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# **Influence of Gap Sizes around Swinging Doors with Builders Hardware on Fire and Smoke Development**

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**FINAL REPORT BY:**

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## **FOREWORD**

Fire development, smoke movement and ability of fire door to meet the test standards are affected by the gap sizes around the perimeter of the door, within the frame and between the bottom of the door and floor. Hence these gap sizes are regulated and the current regulations in NFPA 80 for the door clearances are from information and data gathered several years ago. Door clearances are one of the most frequently cited deficiencies on swinging doors with builders hardware. NFPA 80 currently allows a maximum bottom gap of 3/4 inch and a maximum of 1/8 inch for the perimeter (e.g. along vertical and top edges) of the swinging fire doors (with an additional 1/16 inch over-tolerance for steel doors). The clearance under swinging fire doors is frequently found to be greater than the maximum allowable gap size currently allowed by NFPA 80, due to irregularities in flatness and levelness of concrete slab floors at and around door openings. Hence it is important to have a deeper understanding of the impact of gap sizes on fire development and smoke movement.

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Swinging Doors on Fire  
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## Executive Summary

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Swinging fire doors with builders hardware are critical components of maintaining building compartmentation. The ability for Swinging Doors with Builders Hardware (Chapter 6, NFPA 80) to restrict fire and smoke is determined by meeting the requirements in Chapter 6 of NFPA 80, Standard for Fire Doors and Other Opening Protectives (2016) and passing the NFPA 252, Standard Methods of Fire Tests of Door Assemblies (2015) standardized fire door test. The ability for swinging fire doors to resist the passage of fire and smoke and to comply with the applicable standards is affected by the gap sizes around the perimeter of the door, and as a result, the maximum allowable gaps around swinging fire doors are codified.

While the gap sizes identified in NFPA 80 have been written into the codes and standards for more than 50 years, recent requirements written to improve inspections, testing, and maintenance (ITM) have resulted in door clearance issues being one of the most frequently cited deficiencies. NFPA 80 currently allows a maximum bottom gap of 3/4 in. and a maximum of 1/8 in. for the perimeter (e.g. along vertical and top edges) of the swinging fire doors (with an additional 1/16 in. over-tolerance for steel doors). The clearance under swinging fire doors is frequently found to be greater than the maximum allowable gap size currently allowed by NFPA 80, due to irregularities in flatness and levelness of concrete slab floors at and around door openings.

The difficulty in achieving the 3/4 in. bottom gap instigates the question at the heart of this research, of what effect increasing the maximum allowable bottom gap size has on fire development.

This study was conducted, in part, to assist standards writers with the information necessary to establish the effective maximum gap sizes for wood and steel fire doors.

## NFPA 80 & 252

This research project consisting of a literature review and a computational fluid dynamics (CFD) modeling exercise was conducted. The literature review traced the historical development of NFPA 80 to determine the technical basis used to determine the maximum allowable gap sizes currently in the standard.

The NFPA Technical Committee on Fire Doors and Windows has dealt with concerns about the clearance dimensions under and around swinging doors for many years. In 1959, NFPA 80 limited the clearance under swinging doors to a maximum of 3/8 in. Sometime between then and the 1966 edition, the maximum clearance dimension was changed to 3/4 in. In later editions, the clearance dimensions under doors continued to evolve. For instance, in the 1999 edition of NFPA 80 a new Table (*Table 1-11.4 Clearances Under the Bottoms of Doors*) was introduced (see Table 1). In 2007, the NFPA 80 requirements for clearance

dimensions under doors returned to the maximum 3/4 in. dimension, irrespective of the finished floor material or covering.

Table 1: Table 1-11.4 extracted from NFPA 80 (1995) displaying the clearances under doors including differences for different floor materials and arrangements (© National Fire Protection Association).

Table 1-11.4 Clearances Under the Bottoms of Doors		
Clearance Between	Swinging Doors with Builders Hardware	
	in.	mm
Bottom of door and raised		
noncombustible sills	3/8	9.5
Floor where no sill exists	3/4	19.1
Rigid floor tile	5/8	15.9
Floor coverings	1/2	12.7

The NFPA 80 requirements for clearance dimensions along the vertical and top edges of doors evolved over the years. In 1941, NFPA 80 **Section 1624**, Operation of Doors, stated: “Doors shall be mounted in such a manner that they will swing easily and freely on their hinges and close accurately against the stops on the wall frame, fitting snugly but without binding....” [Underlining added for emphasis.] No clearance dimensions were specified in the 1941 edition of NFPA 80.

In 1959, NFPA 80 **Section 503**, Door Frames, stated: “d. The clearance between the head piece and the jambs for wood or plastic composite doors shall not exceed 1/16 in. For other doors the clearance between the head piece and jambs, and between meeting edges of doors swinging in pairs shall not exceed 1/8 in...” [Underlining added for emphasis.]

Between 1959 and 1966, the clearance dimensions were modified to be a maximum of 1/8 in. regardless of door frame or door material/construction. These clearance dimensions remained unchanged until the 1990 edition of NFPA 80 when a 1/16 in. over tolerance for steel doors was introduced. Section 2-5.4 of the 1990 edition of NFPA 80 stated: “The clearance between the door and the frame and between meeting edges of doors swinging in pairs shall be 1/8 in. + 1/16 in. (3.18 mm + 1.59 mm) for steel doors and shall not exceed 1/8 in. (3.18 mm) for wood doors.” Another change to these clearance dimensions occurred in the 1995 edition of NFPA 80; an under-tolerance of minus 1/16 in. was added to section 2-6.4. (Note: The maximum clearance for wood doors remained at 1/8 in. during this time period.)

The latest change to the NFPA 80 clearance requirements occurred in the 2016 edition of NFPA 80. Section 6.3.1.7 was expanded to include several new

subparagraphs that specify clearance requirements for specific doorframe and door construction materials. Most notably, new paragraph 6.3.1.7.3 addresses 1/3-hour (20-minute) rated wood, high pressure decorative laminate (HPDL), and stile and rail wood doors installed in hollow metal door frames; it states that these doors “...shall not have clearances greater than 1/8 in.  $\pm$  1/16 in. (3.18 mm  $\pm$  1.59 mm).”

Throughout all of these changes, the technical committee records do not seem to show any supporting technical/scientific justification for the NFPA 80 clearance dimensions. Hence, the need and purpose for this research project.

It is important to note that NFPA 80 is the installation standard for swinging fire doors; it is not a fire door test standard. NFPA 252 is the primary test standard for swinging fire doors referenced by NFPA 80. Under NFPA 252 the maximum allowable bottom gap size permitted during door testing is 3/8 in. for single doors and 1/4 in. for paired doors, which differs from the maximum allowable bottom gap, 3/4 in., when the door is installed per NFPA 80 (see Table 2).

Table 2: NFPA Gap Comparison

Gap Type	Additional Criteria	NFPA 80	NFPA 252
Door to Frame		1/16 to 3/16 inches	1/16 to 1/8 inches
Door to Floor/Sill	Single Swing Door	Up to 3/4 inches	5/16 to 3/8 inches
	Double Swing Door		3/16 to 1/4 inches
Between a pair of doors		1/16 to 3/16 inches	1/16 to 1/8 inches

## Literature Review

The literature review was conducted to better understand the technical basis of the standard development process and how the standard arrived at the currently designated bottom gaps. The research focused on three main topics;

- the historical versions of NFPA 80 and NFPA 252,
- full-scale testing experiments on swinging fire doors, and
- computational modelling exercises

There are a compendium of important research papers and reports that were discovered in the course of this project (see Appendix A2: Compendium of related resources). The literature review revealed that there is minimal evidence to suggest that the gap sizes were directly related to any testing that was conducted. Several reports between the 1950s and 1970s discussed the importance of fit, rebate and intumescent elements for wood doors to attain their 20-minute rating. There was not a direct comment as to what the gap sizes should be. The computational modelling exercises that were conducted in the last two to three decades provided different modeling methods (i.e. computational fluid dynamics modeling, finite element modeling, etc.) that were used to predict the effect of a fire on the doors

implemented into the models. There was not a clear conclusion drawn between door gap size and the fire performance of the swing fire doors.

## Computer Modeling

A modeling exercise was conducted following the literature review. The design of the computer modeling exercise was constructed based upon the results of the literature review and discussions with the panel on the modeling approach to take, and the variables to consider in the study. Models were conducted using Fire Dynamics Simulator (FDS) a computational fluid dynamics (CFD) software package, to evaluate the effects of a larger bottom gap on fire development as well as the effects of larger side and top gaps.

