Analysis of Hold Time Models for Total Flooding Clean Extinguishing Agents

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Abstract

This study documents the experimental results of a research program designed to evaluate the validity of the widely published hold time prediction models found in NFPA 2001, Annex C and ISO 14520-1, Annex E. The models discussed in these standards obtain a measure of the equivalent leakage area, which, when coupled with 'worst case' assumptions, can be used to determine the minimum hold time. Three hold time prediction theories are adopted from these standards for validation; a wide descending interface model as implemented in ISO 14520-1 and two sharp descending interface models from the 2004 and 2008 publications of NFPA 2001.

The experimental program is comprised of thirty four tests conducted in a 103 m^3 test enclosure. Seven clean agents are utilized in the study; selected to include both inert gas and chemical agent types while spanning a wide range of agent vapor densities. This includes FK-5-1-12, HFC-125, HFC-227ea, HFC-23, IG-100, IG-541, and IG-55. A series of holes were drilled through enclosure boundaries at upper and lower elevations which were opened or closed as a means of regulating the amount of leakage area for any given test. Vertical profiles of agent concentration and ambient pressure are used to evaluate the agent concentration distribution, rates of agent draining, and the effective lower leakage fraction.

A nondimensional hold time is used to compare experimental results involving differing agent types and leakage areas. Results show that experimental values of the hold time are generally up to 50% longer than the theoretical hold time predictions when evaluated as the time to reduce the agent concentration to half its initial value. When evaluated as a 15% drop in concentration each model's validity is significantly reduced. Under this condition, experimental hold time values are up to 50% shorter than the predictions of the sharp descending interface models and up to 150% longer than the wide descending interface model.

Nomenclature

A_F	Enclosure floor area [m^2]
A_i	Orifice area for gas flowing into enclosure [m^2]
A_o	Orifice area for gas flowing out of enclosure [m^2]
C_o	Discharge coefficient for the orifice described by A_o [-]
C_U	Unit conversion constant in the semi-empirical orifice flow equation [s^{2n-1}/m^{2n-1}]
c_i	Initial clean agent volume concentration [Vol. %]
c_f	Final clean agent volume concentration [Vol. %]
F	Lower leakage fraction, Equation 2 & 4 [-]
$\tilde{F}$	Dimensionless ratio of outflow and inflow orifice areas [-]
g	Acceleration due to gravity [9.81 m/s^2]

H_0	Enclosure maximum height [m]
H_e	Interface equivalent height [m]
H_i	Interface height [m]
H_p	Protected height [m]
$\tilde{H}_{SDI_{2004}}$	Dimensionless height for the sharp interface theory of the 2004 NFPA publication [-]
$\tilde{H}_{SDI_{2008}}$	Dimensionless height for the sharp interface theory of the 2008 NFPA publication [-]
$\tilde{H}_{WDI}$	Dimensionless height for the wide interface theory of published in ISO 14520-1 [-]
n	Orifice flow exponent in the orifice flow equation [-]
$\tilde{t}_1$	Dimensionless hold time used when orifice flow exponent is variable [-]
$\tilde{t}_2$	Dimensionless hold time used when orifice flow exponent is equal to 0.5 [-]

Greek Symbols

β_1	Dimensionless coefficient used when orifice flow exponent is variable [-]
β_2	Dimensionless coefficient used when orifice flow exponent is equal to 0.5 [-]
$\tilde{\rho}$	Dimensionless density parameter [-]
ρ_{ag}	Clean extinguishing agent vapor density at 21°C [kg/m^3]
ρ_{air}	Density of air; 1.202 in NFPA & 1.205 in ISO standards [kg/m^3]
ρ_{mix}	Agent and air mixture density [kg/m^3]

Abbreviations

FK	Fluoroketone
HFC	Hydrofluorocarbon
IG	Inert Gas
ISO	International Standards Organization
NFPA	National Fire Protection Association

Introduction

Total flooding fire suppression involves the discharge of a clean extinguishing agent that is typically required to provide protection within the design envelope for a minimum ten minute period. The hold time is defined as the period of time required for a clean agent concentration to drop to a specified threshold (usually 80% of the initial discharge concentration) at a specified height in the enclosure (often chosen as the point of highest combustibles or at 75% of the maximum enclosure height) [1]. The goal of this study is to validate industry-standard hold time prediction models as they apply to a variety of clean extinguishing agents. A 103 cubic meter experimental enclosure is used to observe leakage flows through enclosure boundaries. The upper and lower leakage areas are varied to determine the effect on hold times of seven commercially available gaseous suppression agents: FK-5-1-12, HFC-125, HFC-227ea, HFC-23, IG-100, IG-541 and IG-55. Previous studies evaluating agent leakage rates show that model predictions are often inaccurate; resulting in both overly conservative and optimistic hold time approximations [2-5].

