Tower 9 HFG Thermocouples

Igloo Fire Test 1
Wall HFG (4,6,8) Thermocouples

Igloo Fire Test 1
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 1
Floor HFG (1-5) Thermocouples

Igloo Fire Test 1
Wall HFG (10-12) Thermocouples

Igloo Fire Test 1
Floor HFG (6-10) Thermocouples

Igloo Fire Test 1
Floor HFG (11-15) Thermocouples

Igloo Fire Test 1
Floor HFG (21-23) Thermocouples

Igloo Fire Test 1
Floor HFG (16-20) Thermocouples

Igloo Fire Test 1
Simulated Weapon (WP-1 & WP-2) Thermocouples

Igloo Fire Test 1
Simulated Weapon (WP-3 & WP-4) Thermocouples

Igloo Fire Test 1
Long Pool 1 Thermocouples

Igloo Fire Test 1
Quarter Pool Thermocouples

Igloo Fire Test 1
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 1
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 1
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 1
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 1
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 1
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 1
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 1
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 1
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 1
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 1
Tower 2 HFG Heat Fluxes

Igloo Fire Test 1
Tower 1 HFG Heat Fluxes

Igloo Fire Test 1
Tower 3 HFG Heat Fluxes

Igloo Fire Test 1
Tower 4 HFG Heat Fluxes

Igloo Fire Test 1
Tower 6 HFG Heat Fluxes

Igloo Fire Test 1
Tower 5 HFG Heat Fluxes

Igloo Fire Test 1
Tower 7 HFG Heat Fluxes

**Igloo Fire Test 1
Tower 8 HFG Heat Fluxes**

**Igloo Fire Test 1
Wall HFG (1-3) Heat Fluxes**

**Igloo Fire Test 1
Tower 9 HFG Heat Fluxes**

**Igloo Fire Test 1
Wall HFG (4,6,8) Heat Fluxes**

Igloo Fire Test 1
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 1
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 1
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 1
Floor HFG (6-10) Heat Fluxes

**Igloo Fire Test 1
Floor HFG (11-15) Heat Fluxes**

**Igloo Fire Test 1
Floor HFG (21-23) Heat Fluxes**

**Igloo Fire Test 1
Floor HFG (16-20) Heat Fluxes**

**Igloo Fire Test 1
Simulated Weapon (WP-1 & WP-2) Heat Fluxes**

Igloo Fire Test 1
Simulated Weapon (WP-3 & WP-4) Heat Fluxes

Igloo Fire Test 1
Velocities Probes (6-10)

Igloo Fire Test 1
Velocities Probes (1-5)

Igloo Fire Test 1
Velocities Probes (11-15)

Igloo Fire Test 1
Velocities Probes (16-20)

Igloo Fire Test 1
Velocities Probes (21-25)

Appendix C

Igloo Fire Experiment 2

**Igloo Fire Test 2
Tower 1 Thermocouples**

**Igloo Fire Test 2
Tower 3 Thermocouples**

**Igloo Fire Test 2
Tower 2 Thermocouples**

**Igloo Fire Test 2
Tower 4 Thermocouples**

**Igloo Fire Test 2
Tower 5 Thermocouples**

**Igloo Fire Test 2
Tower 7 Thermocouples**

**Igloo Fire Test 2
Tower 6 Thermocouples**

**Igloo Fire Test 2
Tower 8 Thermocouples**

**Igloo Fire Test 2
Tower 9 Thermocouples**

**Igloo Fire Test 2
Tower 2 HFG Thermocouples**

**Igloo Fire Test 2
Tower 1 HFG Thermocouples**

**Igloo Fire Test 2
Tower 3 HFG Thermocouples**

Igloo Fire Test 2
Tower 4 HFG Thermocouples

Igloo Fire Test 2
Tower 6 HFG Thermocouples

Igloo Fire Test 2
Tower 5 HFG Thermocouples

Igloo Fire Test 2
Tower 7 HFG Thermocouples

Igloo Fire Test 2
Tower 8 HFG Thermocouples

Igloo Fire Test 2
Wall HFG (1-3) Thermocouples

Igloo Fire Test 2
Tower 9 HFG Thermocouples

Igloo Fire Test 2
Wall HFG (4,6,8) Thermocouples

Igloo Fire Test 2
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 2
Floor HFG (1-5) Thermocouples