In total 20 models were run over which the variables were the construction material of the door (wood or steel), the hourly rating of the door (20 min or 3 hr.), the number of doors (single or double), the bottom gap size (3/8 in., 3/4 in. in., 1 in.), and the top and side gaps (1/16 in., 1/8 in., 1/4 in.). These models were designed to focus on the furnace environment, following the geometry and inputs found in NFPA 252 as well as other sources from our literature review.

The modeling study shows that there are important thermal-fluid relationships that develop, but that the CFD models did not accurately model several important physical phenomena that doors undergo during a furnace test (i.e. thermo-mechanical effects on the door, such as expansion and warping).

## Future Work

The results of the literature review indicated several knowledge gaps where future work could provide the industry with confidence of the effect of the gaps around swinging doors. The knowledge gaps where additional work should be done are:

1. Forming a correlation between gap sizes around swinging fire doors and the corresponding fire performance.
2. Developing a computationally inexpensive way to provide guidance to stakeholders on the door performance based upon the gap sizing.
3. Providing solutions for stakeholders who have discovered non-compliant door gaps after conducting their inspection, testing, and maintenance (ITM) program.

The requirements of NFPA 80 and the NFPA 252 test have been in existence for many years and the performance of fire doors with swinging hardware has been providing an adequate level of safety. This indicates that this research is not reactionary to a fire event, indicative of a safety issue. Rather this issue was a result of inspections that resulted in a large number of failures.

NFPA 252 does not currently consider the fluid flow through doors so the performance of the standard does not include any comment as to air or smoke movement through the door. Through the literature review little to no information was found on the acceptable level of fluid flow through the door gaps as this is not a performance criterion in NFPA 252. It is therefore important to determine whether there should be any criteria for smoke flow through a fire door that results in a life safety hazard.

To clarify the effects of the door gaps on fire development is recommended that full scale testing be conducted. This approach is the only reliable way found by this research to determine what the effect of a larger gap size has on fire development, due to the complexity of how a door reacts in a furnace.

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Discussion of Modeling Effort

# 1 Introduction

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The gap sizes around swinging doors can influence the fire and smoke spread through fire rated construction. The current standard (i.e. NFPA 80) prescribes that the bottom gap be no larger than 3/4 in. (19.05 mm), and the side and top gaps be no larger than 1/8 in. (3.175 mm) — with an additional 1/16 in. (1.59 mm) over-tolerance for steel doors and 1/3-hour rated wood doors installed in hollow metal doorframes. Recently there has been more discussion regarding the exact performance of a gap size as it relates to fire doors, which forms the basis of this study.

The initial chapters of this research report (Chapter 2 and Chapter 3) provide a review of the historical NFPA 80 and NFPA 252 standards and summaries of the key reports and papers that were discovered over the course of the literature review. The literature review focused on investigations, studies and research papers, and information from manufacturers.

This research attempted to understand the effects of gap sizes around swinging doors on fire development, which includes not only the fire and heat transfer through the doors, but also smoke flow through the doors. It should be noted that these are considered separate in the standards as NFPA 80 and NFPA 252 focus on fire doors and NFPA 105 and UL 1784 are standards that address air-leakage rates around the perimeter of doors (i.e. smoke door assemblies).

The next chapters focus on the variables developed through the literature study, the physical phenomena which are important to replicate through modeling. Research efforts, particularly those which conduct full scale testing, are restricted to only analyzing a small number of variables. A listing of the variables that were either found in the literature or considered for this research are discussed in Chapter 4. The physical phenomena were decoupled and described to provide a dissection of the furnace test and how the door reacts during testing. The computational modeling exercises are then described in terms of the goal of the models and how the furnace geometry, door characteristics, and door flows, and different gap sizes were implemented into the CFD model.

## 2 Review of Codes and Standards

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In the United States, the use of fire doors is commonly required by the two most adopted life safety codes, NFPA 101 and the International Building Code (IBC). Fire doors are required when there are openings in a fire-resistance rated wall. The issue of protecting openings in walls has been a known problem by the National Fire Protection Association (NFPA) since as early as 1897 [1, p. p.1].

One of the most commonly adopted building codes in the United States is the International Building Code (IBC). This code requires the use of 20-minute doors in corridor walls with 1-hour rated fire partitions; in all 1/2-hour fire rated partitions; and in all 1-hour rated smoke barriers. 3-hour rated doors are required in fire walls and barriers of 3 and 4-hour fire resistance rated construction and for openings in fire walls [2, p. Table 716.5]. The IBC (2015 edition) requires doors to be installed in accordance with the 2013 Edition of NFPA 80 and swinging doors to be tested to NFPA 252 *Standard Methods of Fire Tests of Door Assemblies* or UL 10C *Standard for Positive Pressure Fire Tests of Door Assemblies* [2, p. §716.5]. The doors in smoke barriers and corridors are not required to pass a hose stream test [2, p. §716.5.3].

IBC requires installation of new fire doors to be in compliance with the inspection, testing, and maintenance requirements of NFPA 80 [2, p. §716.5]. The International Fire Code (IFC) Section 703.1.3 requires openings in walls, barriers, and partitions to be protected with approved doors that are maintained in accordance with NFPA 80. It's important to note that the NFPA 80 requirements for inspection, testing, and maintenance requirements apply to both new and existing fire door assemblies.

There has been an increase in the volume of questions and comments pertaining to the inspection, testing, and maintenance (ITM) requirements in NFPA 80 that is understood to be a result of the adoption of the 2012 edition of NFPA 101 *Life Safety Code* by the US Centers for Medicare & Medicaid Services (CMS) and the Joint Commission. CMS issued the regulation titled *Fire Safety requirements for Certain Health Care Facilities*, requiring all “Medicare and Medicaid participating hospitals, critical access hospitals, long-term care facilities, intermediate care facilities for individuals with intellectual disabilities, ambulatory surgery centers, hospices which provide inpatient services, religious non-medical health care institutions, and programs of all-inclusive care for the elderly facilities” to comply with NFPA 101 by July 5, 2016 [3]. While the initial application of the NFPA 80 door safety inspections is in health care facilities, it is likely that AHJs will begin applying these inspections and maintenance requirements to other types of buildings and facilities.

NFPA 101 references the 2013 Edition of NFPA 80 not only for fire door installation (§8.3.3.1) but also inspection and testing [4, p. §8.3.3.13]. The code requires fire door ratings be in accordance with NFPA 252, UL 10C or UL 10B *Standard for Fire Tests of Door Assemblies*. Additionally, there is reference to

ASTM E2074 in Table 8.3.4.2 permitting 20-minute doors to not be subjected to a hose stream test.

## 2.1 NFPA Document History and Comparison

### 2.1.1 NFPA 80

In 1897 the Committee on Fire Protection Covering for Window and Door Openings was formed. Over the years the standard has undergone many name changes and the scope has expanded to include more types of doors and opening protectives. The present scope of NFPA 80 is:

*“...the installation and maintenance of assemblies and devices used to protect openings in walls, floors, and ceilings against the spread of fire and smoke within, into, or out of buildings.”* [1, p. §1.1].

NFPA 80, as an installation standard, addresses the industry practices for door installation including larger door clearances [1, p. §A.4.8.4.1].

Reports on fire doors and shutters were presented at the annual meetings in 1897 and 1898 [5]. Between 1902 and 1907 fire testing was conducted [6], insurance organizations and manufacturers were consulted, and NFPA members were surveyed [7]. The finalized reports were published in 1908. These early rules and reports did not include any clearance guidelines.

It is believed that there was some understanding that a door not fitting the opening would not perform the same under fire conditions. In the 1915 edition, Rules 45 and 60, regarding door operation, noted that doors should be mounted so that they swing easily and close accurately [8]. Additionally, there was guidance that doors should fit the opening snugly and not bind. With regards to the installation of doors at this time, Rule 24 regarding the mounting of single swing doors instructed users to mount doors using 1/4 in. blocking between the bottom of the door and sill on the hinge side and 1/2 in. blocking on the lock side [8].

Changes to the standard occurred in 1916, 1917, 1918, 1927, 1928, 1931, 1937, and 1941; however, it was not until the late 1950s that the first gap sizes were introduced. In 1957 and 1959 the standard was reorganized with chapters focused on the type of door (i.e. swinging, rolling, etc.) instead of the rating of the door and material of door construction. It was finalized and accepted in 1959. Clearances values for flush-mounted doors included 1/16 in. between the head piece and jamb of wood or plastic composite doors; 1/8 in. between the head piece and jamb of other swinging doors; 1/8 in. between the meeting edge of doors swinging in pairs; and 3/8 in. bottom gaps [9]. A summary of the changes of the clearances in NFPA 80 can be found below in Table 3, Table 4, and Table 5.