The 'fan integrity test' encompasses the test method and leakage modeling used to evaluate the total flooding system design with respect to the 'hold time' or 'retention time' requirement. NFPA 2001, Annex C and ISO 14520-1, Annex E contain enclosure integrity design standards, which are chosen for comparative analysis in this paper due to the prevalent adoption and use around the world. Experimental results will be validated against these standards' predictions of hold time. Modifications were made to the hold time theory in NFPA 2001 from the 2004 edition to the 2008 publication. Comparative analysis in this paper will utilize both NFPA publications to further help in understanding these changes.

Background & Theoretical Considerations

Total flooding fire protection systems discharge a gaseous agent in large quantities such that a protected enclosure will be filled to an extinguishing or inerting concentration. In the present study, only the application of clean extinguishing agents is assumed. Clean agents are frequently referred to as *halon replacement agents* due to the enactment of the Montreal Protocol in 1989, which prohibits the continued use of halogenated (or ozone-depleting) agents in total flooding applications. Clean extinguishing agents are classified in NFPA 2001 as electrically nonconductive and either readily volatile, or gaseous fire extinguishants that do not leave a residue upon evaporation [6, 7]. A typical total flooding system includes one or many high pressure, agent cylinders that are connected to a delivery pipe network through a manifold. The pipe network terminates at one or many discharge nozzles within a design envelope. Upon manual or automatic activation all cylinders are simultaneously opened and the discharge duration is targeted for 10 s for chemical agents and 60 s for inert gas agents.

The discharge event is turbulent, resulting in a relatively uniform mixture of clean agent and air inside the design envelope. The agent and air mixture mass density inside the design envelope is generally greater inside the enclosure than the density of air surrounding it. This density disparity exerts a positive hydrostatic pressure on lower enclosure boundaries and a negative interior-to-exterior pressure differential at upper enclosure boundaries. These pressure differentials drive a convective flow of agent-air mixture out lower leakages in enclosure boundaries, which, is balanced by fresh air flowing in upper leakages. This is the only transport method considered in evaluating the global rate at which agent drains from the enclosure.

The present study seeks to evaluate three different hold time models that predict the rate of agent draining; two *sharp descending interface* models (as theorized in the 2004 and 2008 editions of NFPA 2001) and the *wide descending interface* model (as employed in the 2006 edition of ISO 14520-1). Extensive derivations of the hold time theory contained in these documents are published elsewhere [2, 4, 5].

An analytical form relating the rate of agent draining to other configuration parameters can be achieved by introducing the following assumptions (central to each hold time model considered in this study). (1) Thermal effects are ignored. The agent-air mixture resulting after the discharge event and the air surrounding the enclosure are both assumed to exist at standard atmospheric temperature (21°C). Further, the thermal affects produced during a real fire incident are not considered. (2) Species diffusive transport is either neglected (sharp interface) or assumed to mix at an infinitesimal rate in known proportions (wide interface). (3) The leakage areas in enclosure boundaries are assumed to exist at only two locations: the extremes of upper and lower elevation.

The three theoretical models' governing equations are presented in the following. Only the main equations are discussed. A detailed derivation can be found in previous work reported in literature [2, 8, 9].