Igloo Fire Test 2
Wall HFG (10-12) Thermocouples

Igloo Fire Test 2
Floor HFG (6-10) Thermocouples

Igloo Fire Test 2
Floor HFG (11-15) Thermocouples

Igloo Fire Test 2
Floor HFG (21-23) Thermocouples

Igloo Fire Test 2
Floor HFG (16-20) Thermocouples

Igloo Fire Test 2
Simulated Weapon (WP-1 & WP-2) Thermocouples

Igloo Fire Test 2
Simulated Weapon (WP-3 & WP-4) Thermocouples

Igloo Fire Test 2
Long Pool 1 Thermocouples

Igloo Fire Test 2
Quarter Pool Thermocouples

Igloo Fire Test 2
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 2
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 2
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 2
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 2
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 2
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 2
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 2
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 2
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 2
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 2
Wind Direction

Igloo Fire Test 2
Wind Speed

Igloo Fire Test 2
Tower 1 HFG Heat Fluxes

**Igloo Fire Test 2
Tower 2 HFG Heat Fluxes**

**Igloo Fire Test 2
Tower 4 HFG Heat Fluxes**

**Igloo Fire Test 2
Tower 3 HFG Heat Fluxes**

**Igloo Fire Test 2
Tower 5 HFG Heat Fluxes**

**Igloo Fire Test 2
Tower 6 HFG Heat Fluxes**

**Igloo Fire Test 2
Tower 8 HFG Heat Fluxes**

**Igloo Fire Test 2
Tower 7 HFG Heat Fluxes**

**Igloo Fire Test 2
Tower 9 HFG Heat Fluxes**

Igloo Fire Test 2
Wall HFG (1-3) Heat Fluxes

Igloo Fire Test 2
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 2
Wall HFG (4,6,8) Heat Fluxes

Igloo Fire Test 2
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 2
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 2
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 2
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 2
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 2
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 2
Simulated Weapon (WP-3 & WP-4) Heat Fluxes

Igloo Fire Test 2
Simulated Weapon (WP-1 & WP-2) Heat Fluxes

Igloo Fire Test 2
Velocities Probes (1-5)

**Igloo Fire Test 2
Velocities Probes (6-10)**

**Igloo Fire Test 2
Velocities Probes (16-20)**

**Igloo Fire Test 2
Velocities Probes (11-15)**

**Igloo Fire Test 2
Velocities Probes (21-25)**

Igloo Test #2
Center tower and velocity array temperatures
versus exhaust vent oxygen

Igloo Test #2
Center tower and velocity array temperatures
versus exhaust vent oxygen

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Appendix D

Igloo Fire Experiment 3

**Igloo Fire Test 3
Tower 1 Thermocouples**

**Igloo Fire Test 3
Tower 3 Thermocouples**

**Igloo Fire Test 3
Tower 2 Thermocouples**

**Igloo Fire Test 3
Tower 4 Thermocouples**

**Igloo Fire Test 3
Tower 5 Thermocouples**

**Igloo Fire Test 3
Tower 7 Thermocouples**

**Igloo Fire Test 3
Tower 6 Thermocouples**

**Igloo Fire Test 3
Tower 8 Thermocouples**

**Igloo Fire Test 3
Tower 9 Thermocouples**

**Igloo Fire Test 3
Tower 2 HFG Thermocouples**

**Igloo Fire Test 3
Tower 1 HFG Thermocouples**

**Igloo Fire Test 3
Tower 3 HFG Thermocouples**

Igloo Fire Test 3
Tower 4 HFG Thermocouples

Igloo Fire Test 3
Tower 6 HFG Thermocouples

Igloo Fire Test 3
Tower 5 HFG Thermocouples

Igloo Fire Test 3
Tower 7 HFG Thermocouples

**Igloo Fire Test 3
Tower 8 HFG Thermocouples**

**Igloo Fire Test 3
Wall HFG (1-3) Thermocouples**

**Igloo Fire Test 3
Tower 9 HFG Thermocouples**

**Igloo Fire Test 3
Wall HFG (4,6,8) Thermocouples**

Igloo Fire Test 3
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 3
Floor HFG (1-5) Thermocouples

Igloo Fire Test 3
Wall HFG (10-12) Thermocouples

Igloo Fire Test 3
Floor HFG (6-10) Thermocouples

**Igloo Fire Test 3
Floor HFG (11-15) Thermocouples**

**Igloo Fire Test 3
Floor HFG (21-23) Thermocouples**

**Igloo Fire Test 3
Floor HFG (16-20) Thermocouples**

**Igloo Fire Test 3
Simulated Weapon (WP-1 & WP-2) Thermocouples**

Igloo Fire Test 3
Simulated Weapon (WP-3 & WP-4) Thermocouples

Igloo Fire Test 3
Long Pool 1 Thermocouples

Igloo Fire Test 3
Quarter Pool Thermocouples

Igloo Fire Test 3
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 3
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 3
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 3
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 3
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 3
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 3
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 3
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 3
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 3
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 3
Wind Direction