The present clearances allowed around frames were established in 1995. The current gaps address steel and wood doors. Over the years there have been

clearance values for plastic doors and specific types of metal doors. In the 1973 edition the sentence regarding frame clearances was deleted during the rewrite, but was included again in the 1975 edition.

The tolerance that is seen today was established in the 1990 edition from a public comment submitted by the Steel Door Institute. The substantiation for the change was that

*“in actual practice, fire door assemblies are tested with clearances that average 1/8 in. and the ‘...shall not exceed 1/8 in.’ statement currently in 2-5.4 is overly restrictive. The clearance between the frame head and top of the door is especially susceptible to dimensions slightly in excess of 1/8 in.”*

The gap requirements at the bottom of doors has ranged from 1/4 in., (in 1915) to 3/4 in. (current requirement). Initially requirements were based on the mounting of doors; however, in 1967 the requirements switched to being based on the door construction. Additionally, certain door construction types were associated with specific hardware. By 1979, clearances from doors to raised non-combustible sills for all door types were 3/8 in. and door to floor clearances were 3/4 in. These values remained until 1986. Over the course of 20 years a new concept of clearance to floor coverings was added. In 2007 all bottom clearance types were removed and simplified to one value for all gaps under doors.

The door gap for the meeting edge of a pair of doors has fluctuated between 1/16 in. and 1/8 in. (with a  $\pm 1/16$  in. tolerance for steel doors) over the past 40+ years. Like the frame gaps, the tolerance of  $\pm 1/16$  in. was first established in 1990 and only applied to steel doors with builders hardware until the 2016 edition of NFPA 80. In 2016, an additional 1/16 in. over-tolerance was added for 1/3-hr (20-minutes) wood, HPDL, and stile & rail wood doors installed in hollow metal door frames.

Table 3: NFPA 80 Bottom Gap Size History for Swinging Doors with Builders Hardware

	1959	1966	1967	1968	1973-79	1986	1992	1995	1999	2007-16
Clearance Dimension Between Doors and [Unfinished] Floors without sills	3/8 in.	3/4 in.	3/4 in.	3/4 in.	3/4 in.	3/4 in.	3/4 in.	3/4 in.	3/4 in.	3/4 in. <sup>a</sup>
Between doors and raised noncombustible sills <sup>c</sup>						3/8 in.	3/8 in.	3/8 in.	3/8 in.	3/8 in. <sup>b</sup>
Between doors and surface of floor covering [carpet]						1/2 in.		1/2 in.	1/2 in.	
Between doors and surface of rigid floor tile										
<sup>a</sup> Clearance dimension measured between bottom of door and nominal surface of floor covering materials or unfinished floor.										
<sup>b</sup> Where bottom of door is more than 38 inches above the floor (see 4.8.4.3, NFPA 80 2016).										
<sup>c</sup> Noncombustible sills are a structural building element that supports door openings (see Section 4.8.2, NPFA 80 2016).										

Table 4: NFPA 80 Door to Frame Gap Size History for Swinging Doors with Builders Hardware

	1959	1966-79	1986	1990-92	1995-99	2007-13	2016
Wood and Plastic Faced Doors Rated for 1/3 <sup>a</sup> , 1/2, 3/4, 1, 1-1/2 hours	1/16 in.	1/8 in.	1/8 in.	1/8 in.	1/8 in.	1/8 in.	1/8 in. <sup>b</sup>
1/3-hr Flush Wood, HPDL, and Stile and Rail Doors Installed in Hollow Metal Door Frames							1/8 in. + 1/16 in.
Wood, HPDL, and Stile and Rail Doors Installed in Door Frames <u>OTHER</u> than Hollow Metal (all levels of fire rating)							1/8 in.
Steel/Hollow Metal Doors (all levels of fire rating)	1/8 in.	1/8 in.	1/8 in.	1/8 in. + 1/16 in.	1/8 in. ± 1/16 in.	1/8 in. ± 1/16 in.	1/8 in. ± 1/16 in.
Doors of Other Construction <sup>d</sup>							1/8 in. <sup>c</sup>

<sup>a</sup> An over-tolerance of 1/16 in. for 1/3-hr rated wood and plastic faced doors installed in hollow metal door frames was added to the 2016 edition of NFPA 80 (see 6.3.1.7.3).

<sup>b</sup> For flush wood, High Pressure Decorative Laminate (HPDL) faced doors, and stile and rail wood doors with ratings greater than 1/3-hour (see 6.3.1.7.4 in NFPA 80 2016).

<sup>c</sup> Unless otherwise permitted in the door frame, door, and latching hardware manufacturers’ published listings (see 6.3.1.7.5 in NFPA 2016).

<sup>d</sup> Other materials used in the production of labeled fire doors include fiberglass reinforced polyester (FRP) and aluminum.

Table 5: NFPA 80 Meeting Edge of Door Pairs Gap Size History for Swinging Doors with Builders Hardware

	1959	1966-79	1986	1990-92	1995-99	2007-13	2016
Wood and Plastic Faced Doors Rated for 1/3 <sup>a</sup> , 1/2, 3/4, 1, 1-1/2 hours	Not Specified	1/8 in.	1/8 in.	1/8 in.	1/8 in.	1/8 in.	1/8 in. <sup>b</sup>
1/3-hr Flush Wood, HPDL, and Stile and Rail Doors Installed in Hollow Metal Door Frames							1/8 in. + 1/16 in.
Wood, HPDL, and Stile and Rail Doors Installed in Door Frames <u>OTHER</u> than Hollow Metal (all levels of fire rating)							1/8 in.
Steel/Hollow Metal Doors (all levels of fire rating)	1/8 in.	1/8 in.	1/8 in.	1/8 in. + 1/16 in.	1/8 in. ± 1/16 in.	1/8 in. ± 1/16 in.	1/8 in. ± 1/16 in.
Doors of Other Construction <sup>d</sup>							1/8 in. <sup>c</sup>

<sup>a</sup> An over-tolerance of 1/16 in. for 1/3-hr rated wood and plastic faced doors installed in hollow metal door frames was added to the 2016 edition of NFPA 80 (see 6.3.1.7.3).

<sup>b</sup> For flush wood, High Pressure Decorative Laminate (HPDL) faced doors, and stile and rail wood doors with ratings greater than 1/3-hour (see 6.3.1.7.4 in NFPA 80 2016).

<sup>c</sup> Unless otherwise permitted in the door frame, door, and latching hardware manufacturers' published listings (see 6.3.1.7.5 in NFPA 2016).

<sup>d</sup> Other materials used in the production of labeled fire doors include fiberglass reinforced polyester (FRP) and aluminum.

## 2.1.2 NFPA 252

The fire test standard NFPA 252 was adopted by NFPA in 1942. The basic procedures for conducting the fire test were developed by Underwriters Laboratories Inc. (UL). Over the years small changes have occurred to the documents including the flexibility to conduct the test under positive or atmospheric pressure, revising the hose stream test procedures which were ultimately replaced with a reference to ASTM E2226, and the addition of tighter tolerances for furnace control [10].

The standard provides guidance on installation of the test specimen, device setup and layout, furnace test procedures, and performance criteria. Test specimen setup requirements include mounting the door to swing into the furnace and providing representative walls and flooring. Devices are used both to collect data and maintain the furnaces pressure and temperature. Data collected during the testing include the furnace temperatures by a minimum of nine thermocouples. The average of the temperature readings of these thermocouples is used to control the furnace to ensure the specified time-temperature curve is maintained. Tests can occur at atmospheric or positive-pressure. Performance criteria include the observation of flaming, the door remaining in the test wall, and movement of the edges of the door. If the door meets all of the performance criteria, then it passes the test.

As with NFPA 80, the gap sizes presently included in the standard have changed over time. The first edition included minimum clearances for doors based on their material of construction [11]. In the 1958 edition, clearances were revised, increasing the gap size at the top of frames and providing additional guidance that clearances may fluctuate by 1/16 inch [12]. The clearances presently seen in NFPA 252 were established in the 1972 edition [13]. A summary of the gap sizes in NFPA 252 can be found in Table 6.