The wide descending interface model incorporated in ISO 14520-1 is given as Equation 1. In order to facilitate direct comparisons between various test configurations a dimensionless form is derived, which results in

$$\tilde{H}_{WDI} = \left[1 - \beta_1 \tilde{t}_1\right]^{\frac{1}{1-n}}, \tag{1}$$

where $$\tilde{H}_{WDI} = \frac{H_e}{H_0}, \quad \tilde{F} = \left(\frac{A_o}{A_i}\right) = \frac{F}{1-F}, \quad \tilde{\rho} = \frac{\rho_{mix}}{\rho_{air}},$$

$$H_e = H_0 - \left(H_0 - H_p\right)\frac{c_i}{2c_f}, \quad \tilde{t}_1 = \left(t_f - t_0\right)\frac{C_o A_o C_U g^n}{A_F H_0^{1-n}}, \quad \beta_1 = (1-n)\left(\frac{2\left(1-\tilde{\rho}^{-1}\right)}{1+\tilde{\rho}^{-1}\tilde{F}^{1/n}}\right)^n,$$

and $$\rho_{mix} = \rho_{ag}\left(\frac{c_i}{100}\right) + \rho_{air}\left(\frac{100 - c_i}{100}\right).$$

The dimensionless parameters found to govern the rate of agent draining include the ratio of the equivalent height to the enclosure's maximum height, $\tilde{H}_{WDI}$, the ratio between the outlet and inlet leakage areas, $\tilde{F}$, and the ratio of the agent-air mixture density relative to the density of ambient air, $\tilde{\rho}$. The equivalent interface height, H_e, is given as a function of the enclosure's maximum height, H_0, the protected height, H_p, and the initial and final agent concentrations, c_i and c_f, respectively. The hold time is thus evaluated as the time at which a specified concentration (c_f) exists at a specified height (H_p). The hold time in seconds is given as the $\left(t_f - t_0\right)$ where the dimensionless hold time is formulated as $\tilde{t}$. β_1 is a combined dimensionless coefficient. The vapor densities of atmospheric air and the agent-air mixture are ρ_{air} and ρ_{mix}, respectively.

The 2008 edition of NFPA 2001, Annex C espouses a sharp interface model that uses a variable value of the orifice flow exponent, n, as implemented in the wide interface theory [6, 9]. The above theory may be simplified into the 2008 edition of the sharp interface theory by setting the agent concentration at the end of the hold time, c_f, equal to one half the initial concentration, c_i (resulting in $H_e = H_p$). By redefining the dimensionless height parameter as the ratio of the actual interface height, H_i, to the enclosure's maximum height the intent of the 2008 edition of NFPA 2001, Annex C is met. Equation 2 shows this model in dimensionless form as

$$\tilde{H}_{SDI_{2008}} = \left[1 - \beta_1 \tilde{t}_1\right]^{\frac{1}{1-n}}, \tag{2}$$

where $$\tilde{H}_{SDI_{2008}} = \frac{H_i}{H_0}.$$

The sharp descending interface theory is also published in the 2004, and prior editions of NFPA 2001, Annex C [7]. The primary disparity between the 2004 and 2008 editions of NFPA 2001 lies in the application of the orifice flow equation. In the theoretical models above the orifice flow exponent, n, is a variable model input parameter. The 2004 edition of NFPA 2001 assumes that n is equal to 0.5. Equation 3 gives the dimensionless governing equation for the simple, sharp descending interface model as

$$\tilde{H}_{SDI_{2004}} = \left(1 - \beta_2 \tilde{t}_2\right)^2, \tag{3}$$

where $$\tilde{H}_{SDI_{2004}} = \frac{H_i}{H_0}, \quad \tilde{t}_2 = (t - t_0)\left(\frac{C_o A_o}{A_F}\right)\left(\frac{g}{H_0}\right)^{1/2}, \quad \beta_2 = \left(\frac{1-\tilde{\rho}^{-1}}{2\left(1+\tilde{\rho}^{-1}\tilde{F}^2\right)}\right)^{1/2}.$$

This can be derived from the sharp interface model (Equation 2) by introducing the assumption that n equals 0.5. Thorough derivation of this model is published elsewhere [4, 5].