Igloo Fire Test 3
Wind Speed

Igloo Fire Test 3
Tower 1 HFG Heat Fluxes

Igloo Fire Test 3
Tower 2 HFG Heat Fluxes

Igloo Fire Test 3
Tower 4 HFG Heat Fluxes

Igloo Fire Test 3
Tower 3 HFG Heat Fluxes

Igloo Fire Test 3
Tower 5 HFG Heat Fluxes

**Igloo Fire Test 3
Tower 6 HFG Heat Fluxes**

**Igloo Fire Test 3
Tower 8 HFG Heat Fluxes**

**Igloo Fire Test 3
Tower 7 HFG Heat Fluxes**

**Igloo Fire Test 3
Tower 9 HFG Heat Fluxes**

Igloo Fire Test 3
Wall HFG (1-3) Heat Fluxes

Igloo Fire Test 3
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 3
Wall HFG (4,6,8) Heat Fluxes

Igloo Fire Test 3
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 3
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 3
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 3
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 3
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 3
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 3
Simulated Weapon (WP-3 & WP-4) Heat Fluxes

Igloo Fire Test 3
Simulated Weapon (WP-1 & WP-2) Heat Fluxes

Igloo Fire Test 3
Velocities Probes (1-5)

**Igloo Fire Test 3
Velocities Probes (6-10)**

**Igloo Fire Test 3
Velocities Probes (16-20)**

**Igloo Fire Test 3
Velocities Probes (11-15)**

**Igloo Fire Test 3
Velocities Probes (21-25)**

Appendix E

Igloo Fire Experiment 5

Igloo Fire Test 5
Tower 1 Thermocouples

Igloo Fire Test 5
Tower 3 Thermocouples

Igloo Fire Test 5
Tower 2 Thermocouples

Igloo Fire Test 5
Tower 4 Thermocouples

**Igloo Fire Test 5
Tower 5 Thermocouples**

**Igloo Fire Test 5
Tower 7 Thermocouples**

**Igloo Fire Test 5
Tower 6 Thermocouples**

**Igloo Fire Test 5
Tower 8 Thermocouples**

**Igloo Fire Test 5
Tower 9 Thermocouples**

**Igloo Fire Test 5
Tower 2 HFG Thermocouples**

**Igloo Fire Test 5
Tower 1 HFG Thermocouples**

**Igloo Fire Test 5
Tower 3 HFG Thermocouples**

Igloo Fire Test 5
Tower 4 HFG Thermocouples

Igloo Fire Test 5
Tower 6 HFG Thermocouples

Igloo Fire Test 5
Tower 5 HFG Thermocouples

Igloo Fire Test 5
Tower 7 HFG Thermocouples

**Igloo Fire Test 5
Tower 8 HFG Thermocouples**

**Igloo Fire Test 5
Wall HFG (1-3) Thermocouples**

**Igloo Fire Test 5
Tower 9 HFG Thermocouples**

**Igloo Fire Test 5
Wall HFG (4,6,8) Thermocouples**

Igloo Fire Test 5
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 5
Floor HFG (1-5) Thermocouples

Igloo Fire Test 5
Wall HFG (10-12) Thermocouples

Igloo Fire Test 5
Floor HFG (6-10) Thermocouples

**Igloo Fire Test 5
Floor HFG (11-15) Thermocouples**

**Igloo Fire Test 5
Floor HFG (21-23) Thermocouples**

**Igloo Fire Test 5
Floor HFG (16-20) Thermocouples**

**Igloo Fire Test 5
Simulated Weapon (WP-1 & WP-2) Thermocouples**

Igloo Fire Test 5
Simulated Weapon (WP-3 & WP-4) Thermocouples

Igloo Fire Test 5
Long Pool 1 Thermocouples

Igloo Fire Test 5
Quarter Pool Thermocouples

Igloo Fire Test 5
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 5
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 5
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 5
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 5
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 5
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 5
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 5
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 5
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 5
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 5
Wind Direction