Table 6: NFPA 252 Gap Size History

Gap Type	1941 <sup>b</sup>	1958 <sup>c</sup>	1972 <sup>d</sup>	2015
<b>Clearances at top of frame</b>		3/32 in.	1/8 in.	1/8 in.
Wood doors	1/16 in.			
Hollow metal doors	1/16 <sup>a</sup> in.			
<b>Clearance at sides of frame</b>		3/32 in.	1/8 in.	1/8 in.
Wood doors	1/16 in.			
Hollow metal doors	3/32 <sup>a</sup> in.			
<b>Clearance at sill</b>		3/16 in.		
Wood doors	3/16 in.			
Hollow metal doors	3/16 <sup>a</sup> in.			
Single swing door			3/8 in.	3/8 in.
Pair of doors			1/4 in.	1/4 in.
<b>Clearance at meeting edge of doors in pairs</b>			1/8 in.	

<sup>a</sup> Clearances to conform to good practices

<sup>b</sup> Clearances should not be less than given values

<sup>c</sup> Tolerance of  $\pm 1/16$  inch allowed

<sup>d</sup> Tolerance of minus 1/16 inch allowed



### 2.1.3 Gap Comparison

NFPA 80 and 252 consider three types of gaps in swinging fire doors. The differences in the allowable clearances between the two standards are summarized in Table 7 below. In addition to the tolerance differences the greatest fluctuation is seen with the gap between the door and floor (i.e. bottom gap).

Table 7: NFPA 80 & NFPA 252 Gap Comparison

Gap Type	Additional Criteria	NFPA 80	NFPA 252
Door to Frame		$1/16$ to $3/16$ inches	$1/16$ to $1/8$ inches
Door to Floor/Sill	Single Swing Door Double Swing Door	Up to $3/4$ inches	$5/16$ to $3/8$ inches $3/16$ to $1/4$ inches
Between a pair of doors		$1/16$ to $3/16$ inches	$1/16$ to $1/8$ inches

## 2.2 United States Testing Standards Comparison

NFPA 252 is just one of the fire door test standards accepted by the IBC and NFPA 101. Table 8 has a comparison of NFPA 252, the UL standards, 10B and 10C, and the withdrawn ASTM standard E2074, predominantly highlighting the discrepancies.

Table 8: Fire Test Comparison

	NFPA 252	UL 10B	UL 10C	ASTM E2074
<b>Test Setup</b>				
Ambient test temperature range	✓			
Furnace construction requirements	✓		✓	✓
Burner requirements			✓	✓
Door mounting must swing into furnace	✓	✓	✓	
Time-temperature curve	✓	✓	✓	✓
Door gap sizes (see <b>Table 7</b> )	✓	✓	✓	✓
Thermocouples used for furnace control	9	3	3	9
Neutral pressure plane at 40 inches above sill	✓			✓
Oxygen percentage readings			✓	
<b>Test Requirements</b>				
Hose stream required for 20-min door		✓	✓	
Hose stream required for 3-hour door	✓	✓	✓	✓
Hose stream test timing (minutes after furnace test)	2	3	3	3
Cotton pad test			✓	✓

	NFPA 252	UL 10B	UL 10C	ASTM E2074
<b>Performance Criteria</b>				
Door must stay in test wall	✓	✓		✓
Limited openings shall develop	✓	✓	✓	✓
Astragals	✓		✓	✓

## 2.3 Global Codes and Standards Overview

NFPA 80 and 252 are just two of the standards used globally. This section summarizes some of the other standards utilized around the globe with regards to fire door testing and installation.

### 2.3.1 Fire Door Tests and Classifications

In researching global codes and standards, it was found that there are often multiple standards needed to gather a complete picture of the test setup, procedures, and classification requirements. Often times general test requirements including furnace and device setup and the time-temperature curve are located in an overarching standard. More specific requirements for doors are located in a separate standard focused on building components.

AS/NZS 1530.4: Methods for fire tests on building materials, components and structures – Fire resistance test of elements of construction

This is an Australian and New Zealand standard. It includes the methodology for a furnace test and method for determining the fire resistance rating. The door is to be installed in a fashion representative of the intended use [14]

BS 476: Fire Tests on building materials and structures

This British Standard contains multiple parts. Part 20 has the general principles and requirements for determining the fire resistance ratings of building elements. If door to frame gaps grow to 6 mm (~1/4 in.) or if the door-to-sill gaps grow to 25 mm (~1 in.) the door fails the test [15]. Part 22 addresses fire test procedures for non-loadbearing elements of construction including fire doors. The fire doors are to be designed and constructed as used in practice. For pre-hung doors the gaps shall be at least 3 mm (~1/8 in.) [16].

BS EN 1634-1: Fire resistance and smoke control tests for door and shutter assemblies, openable windows and elements of building hardware

This British and European standard addresses the fire resistance tests for doors. It defers to EN 1363 for test conditions, some test specimen features, general test procedures, and performance criteria. The standard includes gap size requirements

for test specimen installation. The frame gaps shall not exceed 6 mm (~1/4 in.) and sill gaps shall not exceed 25 mm (~1 in.) [17]. Additionally, procedures on taking gap measurement and calculating the maximum size of gaps are included in the standard.

**BS EN 13501-2:** *Fire classification of construction products and building elements. Classification using data from fire resistance tests, excluding ventilation services.*

This British and European standard is used to determine the fire resistance rating of a door that has been tested using the procedures outlined in BS EN 1634. The standard discusses assessing fire doors for integrity, insulation and radiation and provides the classes of fire doors and other elements [18].

**CAN/ULC-S104:** *Standard Method for Fire Tests of Door Assemblies*

This Canadian standard was developed by UL. This standard is a test method for door assemblies similar to NFPA 252. The test method can also be used to evaluate individual components of a door assembly.

**BS EN 1363-1:** *Fire resistance tests – Elements of building construction*

This European standard contains the general principles for determining fire resistance. This standard includes common principles used in tests of a variety of elements of construction. It is similar to ISO 834; however, there are small differences including the pressure in the furnace [19].

**GB 12955:** *Fire resistance tests for fire resistant doors*

This Chinese standard has the testing and classification requirements for fire doors [20].

**ISO 3008:** *Fire-resistance tests – Door and shutter assemblies*

This international standard includes the guidance on the installation of the test specimen, location of instrumentation, and test procedures. It is to be used in conjunction with ISO 834-1. The standard notes that gaps shall be representative of those used in practice and a tolerance range shall be specified by the sponsor. The gaps utilized must be between the middle value and the maximum value of the sponsor specified range [21].

**ISO 834-1:** *Fire-resistance tests – Elements of building construction*

This standard is a commonly referenced standard for the heating curve used in British and European tests. Additionally, it includes the pressure conditions, test specimen construction and conditioning, instrumentation types, and integrity criteria for tested specimens. The standard information on gap gauge construction and procedures [22].

### 2.3.2 Installation and Maintenance

Many of the global codes and standards have separate installation and maintenance guidance, similar to NFPA 80. The Australian, and British, Hong Kong, and Singapore codes all provide guidance on how fire doors should be installed and maintained.

#### AS 1905.1: Components for the protection of openings in fire-resistant walls – Fire-resistant doorsets

This Australian standard has the minimum design and installation requirements for fire doors. The gap between the door and top surface of the floor shall be between 3 and 10 mm (~1/8 to 3/8 inches) and the distance between the leaf and the top of a non-combustible threshold shall be not more than 25 mm (~1 inch) [23]. The door should be not more than 3 mm from the frame with measurements taken at multiple points along the edge. Between the door and the doorstep, the clearance shall not more than 3 mm; however, the maximum at any one location may be up to 5 mm (~3/16 inches).

#### AS 1851: Routine service of fire protection systems and equipment

This standard includes requirements for maintaining fire doors. It however is not adopted by the Australian building code. It is a best practice maintenance standard and often adopted by state regulations. It recommends inspection of fire doors every six months [24].

#### BS 8214: The Code of practice for fire door assemblies

This code has guidance on the specification, installation and maintenance of fire doors. The newest version, 2008 edition, address all types of doors. However, the 1990 edition cited by the Building Regulations of the United Kingdom only applies to non-metallic doors. Additionally, this code only applies to doors with fire resistance ratings up to 2 hours. The door to frame clearances are to be equal on all sides [25]. For timber doors a recommended gap of 2 to 4 mm (~1/16 to 3/16 inches) is discussed. The standard provides requirements for sealing openings with intumescent materials where gaps sizes are exceeded. The door to threshold gap is to be in accordance with the manufacturer's installation instructions.