Experimental Apparatus & Instrumentation

All testing reported herein was conducted at the Fike Corporation test facility in Blue Springs, Missouri, USA, in the same enclosure with no significant modifications made between test sessions. A schematic of the experimental enclosure is shown in Figure 1. Internal dimensions are 4.61 m (181.5 in) by 4.62 m (181.75 in) by 4.88 m. (192 in) in height, which totals 103.8 m^3 (3640 ft^3) in volume. Construction consists of 5.1 cm by 20.3 cm (2 in by 8 in) wood studs on 40.6 cm (16 in) centers with two interior layers of 15.9 mm (5/8 in) plywood and one layer of fiberglass sheeting as an interior finish. Intentional leakage area is supplied in two forms; (1) 84 drill holes 2.5 cm (1 in) diameter about the upper and lower enclosure boundaries and (2) a ceiling vent for discharge pressure venting of inert agents[1]. The drill holes are located near the extremes of enclosure elevation such that assumption (3) in the hold time models is met as closely as possible. All drill holes are offset from lower and upper boundaries by 30.5 cm (12 in) and equally distributed across each wall facing such that a nominal 10 upper and 10 lower holes exist per wall. A floor drain is located in the room's center that was closed by means of an existing ball valve.

For each clean agent tested, a series of controlled leakage area configurations were simulated by plugging and/or unplugging drill holes. Dense rubber stoppers were used to plug holes from the inside where they made a reliable seal with the fiberglass sheeting. Each specified leakage configuration was accomplished in such a way as to produce a *symmetrical* leakage pattern. For example, an experiment with 16 open drill holes would be accomplished by opening a single hole at 1/3 and 2/3 of the wall width on each wall, upper and lower.

Measured quantities include nozzle and ambient pressures, gas species vapor concentrations, and enclosure air temperatures. Nozzle pressures are retained as a means to ensure proper agent delivery and to diagnose potential problems in system design. Ambient pressures are recorded to document (1) the peak pressure pulses generated during agent discharge and (2) the hydrostatic pressure profile throughout the hold time. The present study focuses on the later, leaving the topic of room integrity for subsequent analysis. Clean agent volume concentrations are used to observe the drop in agent concentration as a function of height and time. Enclosure air temperature measurements are used to further analyze the applicability of neglecting this variable in hold time predictions (as prescribed by NFPA 2001 and ISO 14520-1 design standards).

Environmental conditions perceived to have an affect on agent draining were controlled as closely as possible. For all tests conducted the relative humidity was below 40% and the average ambient temperature before discharge ranged between 21 and 31°C (70 to 88°F). Generally, bias pressures & wind affects were sufficiently avoided simply due to the test enclosure location being encapsulated in a much larger warehouse.

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[1] Experiments 2, 3 and 4 from the IG-541 test set involve relatively 'tight' leakage configurations. In these tests only, concern for the potential to over-pressurize the enclosure was mitigated by using the vent.

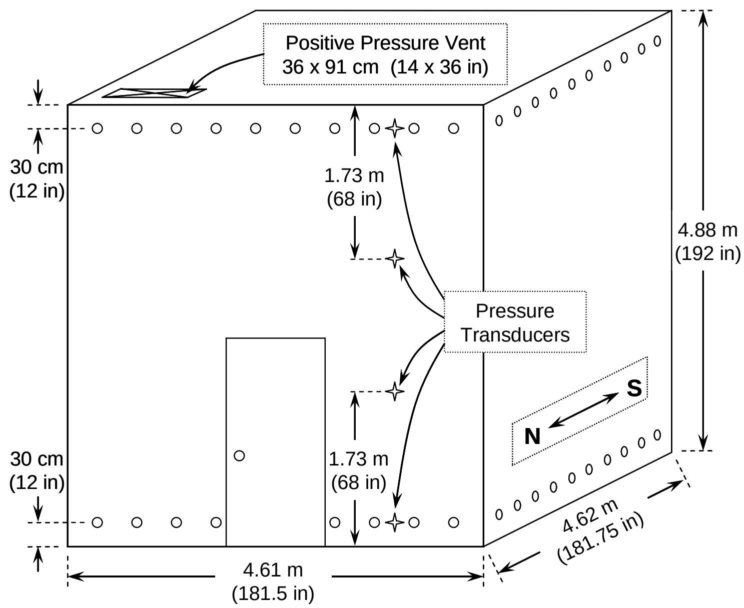

Figure 1: Schematic of the test enclosure. Ambient pressure probes and controllable leakage areas are shown. The positive pressure relief vent was allowed to open only for select IG-541 tests.

Agent concentration measurements were made with a variety of instruments. For each, an exhaustive effort is made to ensure that the recorded values are interpreted, filtered and scaled into engineering units according to that prescribed by well-established measurement theory[2]. Note that the recorded values are from a *relative* measurement technique which results in the inability to measure units of *absolute* concentration. Measurement uncertainty is likely less than ±10% of full scale, however, an investigation of measurement error bounds and propagated uncertainty in the calculated quantities is yet to be completed.