Igloo Fire Test 5
Wind Speed

Igloo Fire Test 5
Tower 1 HFG Heat Fluxes

**Igloo Fire Test 5
Tower 2 HFG Heat Fluxes**

**Igloo Fire Test 5
Tower 4 HFG Heat Fluxes**

**Igloo Fire Test 5
Tower 3 HFG Heat Fluxes**

**Igloo Fire Test 5
Tower 5 HFG Heat Fluxes**

Igloo Fire Test 5
Tower 6 HFG Heat Fluxes

Igloo Fire Test 5
Tower 8 HFG Heat Fluxes

Igloo Fire Test 5
Tower 7 HFG Heat Fluxes

Igloo Fire Test 5
Tower 9 HFG Heat Fluxes

Igloo Fire Test 5
Wall HFG (1-3) Heat Fluxes

Igloo Fire Test 5
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 5
Wall HFG (4,6,8) Heat Fluxes

Igloo Fire Test 5
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 5
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 5
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 5
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 5
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 5
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 5
Simulated Weapon (WP-3 & WP-4) Heat Fluxes

Igloo Fire Test 5
Simulated Weapon (WP-1 & WP-2) Heat Fluxes

Igloo Fire Test 5
Velocities Probes (1-5)

**Igloo Fire Test 5
Velocities Probes (6-10)**

**Igloo Fire Test 5
Velocities Probes (16-20)**

**Igloo Fire Test 5
Velocities Probes (11-15)**

**Igloo Fire Test 5
Velocities Probes (21-25)**

Appendix F

Igloo Fire Experiment 6

**Igloo Fire Test 6
Tower 1 Thermocouples**

**Igloo Fire Test 6
Tower 3 Thermocouples**

**Igloo Fire Test 6
Tower 2 Thermocouples**

**Igloo Fire Test 6
Tower 4 Thermocouples**

**Igloo Fire Test 6
Tower 5 Thermocouples**

**Igloo Fire Test 6
Tower 7 Thermocouples**

**Igloo Fire Test 6
Tower 6 Thermocouples**

**Igloo Fire Test 6
Tower 8 Thermocouples**

**Igloo Fire Test 6
Tower 9 Thermocouples**

**Igloo Fire Test 6
Tower 2 HFG Thermocouples**

**Igloo Fire Test 6
Tower 1 HFG Thermocouples**

**Igloo Fire Test 6
Tower 3 HFG Thermocouples**

**Igloo Fire Test 6
Tower 4 HFG Thermocouples**

**Igloo Fire Test 6
Tower 6 HFG Thermocouples**

**Igloo Fire Test 6
Tower 5 HFG Thermocouples**

**Igloo Fire Test 6
Tower 7 HFG Thermocouples**

**Igloo Fire Test 6
Tower 8 HFG Thermocouples**

**Igloo Fire Test 6
Tower 9 HFG Thermocouples**

**Igloo Fire Test 6
Wall HFG (1-3) Thermocouples**

**Igloo Fire Test 6
Wall HFG (4,6,8) Thermocouples**

Igloo Fire Test 6
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 6
Floor HFG (1-5) Thermocouples

Igloo Fire Test 6
Wall HFG (10-12) Thermocouples

Igloo Fire Test 6
Floor HFG (6-10) Thermocouples

Igloo Fire Test 6
Floor HFG (11-15) Thermocouples

Igloo Fire Test 6
Floor HFG (21-23) Thermocouples

Igloo Fire Test 6
Floor HFG (16-20) Thermocouples

Igloo Fire Test 6
Simulated Weapon (WP-1 & WP-2) Thermocouples

Igloo Fire Test 6
Simulated Weapon (WP-3 & WP-4) Thermocouples

Igloo Fire Test 6
Long Pool 1 Thermocouples

Igloo Fire Test 6
Quarter Pool Thermocouples

Igloo Fire Test 6
Long Pool 2 Thermocouples

Igloo Fire Test 6
Long Pool 3 Thermocouples

Igloo Fire Test 6
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 6
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 6
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 6
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 6
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 6
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 6
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 6
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 6
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 6
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 6
Wind Speed