#### BS EN 14600: Doorsets and openable windows with fire resisting and/or smoke control characteristics. Requirements and classification

The European and British standard identifies operational requirements and test methods that are used to ensure a measured fire resistance capability can be assumed over a door's working life [26]. Additionally, it has an annex with inspection and maintenance suggestions for manufacturers to include.

#### Code of Practice for Fire Safety in Buildings

This code used in Hong Kong requires fire doors be “closely fitted around their edges to impede the passage of smoke or flame”. Additionally, it requires the gap between the door and floor be not more than 10 mm. While clearances for the other sides of the door are not stated, the commentary further states that the bottom gap should not be more than the values specified in the door’s fire test report [27, p. Clause C16.4].

SS 332: *Specification for fire doors*

This is the fire door standard in Singapore. The standard specifies the requirements for manufacturing and installing fire doors. It references AS 1530.4, BS 476, BS EN 1636-1, BS EN 1634-1, and ISO 3008 for fire tests [28].

## 3 Review of Literature

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Through the course of the literature review numerous documents were discovered, which lend insight to the effects of the gap size in fire doors on fire development. There are many different topics and studies which lend influence to this topic. The focus of this study was to present testing regimens which were done in the past and especially those that might have been used as a technical basis for changes to requirements in the standard. Studies on computer modeling that have been conducted are also included, where the particular interest is what types of models were used, what inputs were required, and what the limitations are.

### 3.1 Summary of important literature documents

#### 3.1.1 Testing

The fire testing resources that were most detailed were mainly conducted during the 1950s, 1960s, and 1970s, which likely influenced the design and implementation of fire doors in the United States. This section will feature a number of additions to that section as well as information more pertinent to the modeling and testing of doors.

Testing can take many forms and with literature from countries like Canada, the United Kingdom, and the United States, there are variations in standardized testing protocols and procedures. For example, the United States will rely on NFPA 252 or UL 10B, however the standards are not specific in the exact dimensions of the furnace and leave that up to the testing agencies.

#### Doors as Barriers to Fire and Smoke

NBS, "Doors as Barriers to Fire and Smoke," US Department of Commerce, Washington DC, 1966.

The study, conducted by Shou and Gross in 1966, was to better understand how dwelling unit doors performed against fire and smoke. The study found that there were small changes that could be made to improve the fire performance of dwelling unit doors; however, it is impractical to improve dwelling unit doors to the rating level of a commercial fire door assembly.

Normal wood doors, not required to be rated, can survive a normal fire test for approximately 4.75 to 8.5 minutes. Through the experimentation it was determined that the critical variables included:

- Door/door-panel thickness
- Clearance between the door and the frame
- The effects of warping (the warping of the wood over time)
- The type of hardware

- The method of how the door is attached to the frame
- The frame material

An issue with doors, which are both fire resistance rated and smoke rated, is that fire and smoke both find their way into the gaps. Smoke is dangerous to occupants as an asphyxiant as well as the reduction in visibility it causes. From a testing standpoint the only smoke that is developed during a standard fire test is from the door materials themselves, as a furnace is typically very clean burning.

As this research effort was aimed at investigating whether doors to dwelling units could be easily retrofitted, there are many mitigation measures that were added to the door facing material, the door surface coating, the door edge, the door frame, and the door stop.

In this experiment, the doors used were twin panel doors with approximate dimensions of 34 in. x 80 in. x 1-3/8 in., with the panel thickness being 3/8 in. The alterations, which were made to mitigate the effects of the fire, included normal paint, glass fiber reinforced paint, commercial weather stripping to the frame, sheet metal added to the door stop, sheet metal added to the door frame, and intumescent strips added to the door edges.

To evaluate the performance of the doors measurements of different parameters were conducted including quantitative measurement of the smoke obscuration, pressure sensors, thermocouples, as well as visual cues like flaming through the door. The results of the study demonstrated that:

- Conventional paints or fire-retardant paints (circa. 1966) does not offer any protection
- Glass-fiber reinforced paint does provide protection
- Doors covered with sheet steel or asbestos cement board show improvements from 17 min to 41.5min
- The steel doors achieve the longest time.
- *“A standardized and quantitative measurement of smoke transmission around the edges of doors is badly needed, unless it is to be assumed that fire doors are provided without regard to life safety”*
- The location of the neutral plane has a significant effect on flow of smoke out of the door (see Figure 1)

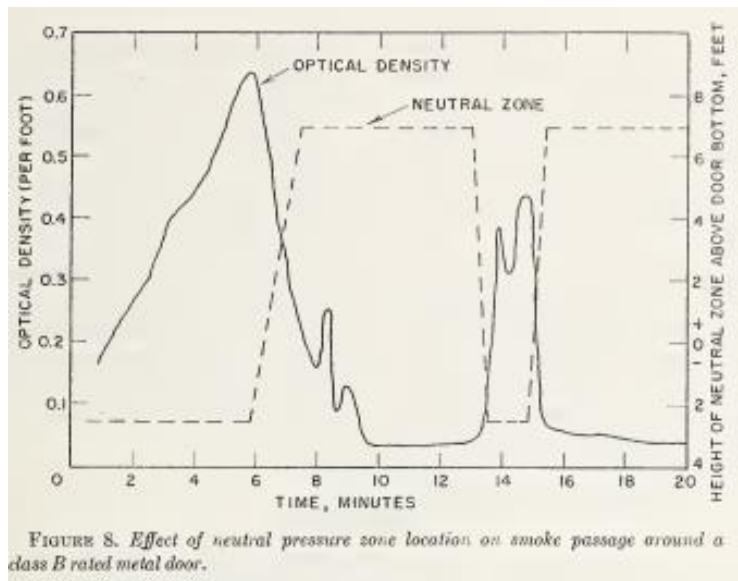


Figure 1: Effect of neutral pressure plan on smoke flow through the door [29]

### Why Important?

This study is important to this research because it speaks to the fire tests history on doors, the critical variables it considered, and possible mitigations options for non-compliant/non-rated doors.



## Fire Tests of Wood Door Assemblies

NRC, "Fire Tests of Wood Door Assemblies," National Research Council Canada, Ottawa, 1975.

This study observes the standard fire tests (ASTM E-152) on 26 solid core and particle board core doors in both wood and steel frames to develop the basis for a door assembly with a 20-min fire-resistance rating.

A testing procedure was developed in accordance with ASTM E-152 for this study. The clearance between the door and the frame was 3/32 in. +/- 1/16 in. (2.4 mm +/- 1.59 mm) at the top and sides of the door and 3/16 in +/- 1/16 in. (4.76 mm +/- 1.59 mm) at the bottom door gap. **This is interesting to note as the bottom gap size is four times smaller than permitted by US regulations.** Temperature rise of the door is not considered a failure criterion. The criteria for the test are:

- Door must remain in the opening during the fire test and subsequent hose stream tests
- The doors cannot move from their original position to a location more than half the thickness of the doors.
- An assembly containing a single swinging door, shall not separate more than ½ in at the latch location
- The test assembly must withstand the fire endurance test and hose stream test, without developing opening through the assembly.

The doors used in this study were wood and therefore contained some inconsistencies. Because of this, the NRC studied the effect of irregularities in the door construction. Figure 2 shows a picture of a door from an infrared camera with the depths noted and demonstrates the types of irregularities that a manufactured door can have. This study found that irregularities in the door construction of the core resulting in holes exceeding 1/16 in. (1.59 mm) allow the fire to break through the door (see Figure 2).