Experimental Results and Analysis

A total of 34 hold time tests were conducted. Seven clean agents are utilized in the study; selected to include both inert gas and chemical agent types while spanning a wide range of agent vapor densities. This includes FK-5-1-12, HFC-125, HFC-227ea, HFC-23, IG-100, IG-541, and IG-55. Discharge concentrations are typically at the agents' listed Class A design concentration. Leakage configurations used throughout the test phase result in hold times in the range of 2.8 to 46.3 minutes with a median value of 9.0 min[3]. This sufficiently spans the likely range of system use and allows for the enclosure *leakiness* level to be investigated as a potential source of prediction error.

Figure 2 shows the dimensionless theoretical hold time prediction plotted with respect to the dimensionless experimental hold time where the data series are grouped by agent type.

[2] Proper calibration of all gas sampling instrumentation was not available. Recorded values were scaled into engineering units based on a Zero value (a 30 s average of sampled fresh air before discharge) and a Full-Scale value (an average of ≥ 90 s of data acquired after agent discharge and readings had stabilized). The full scale value represents the agent discharge concentration, which was calculated using the NFPA 2001 Total Flooding Tables with the agent mass as an input (clean agent retainers were weighed before and after discharge). Data traces exhibiting suspect behavior are discarded.

[3] Hold time calculations performed according to NFPA 2001, 2008 Ed. with the protected height equal to 85% of the maximum enclosure height.

Either axis ranges from 0 to 1 where the interface can be imagined as traveling from the ceiling of the test enclosure (at dimensionless time = 0) to the floor of the enclosure (at dimensionless time = 1). For each test conducted a series of agent concentration measurements are taken across a range of elevations. Each instrument provides a single experimental value of the hold time duration where probes at upper elevations result in nondimensional hold times nearer to a 0 value and lower elevations tend towards values of 1. Figure 2 evaluates the hold time as a 50% reduction in agent concentration; relative to the initial, discharge concentration. Theoretical hold time predictions are based on the sharp descending interface model as published in the 2008 edition of NFPA 2001, Annex C.

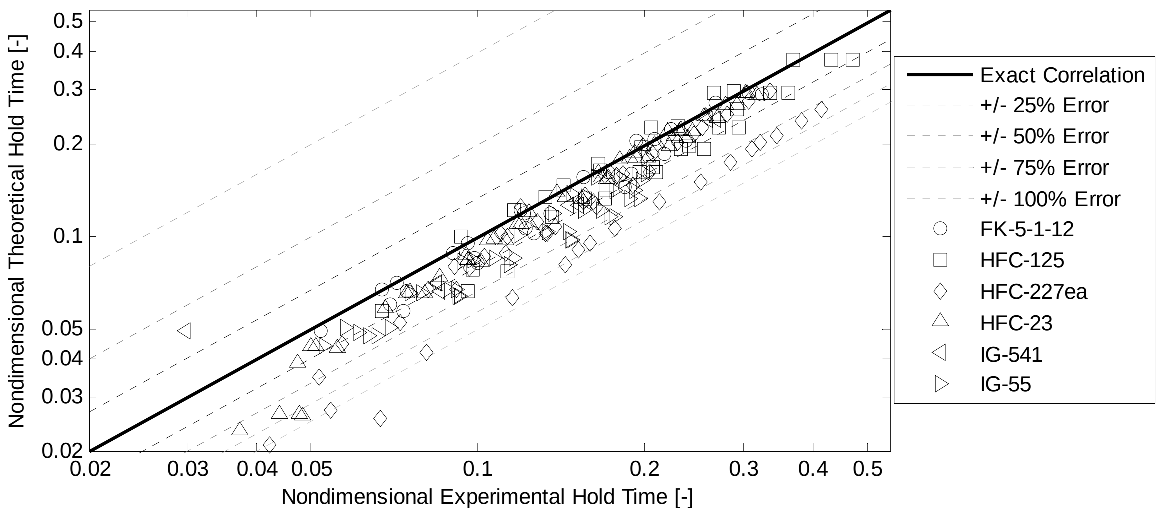

Figure 2: Validation plot of the nondimensional theoretical hold time versus the nondimensional experimental hold time with data series grouped by clean agent type. Plotted values are calculated as the quantity $(\beta \cdot \tilde{t})$. Experimental hold times are evaluated as the time when the agent concentration descends to 50% of the initial discharge concentration. Error lines represent the percent deviation from the theoretical hold time prediction. Theoretical hold time predictions are based on the sharp descending interface model published in NFPA 2001, 2008 Ed.