Igloo Fire Test 6
Wind Direction

Igloo Fire Test 6
Tower 2 HFG Heat Fluxes

Igloo Fire Test 6
Tower 1 HFG Heat Fluxes

Igloo Fire Test 6
Tower 3 HFG Heat Fluxes

**Igloo Fire Test 6
Tower 4 HFG Heat Fluxes**

**Igloo Fire Test 6
Tower 6 HFG Heat Fluxes**

**Igloo Fire Test 6
Tower 5 HFG Heat Fluxes**

**Igloo Fire Test 6
Tower 7 HFG Heat Fluxes**

Igloo Fire Test 6
Tower 8 HFG Heat Fluxes

Igloo Fire Test 6
Wall HFG (1-3) Heat Fluxes

Igloo Fire Test 6
Tower 9 HFG Heat Fluxes

Igloo Fire Test 6
Wall HFG (4,6,8) Heat Fluxes

Igloo Fire Test 6
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 6
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 6
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 6
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 6
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 6
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 6
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 6
Simulated Weapon (WP-1 & WP-2) Heat Fluxes

Igloo Fire Test 6
Simulated Weapon (WP-3 & WP-4) Heat Fluxes

Igloo Fire Test 6
Velocities Probes (6-10)

Igloo Fire Test 6
Velocities Probes (1-5)

Igloo Fire Test 6
Velocities Probes (11-15)

Igloo Fire Test 6
Velocities Probes (16-20)

Igloo Fire Test 6
Velocities Probes (21-25)

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Appendix G

Igloo Fire Experiment 7

**Igloo Fire Test 7
Tower 5 Thermocouples**

**Igloo Fire Test 7
Tower 7 Thermocouples**

**Igloo Fire Test 7
Tower 6 Thermocouples**

**Igloo Fire Test 7
Tower 8 Thermocouples**

**Igloo Fire Test 7
Tower 9 Thermocouples**

**Igloo Fire Test 7
Tower 2 HFG Thermocouples**

**Igloo Fire Test 7
Tower 1 HFG Thermocouples**

**Igloo Fire Test 7
Tower 3 HFG Thermocouples**

Igloo Fire Test 7
Tower 4 HFG Thermocouples

Igloo Fire Test 7
Tower 6 HFG Thermocouples

Igloo Fire Test 7
Tower 5 HFG Thermocouples

Igloo Fire Test 7
Tower 7 HFG Thermocouples

**Igloo Fire Test 7
Tower 8 HFG Thermocouples**

**Igloo Fire Test 7
Wall HFG (1-3) Thermocouples**

**Igloo Fire Test 7
Tower 9 HFG Thermocouples**

**Igloo Fire Test 7
Wall HFG (4,6,8) Thermocouples**

Igloo Fire Test 7
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 7
Floor HFG (1-5) Thermocouples

Igloo Fire Test 7
Wall HFG (10-12) Thermocouples

Igloo Fire Test 7
Floor HFG (6-10) Thermocouples

**Igloo Fire Test 7
Floor HFG (11-15) Thermocouples**

**Igloo Fire Test 7
Floor HFG (21-23) Thermocouples**

**Igloo Fire Test 7
Floor HFG (16-20) Thermocouples**

**Igloo Fire Test 7
Simulated Weapon (WP-1 & WP-2) Thermocouples**

Igloo Fire Test 7
Simulated Weapon (WP-3 & WP-4) Thermocouples

Igloo Fire Test 7
Long Pool 1 Thermocouples

Igloo Fire Test 7
Quarter Pool Thermocouples

Igloo Fire Test 7
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 7
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 7
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 7
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 7
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 7
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 7
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 7
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 7
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 7
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 7
Wind Direction

Igloo Fire Test 7
Wind Speed

Igloo Fire Test 7
Tower 1 HFG Heat Fluxes

**Igloo Fire Test 7
Tower 2 HFG Heat Fluxes**

**Igloo Fire Test 7
Tower 4 HFG Heat Fluxes**

**Igloo Fire Test 7
Tower 3 HFG Heat Fluxes**

**Igloo Fire Test 7
Tower 5 HFG Heat Fluxes**

**Igloo Fire Test 7
Tower 6 HFG Heat Fluxes**

**Igloo Fire Test 7
Tower 8 HFG Heat Fluxes**

**Igloo Fire Test 7
Tower 7 HFG Heat Fluxes**

**Igloo Fire Test 7
Tower 9 HFG Heat Fluxes**

Igloo Fire Test 7
Wall HFG (1-3) Heat Fluxes

Igloo Fire Test 7
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 7
Wall HFG (4,6,8) Heat Fluxes

Igloo Fire Test 7
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 7
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 7
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 7
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 7
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 7
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 7
Simulated Weapon (WP-3 & WP-4) Heat Fluxes

Igloo Fire Test 7
Simulated Weapon (WP-1 & WP-2) Heat Fluxes

Igloo Fire Test 7
Velocities Probes (1-5)