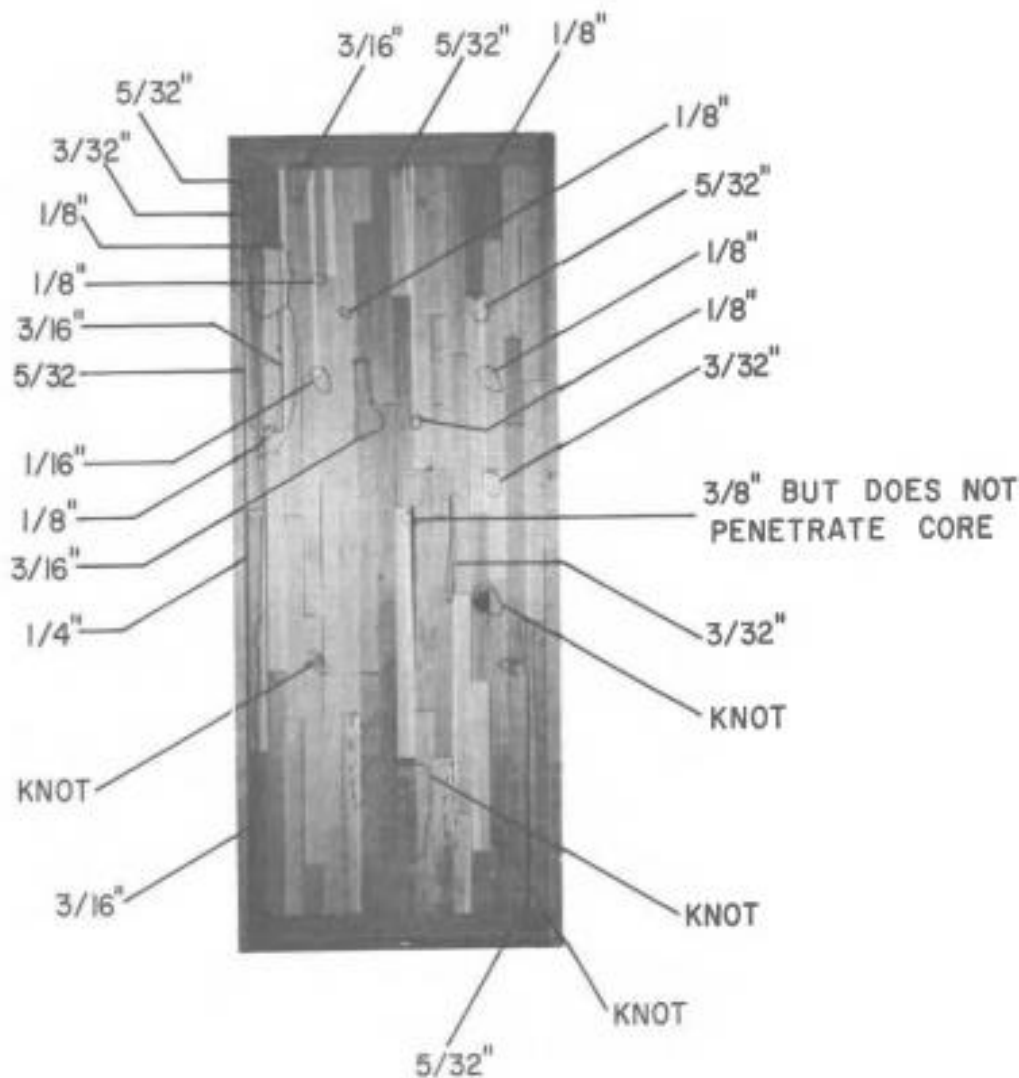


Figure 2: Solid core wood door showing the hot spots on a door as detected by an infrared camera. The callouts are the gaps in these spaces. Showing that the gaps in the core directly affect the temperatures through the door. [30]

The study identified that the behavior of the individual components (i.e. door, frame, and hardware) is important, as is the interaction between the components. During the course of testing the 26 doors there were six common types of failure in respect to fire performance:

- Formation of a hole through the door  
This is ascribed to the natural inconsistencies of the wood and whether there is a 1/16 gap created during the construction of the door (i.e. fastening the pieces of wood together) or by there being a gap in the wood blocks themselves.

- Formation of a hole between door and frame  
For a wood door in a wood frame the fire can affect the gap directly and leads to a hole through the assembly.
- Formation of a hole adjacent to a hinge  
A hinge itself acts as a conductor of heat via the metal and into the wood. This can either cause failure/detachment of the hinge from the door or screws falling out of the hinge elements.
- Formation of a hole adjacent to the latch set  
The hardware that is used on the door can provide a mechanism for heat transfer through the door. Metal conducts heat more readily than wood, so by placing uninsulated/unprotected hardware through the door it provides a path for heat through the space.
- Opening of the door into the furnace  
In several of the tests the doors failed by opening during the test due to a failure of the latch mechanism. It was found during the tests that incorporating a latch with a throw of 1/2 in. (12.7 mm) with proper insulation under the strike plate and using 1.25 in. screws (31.75 mm), the latch mechanism was provided adequate protection from fire.  
  
In several of the tests involving steel doors there were issues with the steel material reacting to the temperature. The conclusion of the study was that steel doors can warp if there is not appropriate blocking between the front and back steel sheets of the door.
- Formation of a hole through the trim between door frame and wall.  
Gaps in the wood framing around the door can result in burn through at the trim area, which can be mitigated by providing mineral wool or insulation of similar performance to any gaps in the frame or trim.

From this research it was clarified that there are a number of design features that wood doors and wood door assemblies should include to provide 20-min fire-resistance. The study also found some guidance for steel door design as well.

- Wood Core - The wood core should be solid without significant gaps (i.e. exceeding 1/16 in. (1.5875 mm))
- Door Frame - A wood frame should be of pine or more dense wood (i.e. having a specific gravity of ~ 0.38 or higher).
- Door - A steel door should include appropriate structural support to prevent the door leaf sheets from warping.
- Door Gaps - A wood door installed with a wood frame should attempt to minimize gaps between the door and the frame or by installing intumescent paint to the door edge surfaces.

- Door Gaps – Minimize gaps between the frame and the door to less than 1/8 in. (3.175 mm). With a mitigating strategy being installing intumescent paste into gaps.
- Door Hardware – The strike plate should be protected with some asbestos cement board, or similar insulation, and/or by the use of 1 ¼ in. (31.75 mm) screws.
- Door Hardware – The latch throw should be at least 1/2 in. (12.7 mm)
- Door Hardware – Protection of the latch set by asbestos paper around the cylinder, or latch cylinders designed to prevent heat transfer through the door
- Door Frame – Protection of the hinges with asbestos paper, or similar insulation, to reduce the propagation of holes.

### **Why important?**

This research is significant because it provides a general overview of research that contributed to development of requirements for 20-min. rated wood doors in Canada. It also highlights failure modes for this door type and potential mitigation options to approve door performance.

## An Investigation into the Fire Resistance of Timber Doors

W. A. Morris, "An Investigation into the Fire Resistance of Timber Doors," Building Research Establishment, United Kingdom, 1971

This report considers an investigation, which was done in the UK on a set of 18 timber doors to review the following variables:

- Effect of the depth of the rebate
- Effect of the fit of the door
- Effect of using an intumescent strip
- Effect of door thickness
- Effect of glazed vision panels

The results of the study showed that the 'fit' of the door is very important. Additionally, it is noted that a fire resistance of 30-min can be achieved by providing a seal at the edges of the door using intumescent strips.

A fire resistance rated door provides a closure in a fire protected wall, while providing the means for occupants to move from one fire resistance rated compartment to the next. A door should maintain or not drastically lower the fire resistance rating of the wall. However, a door is not typically going to be subjected to a fire event and must function properly during normal operation as well. For this reason the clearance between the door and the frame is important as without it the door cannot function.

The doors were tested following the applicable British Standards (BS 459, BS 476) and judged by the criteria of stability and integrity, where stability is the resistance of the door from collapsing and integrity is the resistance of the door from showing cracks, fissures, or orifices. The British Standards do not rely on the temperature of the unexposed face of the door.

Furthermore, failure was defined as showing flaming on the unexposed face for 15 seconds or more, and the development of a gap greater than 1/4 in. (6 mm) wide, accompanied by evidence of burning.

The results of the study demonstrate that those doors used as residential doors, corridor doors, and staircase doors are satisfactory for their purpose. In 1971, the British Standards classified doors based on their passing of the stability and the integrity criteria. A major contributing factor to the integrity failure, was the presence of openings around the edges of doors. The table below represents the time that the types of doors maintained their stability and integrity.

Type of Door	Minimum Duration for Compliance (min)	
	Stability	Integrity
1/2-hour fire check	30	20
1/2-hour fire resisting	30	30
1-hour fire check	60	45
1-hour fire rating	60	60

The effect of the depth of the rebate was tested using two different rebates (25 mm and 12.5 mm). All else being equal (the door fit, door thickness, etc.), the rebate has a direct effect on the fire development. If the frame is 12.5 mm (1/2 in.) with gaps of approximately 3 mm (0.118 in.), it will not satisfy the 20-minute integrity rating. The larger rebate of 25 mm (1 in.) with normal gaps (i.e. 3 mm) also indicates that failure will occur before 30 minutes.

The effect of the fit of the door was found to be the governing factor for determining whether a door would pass or fail the integrity and stability requirements. A direct comparison used doors with rebates of 12.5 mm (1/2 in.) and average gaps of 1.5 mm (1/16 in.) for Door B1 and 3.0 mm (1/8 in.) for Door C1. The failures of the doors occur at 22 minutes for Door B1 and 12 minutes for Door C1.