Figure 2 shows the degree of correlation observed for one agent type versus another. Generally, data points are equally scattered; indicating that the theory works equally well for a range of agent types (an analysis of the mean quadratic error for each agent's data set confirms this). Only the agent HFC-227ea does not conform to this trend as nearly all data points lie to the lower-right of the other agent types. This is potentially due to an unrealistically low vapor density having been used for calculations[4]. Data points in the lower-left region of the chart (highest elevation in the enclosure) display poorer correlation. This is likely due to the close proximity of higher agent concentration probes to the turbulent mixing of inflowing fresh air.

Data points below the *exact correlation* line represent a conservative condition where the agent is observed to drain more gradually from the enclosure than predicted by the theory. Conversely, data points above this line represent an overly optimistic condition where the

[4] Figure 2 analyzes the data according to NFPA 2001, 2008 Ed. All agent vapor densities used for hold time calculations are adopted from this standard and not confirmed with the agent manufacturer.

agent is found to drain more rapidly than the theory predicts. It is observed that when evaluated at a 50% concentration reduction the large majority of the data is in the conservative domain of the chart; generally with an error magnitude less than 50% (excluding HFC-227ea).

Figure 2 analyzes all experimental hold time data according to 2008 sharp descending interface model. Figure 3 analyzes the entire data set of Figure 2 according to the three hold time models in question where data series are grouped by the theory applied in nondimensionalizing the data. Once again, the hold time is evaluated as the time required to reduce the agent concentration to one half the initial value.

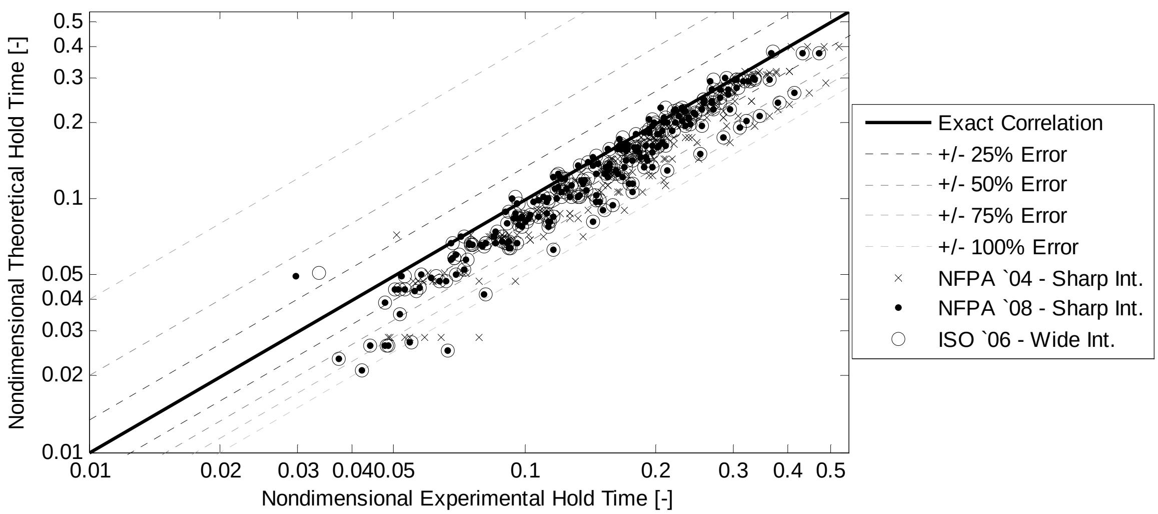

Figure 3: Validation plot of the nondimensional theoretical hold time versus the nondimensional experimental hold time with data series grouped theory type. Plotted values are calculated as the quantity $(\beta \cdot \tilde{t})$. Experimental hold times are evaluated as the time when the agent concentration descends to 50% of the initial discharge concentration. Error lines represent the percent deviation from the theoretical hold time prediction.