**Igloo Fire Test 7
Velocities Probes (6-10)**

**Igloo Fire Test 7
Velocities Probes (16-20)**

**Igloo Fire Test 7
Velocities Probes (11-15)**

**Igloo Fire Test 7
Velocities Probes (21-25)**

Appendix H

Igloo Fire Experiment 9

**Igloo Fire Test 9
Tower 1 Thermocouples**

**Igloo Fire Test 9
Tower 3 Thermocouples**

**Igloo Fire Test 9
Tower 2 Thermocouples**

**Igloo Fire Test 9
Tower 4 Thermocouples**

**Igloo Fire Test 9
Tower 5 Thermocouples**

**Igloo Fire Test 9
Tower 7 Thermocouples**

**Igloo Fire Test 9
Tower 6 Thermocouples**

**Igloo Fire Test 9
Tower 8 Thermocouples**

**Igloo Fire Test 9
Tower 9 Thermocouples**

**Igloo Fire Test 9
Tower 2 HFG Thermocouples**

**Igloo Fire Test 9
Tower 1 HFG Thermocouples**

**Igloo Fire Test 9
Tower 3 HFG Thermocouples**

**Igloo Fire Test 9
Tower 4 HFG Thermocouples**

**Igloo Fire Test 9
Tower 6 HFG Thermocouples**

**Igloo Fire Test 9
Tower 5 HFG Thermocouples**

**Igloo Fire Test 9
Tower 7 HFG Thermocouples**

Igloo Fire Test 9
Tower 8 HFG Thermocouples

Igloo Fire Test 9
Wall HFG (1-3) Thermocouples

Igloo Fire Test 9
Tower 9 HFG Thermocouples

Igloo Fire Test 9
Wall HFG (4,6,8) Thermocouples

Igloo Fire Test 9
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 9
Floor HFG (1-5) Thermocouples

Igloo Fire Test 9
Wall HFG (10-12) Thermocouples

Igloo Fire Test 9
Floor HFG (6-10) Thermocouples

Igloo Fire Test 9
Floor HFG (11-15) Thermocouples

Igloo Fire Test 9
Floor HFG (21-23) Thermocouples

Igloo Fire Test 9
Floor HFG (16-20) Thermocouples

Igloo Fire Test 9
Long Pool 1 Thermocouples

Igloo Fire Test 9
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 9
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 9
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 9
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 9
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 9
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 9
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 9
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 9
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 9
Wind Speed

Igloo Fire Test 9
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 9
Wind Direction

**Igloo Fire Test 9
Tower 1 HFG Heat Fluxes**

**Igloo Fire Test 9
Tower 3 HFG Heat Fluxes**

**Igloo Fire Test 9
Tower 2 HFG Heat Fluxes**

**Igloo Fire Test 9
Tower 4 HFG Heat Fluxes**

Igloo Fire Test 9
Tower 5 HFG Heat Fluxes

Igloo Fire Test 9
Tower 7 HFG Heat Fluxes

Igloo Fire Test 9
Tower 6 HFG Heat Fluxes

Igloo Fire Test 9
Tower 8 HFG Heat Fluxes

**Igloo Fire Test 9
Tower 9 HFG Heat Fluxes**

**Igloo Fire Test 9
Wall HFG (4,6,8) Heat Fluxes**

**Igloo Fire Test 9
Wall HFG (1-3) Heat Fluxes**

**Igloo Fire Test 9
Wall HFG (5,7,9) Heat Fluxes**

Igloo Fire Test 9
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 9
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 9
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 9
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 9
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 9
Velocities Probes (1-5)

Igloo Fire Test 9
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 9
Velocities Probes (6-10)