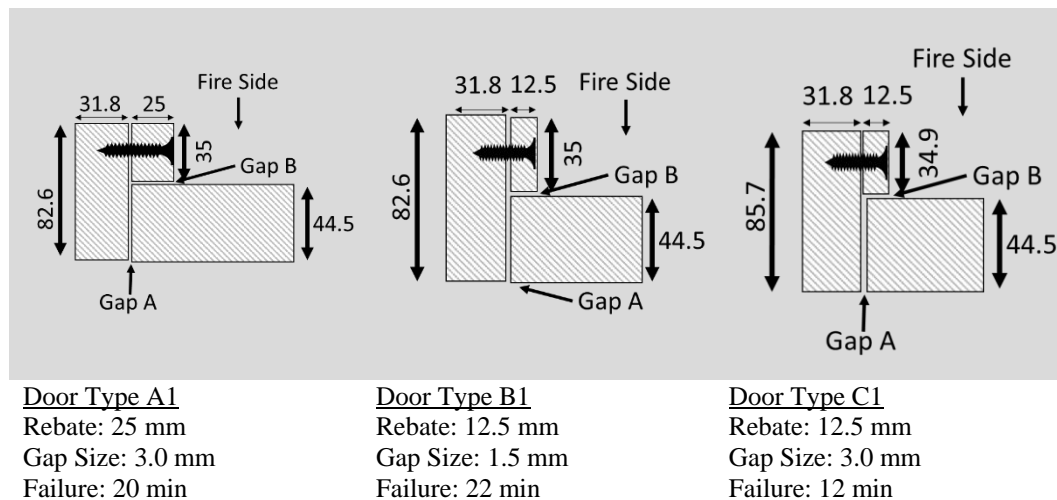


Figure 3: overview of three different door configurations with different Rebate Sizes (25 mm vs 12.5 mm) different gap sizes (3.0 mm vs 1.5 mm) and the resultant failure times. All Dimensions in millimeters (25.4 mm = 1 in.)

While this research indicates that the gap size and fit of the door is the most important factor there are mitigating features of the door that can decrease the hazard that a larger gap size would pose.

- Provide rebates 25 mm (1 in.) or larger (see Figure 3)
- Manufacture the full door assembly at the factory to improve tolerances and reduce field trimming

- Provide intumescent material along the gaps of the door. This works particularly well for loosely fitting doors with little to no rebate.
- A door thickness of 45 mm (1-3/4 in.) provides adequate safety for a 30-minute door

### Why Important?

This research is important because it directly tested different door factors and construction, including directly testing different door gap sizes. The study also shows the effect of other mitigation strategies on the fire performance of doors.

### 3.1.2 Computer Modeling

The development of computational modeling in recent decades has encouraged their use as they get consistently more advanced, faster, and more accurate. The fire community has accepted computational fluid dynamics (CFD) field models and uses them frequently. The structural and mechanical industries use advanced structural and finite element analysis models (FEM). At present there is not a modeling tool that can incorporate the fire environment, the heat transfer, the fluid flow, and the structural-mechanical properties which would be required to fully model a door in a furnace. **The modeling exercises that were studied have varying degrees of success and reinforced the idea that full scale testing is ultimately required to gather the desired information.**

### The influence of gaps of fire-resisting doors on the smoke spread in a building fire

Cheung, S., Lo, S., Yeoh, G., & Yuen, R. K. (2006). The influence of gaps of fire-resisting doors on the smoke spread in a building. *Fire Safety Journal*(41), 539–546. Retrieved from <http://www.sciencedirect.com/science/article/pii/S0379711206000695>

Cheung et al [31] worked on a numerical study that modeled different door bottom gap sizes to determine the effect of the smoke spread from the fire compartment. Their findings indicated that “...fire rated doors with a 3 mm door gap have demonstrated to be the best measure for impeding smoke spread while maintaining reasonable smoothness for the door movement.”

The study referenced that other codes which affect the bottom gap between the bottom of the door and the floor differ from country to country. With Hong Kong being the most restrictive (1/8 in.) and the United States being the most lenient (3/4 in.), see Table 9.

Table 9: Subset of bottom door gap sizes for different countries

Country	Bottom Door Gap
Hong Kong	4 mm (0.1575 in.) [between 1/8 in.-3/16 in.]
Australia	10 mm (0.3937 in.) [between 3/8 in.-7/16 in.]
USA (NFPA 80)	19 mm (0.7500 in.) [3/4 in.]

Many studies have considered compartment fires, however these studies assume that the door is open to look at smoke spread. Additionally, many field models, which look at smoke spread through a building, ignore the small gap areas around fire doors, assuming that they form a complete seal.

Using a three dimensional computational fluid dynamics technique, this study looked at gap sizes of 3 mm, 5 mm, 7 mm, and 10 mm. The goal of the study was to better understand the behavior of smoke through the bottom door gap of doors of different sizes, as well as to determine which door gap size best impedes the passage of smoke.

This study considered a single compartment fire scenario, where there was a fire placed in the center of a compartment (2.8m x 2.8 m x 2.4m). The fire is defined as having a maximum heat release rate of 100 kW, following a t-squared fire growth curve from 0 to 108 seconds, and decaying at the same rate from 136 to 244 seconds.

The simulation model was divided into 103,740 control volumes with the cells defined larger towards the ceiling and smaller towards the door gap. The model assumed a no-slip wall condition and adiabatic wall surfaces. The results of the study were reported in terms of the volumetric smoke spread rate through the door gap and the pressure gradient across the door, the average smoke temperature at the door, and the total volume of smoke spread.

The findings of the study were that the pressure differential between the fire room and the outside, resulting from the expansion of hot gases, forced hot gases through the door gap. The larger the door gap the less resistance to flow occurred and as a result higher temperature gases escaped from the fire compartment. The relationship of door gap height to smoke spread was non-linear.

The study concluded by recommending a gap size of 3 mm for the reason that it was the best at limiting smoke spread, while also maintaining reasonable door movement. Based on the report it is not entirely clear how they determined how much smoke spread would reach dangerous levels. This study used a CFD model and had a fire in a standard compartment, which was allowed to be extinguished. This study did not consider any of the performance metrics of a fire door, particularly endurance against a fire for a long period of time, burn through of the door, or any thermo-mechanical effects (i.e. expansion, warping, etc.).



## Thermo-mechanical Analysis of Fire Doors Subjected to a Fire Endurance Test

Tabaddor, M., Gandhi, P. D., & Jones, G. (2009). Thermo-mechanical Analysis of Fire Doors Subjected to a Fire Endurance Test. *Journal of Fire Protection Engineering*, 51 - 71.  
doi:<http://dx.doi.org/10.1177%2F1042391508098899>

A research project by a joint effort between Underwriters Laboratories and SimuTech Group provided insight into a finite element model that was aimed at studying the thermal and mechanical response of a double steel egress door exposed to a furnace environment. This study also was aimed at identifying the challenges of validating a numerical model with a fire test using a finite element model. As opposed to the CFD method (Cheung et al.), Tabaddor implements a finite element model (FEM) to replicate the thermal and structural effects from the furnace test instead of looking at fluid flow through the gaps.

Traditional furnace testing of fire resistance rated construction generally uses the standard time-temperature curve described in ASTM E119. Additionally, some fire rated door tests also pressurize the compartment to replicate the pressures that can be produced in a fire compartment by the expansion of hot gases.

A finite element model is required to include a necessary level of detail so as to capture a proportionate level of complexity. A number of assumptions were used to simplify the analysis to facilitate replication in the computer model. The frame holding the door(s) was modelled as rigid so that only the door needed to be modeled. A coincident node between the door panel and stiffener coupled the deformations for structural analysis and allowed for perfect thermal contact. The hardware of the door was not modeled, with the hinges assumed to be ridged.

A challenge with finite element modeling, particularly associated with fire, is finding material properties which are accurate for the temperature ranges that would be expected to be experienced during a furnace test; approximately from 0°C to 1000°C. Depending on the material of the door and the other materials in/around the door, there may be references available, with that data. Typically for items like steel, the thermal conductivity, specified heat, density, coefficient of thermal expansion, elastic modulus, and Poisson's ratio parameters can be found for a wide range of temperatures.

Another important consideration is the way that the thermal and structural responses are coupled. De-coupling of the thermal and structural responses was decided so that the thermal response could be modeled and validated before the mechanical response was modeled. For this case this decision to de-couple the thermal analysis and the mechanical/structural analysis lessens the computational load considerably.