In Figure 3 the data tends to lie below the line of exact correlation. The group of data points for any of the three types of applied theory appears to be equally scattered. Although not visually apparent, depending on the value of the flow exponent, n, the sharp interface theory used by the 2004 edition of NFPA 2001 consistently predicts shorter hold times than the 2008 version of this theory. As explained in the Background and Theoretical Considerations section, when evaluated at a 50% concentration reduction the wide descending interface theory of ISO 14520-1 collapses into the sharp interface theory found in the 2008 edition of NFPA 2001. Slight differences in the two standards do exist including the assumed ambient temperature and method of evaluating the enclosure *leakiness*. Due to this, data points for these two theories almost always show perfect correlation except in select instances.

The 2008 publication of NFPA 2001 states that "a minimum concentration of 85 percent of the design concentration shall be held at the highest level of combustibles for a minimum period of 10 minutes or for a time period to allow for response by trained personnel" (i.e. the authority having jurisdiction may set any time threshold deemed appropriate) [6]. This recent modification to NFPA 2001 suggests that the hold time model presented therein will accurately predict the 15% reduction in agent concentration as opposed to the 50% concentration reduction, which is assumed in Figures 2 and 3.

Figure 4 displays the result of analyzing the entire data set for each of three hold time theories when the hold time is assumed to represent a 15% drop in agent concentration. Varying the assumed concentration reduction threshold has an affect on both the experimental and theoretical hold times.

Experimental values of the hold time are found by locating the moment in time, for any given instrument's recorded data trace, at which the agent concentration is found to drop below the specified concentration reduction threshold. The obtained value of the experimental hold time is then rendered dimensionless according to the three theoretical models, which results in slightly varying values for each.

The theoretical hold time is a function of the concentration reduction (below the initial discharge concentration) only when considering the wide interface theory. ISO 14520-1, Annex E limits the applicability of the wide descending interface to concentration reduction thresholds ranging up to 50% (even though the theoretical assumptions allow for a wider applicability range). The sharp descending interface theories do not implement the percent concentration reduction as an input variable. As such, theoretical hold time values for the sharp interface theories' data points in Figures 3 and 4 are identical although the experimental values deviate significantly.

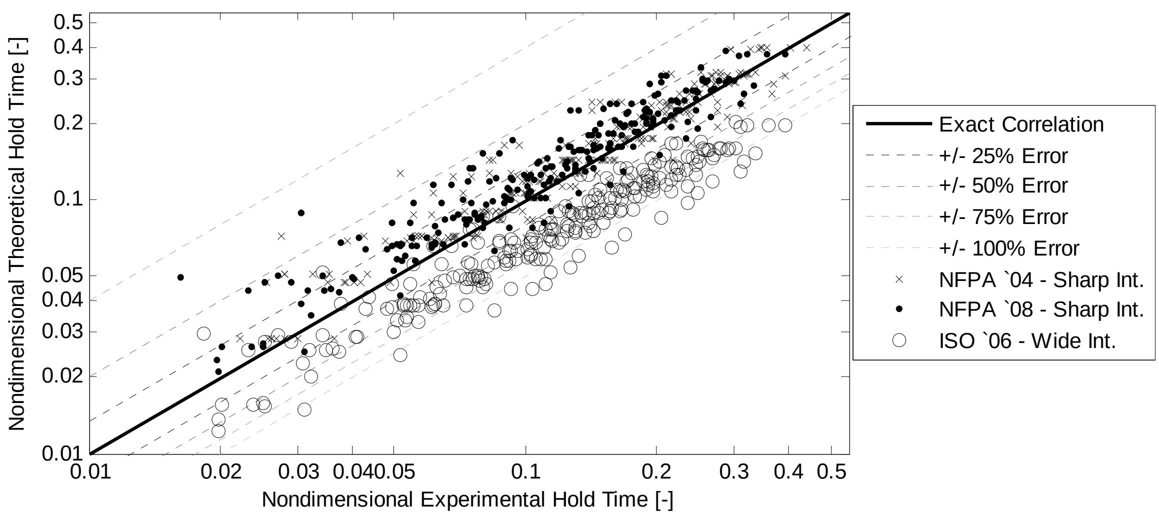

Figure 4: Validation plot of the nondimensional theoretical hold time versus the nondimensional experimental hold time with data series grouped theory type. Plotted values are calculated as the quantity $(\beta \cdot \tilde{t})$. Experimental hold times are evaluated as the time when the agent concentration descends to 15% of the initial discharge concentration. Error lines represent the percent deviation from the theoretical hold time prediction.