**Igloo Fire Test 9
Velocities Probes (11-15)**

**Igloo Fire Test 9
Velocities Probes (21-25)**

**Igloo Fire Test 9
Velocities Probes (16-20)**

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Appendix I

Igloo Fire Experiment 10

Igloo Fire Test 10
Tower 1 Thermocouples

Igloo Fire Test 10
Tower 3 Thermocouples

Igloo Fire Test 10
Tower 2 Thermocouples

Igloo Fire Test 10
Tower 4 Thermocouples

**Igloo Fire Test 10
Tower 5 Thermocouples**

**Igloo Fire Test 10
Tower 7 Thermocouples**

**Igloo Fire Test 10
Tower 6 Thermocouples**

**Igloo Fire Test 10
Tower 8 Thermocouples**

Igloo Fire Test 10
Tower 9 Thermocouples

Igloo Fire Test 10
Tower 2 HFG Thermocouples

Igloo Fire Test 10
Tower 1 HFG Thermocouples

Igloo Fire Test 10
Tower 3 HFG Thermocouples

**Igloo Fire Test 10
Tower 4 HFG Thermocouples**

**Igloo Fire Test 10
Tower 6 HFG Thermocouples**

**Igloo Fire Test 10
Tower 5 HFG Thermocouples**

**Igloo Fire Test 10
Tower 7 HFG Thermocouples**

**Igloo Fire Test 10
Tower 8 HFG Thermocouples**

**Igloo Fire Test 10
Wall HFG (1-3) Thermocouples**

**Igloo Fire Test 10
Tower 9 HFG Thermocouples**

**Igloo Fire Test 10
Wall HFG (4,6,8) Thermocouples**

Igloo Fire Test 10
Wall HFG (5,7,9) Thermocouples

Igloo Fire Test 10
Floor HFG (1-5) Thermocouples

Igloo Fire Test 10
Wall HFG (10-12) Thermocouples

Igloo Fire Test 10
Floor HFG (6-10) Thermocouples

Igloo Fire Test 10
Floor HFG (11-15) Thermocouples

Igloo Fire Test 10
Floor HFG (21-23) Thermocouples

Igloo Fire Test 10
Floor HFG (16-20) Thermocouples

Igloo Fire Test 10
Quarter Pool Thermocouples

Igloo Fire Test 10
Long Pool 1 Thermocouples

Igloo Fire Test 10
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 10
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 10
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 10
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 10
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 10
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 10
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 10
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 10
Velocities Probes (21-25) Pressure Transducers

Igloo Fire Test 10
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 10
Wind Speed

**Igloo Fire Test 10
Wind Direction**

**Igloo Fire Test 10
Tower 2 HFG Heat Fluxes**

**Igloo Fire Test 10
Tower 1 HFG Heat Fluxes**

**Igloo Fire Test 10
Tower 2 HFG Heat Fluxes**

**Igloo Fire Test 10
Tower 4 HFG Heat Fluxes**

**Igloo Fire Test 10
Tower 6 HFG Heat Fluxes**

**Igloo Fire Test 10
Tower 5 HFG Heat Fluxes**

**Igloo Fire Test 10
Tower 7 HFG Heat Fluxes**

Igloo Fire Test 10
Tower 8 HFG Heat Fluxes

Igloo Fire Test 10
Wall HFG (1-3) Heat Fluxes

Igloo Fire Test 10
Tower 9 HFG Heat Fluxes

Igloo Fire Test 10
Wall HFG (4,6,8) Heat Fluxes

Igloo Fire Test 10
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 10
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 10
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 10
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 10
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 10
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 10
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 10
Velocities Probes (1-5)

**Igloo Fire Test 10
Velocities Probes (6-10)**

**Igloo Fire Test 10
Velocities Probes (16-20)**

**Igloo Fire Test 10
Velocities Probes (11-15)**

**Igloo Fire Test 10
Velocities Probes (21-25)**

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Appendix J

Igloo Fire Experiment 11

**Igloo Fire Test 11
Tower 1 Thermocouples**

**Igloo Fire Test 11
Tower 3 Thermocouples**

**Igloo Fire Test 11
Tower 2 Thermocouples**

**Igloo Fire Test 11
Tower 4 Thermocouples**

Igloo Fire Test 11
Tower 5 Thermocouples

Igloo Fire Test 11
Tower 7 Thermocouples

Igloo Fire Test 11
Tower 6 Thermocouples

Igloo Fire Test 11
Tower 8 Thermocouples

**Igloo Fire Test 11
Tower 9 Thermocouples**

**Igloo Fire Test 11
Tower 2 HFG Thermocouples**

**Igloo Fire Test 11
Tower 1 HFG Thermocouples**

**Igloo Fire Test 11
Tower 3 HFG Thermocouples**

**Igloo Fire Test 11
Tower 4 HFG Thermocouples**

**Igloo Fire Test 11
Tower 6 HFG Thermocouples**

**Igloo Fire Test 11
Tower 5 HFG Thermocouples**

**Igloo Fire Test 11
Tower 7 HFG Thermocouples**

Igloo Fire Test 11
Tower 8 HFG Thermocouples

Igloo Fire Test 11
Wall HFG (1-3) Thermocouples

Igloo Fire Test 11
Tower 9 HFG Thermocouples

Igloo Fire Test 11
Wall HFG (4,6,8) Thermocouples

Igloo Fire Test 11
Wall HFG (4,6,8) Thermocouples

Igloo Fire Test 11
Floor HFG (1-5) Thermocouples

Igloo Fire Test 11
Wall HFG (10-12) Thermocouples

Igloo Fire Test 11
Floor HFG (6-10) Thermocouples

Igloo Fire Test 11
Floor HFG (11-15) Thermocouples

Igloo Fire Test 11
Floor HFG (21-23) Thermocouples

Igloo Fire Test 11
Floor HFG (16-20) Thermocouples

Igloo Fire Test 11
Clutter Calorimeter Pipe A Thermocouples

Igloo Fire Test 11
Clutter Calorimeter Pipe B Thermocouples

Igloo Fire Test 11
Clutter Calorimeter Pipe B Thermocouples

Igloo Fire Test 11
Clutter Calorimeter Pipe B Thermocouples

Igloo Fire Test 11
Clutter Calorimeter Pipe B Thermocouples

Igloo Fire Test 11
Clutter Calorimeter Pipe B Thermocouples

Igloo Fire Test 11
Velocities Probes (1-5) Thermocouples

Igloo Fire Test 11
Quarter Pool Thermocouples

Igloo Fire Test 11
Velocities Probes (6-10) Thermocouples

Igloo Fire Test 11
Velocities Probes (11-15) Thermocouples

Igloo Fire Test 11
Velocities Probes (21-25) Thermocouples

Igloo Fire Test 11
Velocities Probes (16-20) Thermocouples

Igloo Fire Test 11
Velocities Probes (1-5) Pressure Transducers

Igloo Fire Test 11
Velocities Probes (6-10) Pressure Transducers

Igloo Fire Test 11
Velocities Probes (16-20) Pressure Transducers

Igloo Fire Test 11
Velocities Probes (11-15) Pressure Transducers

Igloo Fire Test 11
Velocities Probes (21-25) Pressure Transducers

**Igloo Fire Test 11
Wind Speed**

**Igloo Fire Test 11
Tower 1 HFG Heat Fluxes**

**Igloo Fire Test 11
Wind Direction**

**Igloo Fire Test 11
Tower 2 HFG Heat Fluxes**

Igloo Fire Test 11
Tower 3 HFG Heat Fluxes

Igloo Fire Test 11
Tower 5 HFG Heat Fluxes

Igloo Fire Test 11
Tower 4 HFG Heat Fluxes

Igloo Fire Test 11
Tower 6 HFG Heat Fluxes

Igloo Fire Test 11
Tower 7 HFG Heat Fluxes

Igloo Fire Test 11
Tower 9 HFG Heat Fluxes

Igloo Fire Test 11
Tower 8 HFG Heat Fluxes

Igloo Fire Test 11
Wall HFG (1-3) Heat Fluxes

Igloo Fire Test 11
Wall HFG (4,6,8) Heat Fluxes

Igloo Fire Test 11
Wall HFG (10-12) Heat Fluxes

Igloo Fire Test 11
Wall HFG (5,7,9) Heat Fluxes

Igloo Fire Test 11
Floor HFG (1-5) Heat Fluxes

Igloo Fire Test 11
Floor HFG (6-10) Heat Fluxes

Igloo Fire Test 11
Floor HFG (16-20) Heat Fluxes

Igloo Fire Test 11
Floor HFG (11-15) Heat Fluxes

Igloo Fire Test 11
Floor HFG (21-23) Heat Fluxes

Igloo Fire Test 11
Clutter Calorimeter Pipe A Heat Fluxes

Igloo Fire Test 11
Clutter Calorimeter Pipe E Heat Fluxes

Igloo Fire Test 11
Clutter Calorimeter Pipe B Heat Fluxes

Igloo Fire Test 11
Clutter Calorimeter Pipe G Heat Fluxes

Igloo Fire Test 11
Clutter Calorimeter Pipe J Heat Fluxes

Igloo Fire Test 11
Velocities Probes (1-5)

Igloo Fire Test 11
Clutter Calorimeter Pipe K Heat Fluxes

Igloo Fire Test 11
Velocities Probes (6-10)

**Igloo Fire Test 11
Velocities Probes (11-15)**

**Igloo Fire Test 11
Velocities Probes (21-25)**

**Igloo Fire Test 11
Velocities Probes (16-20)**

**Igloo Fire Test 11
Combustible Gas Analyzer Results**

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