When the hold time is evaluated at a 15% reduction in concentration a clear trend is observed. The data set for each theory type in Figure 4 are not equally distributed about one another any more. Rather, a distinct separation between the sharp interface theories and the wide interface theory is found. The sharp interface theories typically result in an overly optimistic prediction of the hold time. The experimental hold time is usually around than 25% shorter than the theoretical prediction but may deviate by as much as 50%. Conversely, the wide descending interface theory provides overly conservative hold time predictions. The data indicate that actual clean agent retention times evaluated for a 15% concentration reduction threshold are typically longer than and up to twice as long in duration as the wide descending interface theory predicts (where data from HFC-227ea tests exhibit error of up to 150%).

As seen in Figure 4, the validity of the hold time predictions is greatly diminished when applied to predict a 15% reduction from the initial, discharge concentration. Although this may be the intended application when using any given theory to predict the hold time, it is apparent that the data spread in Figures 2 and 3 exhibit better correlation than that resulting in Figure 4. Figure 4 demonstrates this with a widely scattered data pattern which ranges from above 50% error in the overly optimistic region (above the line of exact correlation) to over 150% error in the conservative direction. It can be concluded that the validity of the hold time models for all agent types is drastically reduced when the hold time is not evaluated as a 50% reduction in concentration.

Summary and Conclusions

This paper documents the findings of a research program designed to experimentally evaluate the applicability of the widely published hold time prediction models found in NFPA 2001, Annex C and ISO 14520-1, Annex E. Thirty four experiments involving a variety of enclosure leakage configurations are presented for seven clean extinguishing agents: FK-5-1-12, HFC-125, HFC-227ea, HFC-23, IG-100, IG-541 and IG-55. Experimental results are modified to a dimensionless form to permit direct comparison between tests. Results indicate that the actual hold time is longer than the theoretical hold time prediction when evaluated as the time required for the agent concentration to drop to 50% of the initial discharge concentration. Under this condition, experimental hold times are typically up to 50% longer than the theoretical prediction.

The accuracy of theoretical hold time predictions diminishes greatly when the hold time is evaluated as a 15% reduction in agent concentration. Theoretical predictions according to the sharp descending interface theories are typically overly optimistic; resulting in experimental hold times up to 50% shorter than the predicted value. The wide descending interface theory typically results in overly conservative hold time estimates; yielding experimental values typically below 100% but also up to 150% longer than the theoretical value.

The 2008 edition of NFPA 2001 mandates that the clean agent must be retained for the specified hold time duration at no less than 15% below the initial discharge concentration. This study indicates that the application of the theory from NFPA 2001 or ISO 14520-1 design standards to the prediction of hold time for a 15% reduction in agent concentration will inevitably yield inaccurate results. Depending on the design standard of choice the user can expect the actual hold time to deviate from the theoretical prediction by anywhere from negative 50% to positive 150%.

Recommendation for Future Work

The ideal assumptions of spatial agent distribution employed in the sharp and wide interface models do not match the experimental results well. This assumption should be reevaluated and reinstituted in the theoretical derivation to yield a more robust analytical solution. The likely approach would be to model the interface width differently for the various clean agent types; loosely based upon the tendency of an agent to diffuse in air.

Nearly all structures are subject to bias pressure whether intentional (i.e. HVAC design, smoke control pressurization) or not (i.e. stack effect). A controlled introduction of positive and negative bias pressure from high and low elevations should be investigated.

If feasible, the legacy hardware incorporated for halocarbon gas sampling should be calibrated in order to convert the relative measurement technique to an absolute one. The various pressure transducers used simultaneously in testing deviate significantly from one another. More accurate means of monitoring the enclosure pressure profile and peak pressures during agent discharge should be obtained for any future testing.

The cooling affect of a clean agent discharge and resultant temperature change is not accounted for in the models, which may lead to measurable errors in the predicted hold time. Further analysis of these transient thermal effects is warranted.

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