The transient thermal analysis was conducted for the same duration as the fire test, with which the temperatures generally showed good agreement.

## 3.2 Manufacturers and Products

There are many different manufacturers and products available. In this section an overview of the types of doors available will be provided. However, for this study, the goal was to keep everything as generic as possible, to increase the applicability of this research.

Also note that while specific manufacturers are referenced as exemplars for this overview, this research effort is not endorsing any one manufacturer or method over any other.

### 3.2.1 Door Geometry

Door geometry can vary greatly in style, Figure 4 shows a collection of doors. The steel doors have different glazing and ventilation options, as do many of the manufacturers.

The insulating core options for steel doors also vary. Figure 5 displays some of the different options for steel doors. The insulation and the structure of the door are sometimes one in the same (i.e. Honeycomb core) or the structure is surrounded by the insulation.

Another key part of this study is to look at double doors and particularly the astragal location and how it interacts with the center gap as this was identified as a particularly problematic issue (see Figure 6).

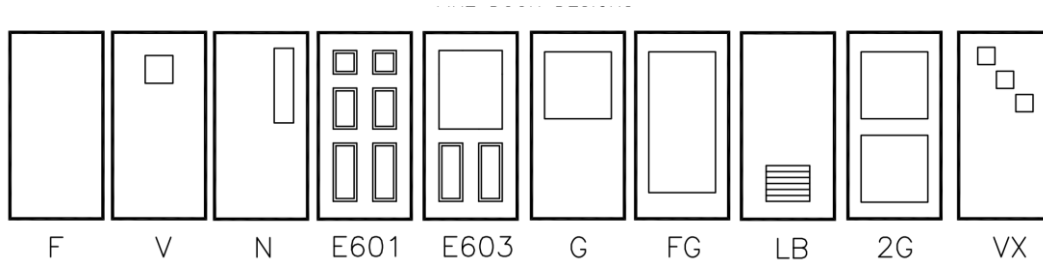


Figure 4: Collection of doors showing the different aesthetic and functional features a fire door can have. [32].

[Courtesy of [www.cecodoor.com](http://www.cecodoor.com)]

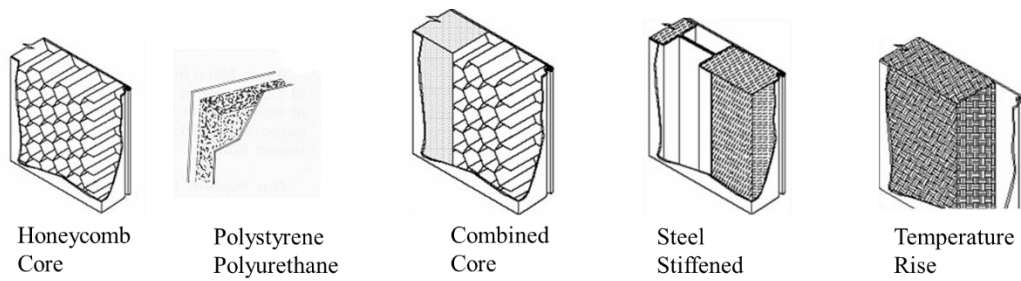


Figure 5: Overview of the insulation types for hollow metal steel doors. [33].

[Courtesy of [www.commdoor.com](http://www.commdoor.com)]

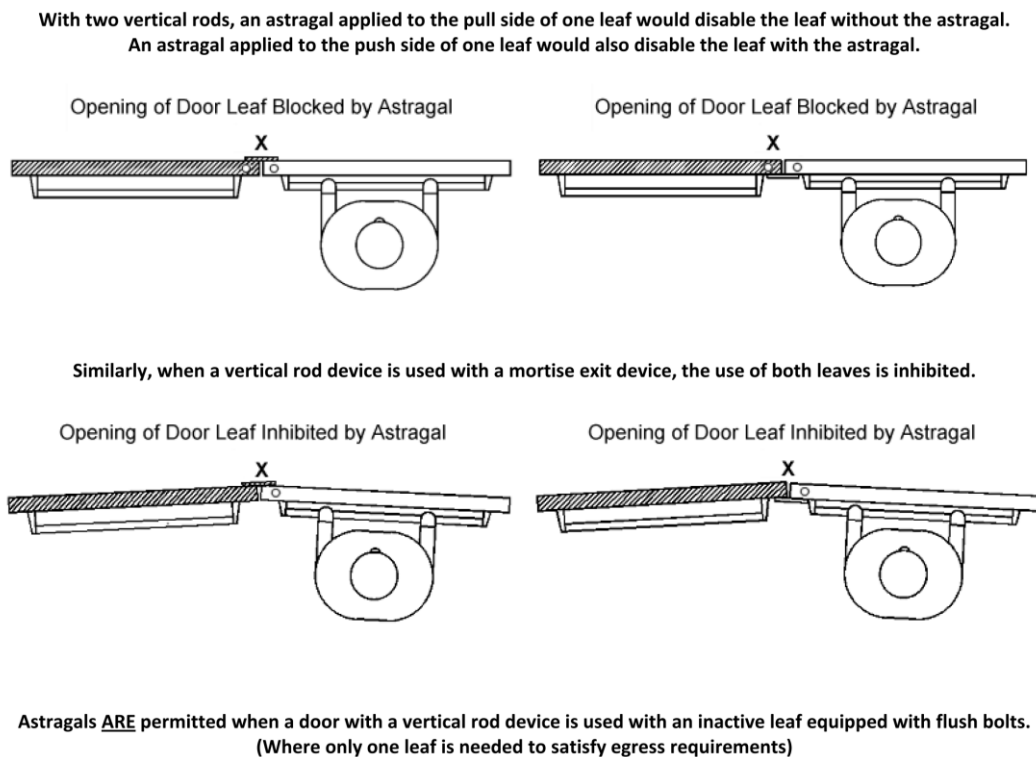


Figure 6: Overview of astragal options for double doors. [34]

[Courtesy of [www.dcihollowmetal.com](http://www.dcihollowmetal.com)]

## 4 Factors Related to Physical Phenomenon

The literature review has demonstrated that there are many factors that can affect the performance of fire and smoke doors, therefore the variables considered were categorized into the four categories as listed in Table 10.

The geometry of a typical wall, frame and door is relatively simple (see Figure 7). The challenge of modeling these specific element is to define sizes and construction, which are generic and reflect a majority of the doors on the market. During the simulations the material properties and dimensions of these elements were important to the accuracy of the models. Additionally, because there has been previous testing and modeling, there is a basis of research to which the results could be compared.

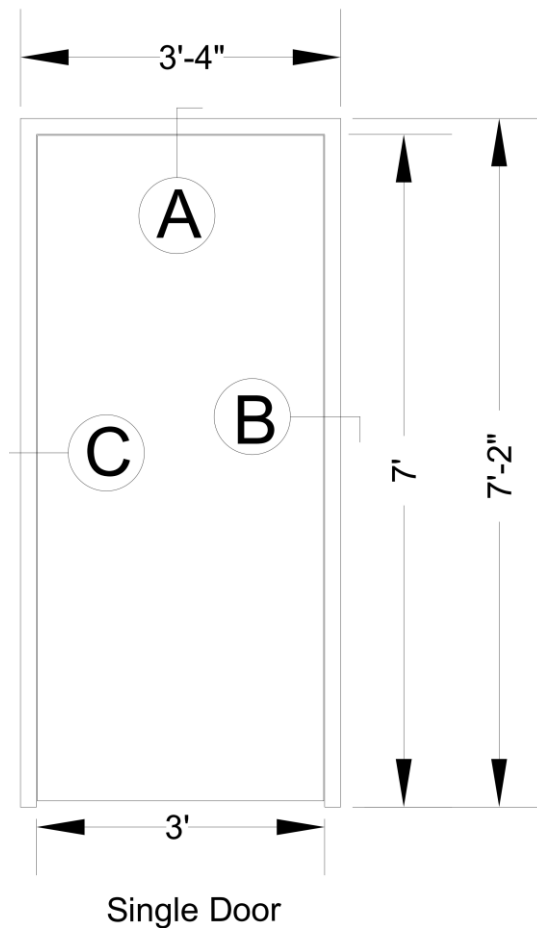


Figure 7: Generic single door model. The letters seen indicate sections that look at different portions of the door. A is extending across the top of the door. B is a section looking at the latch side gap. C is looking at the hinge side gap.

Table 10: Overview of critical variables

Geometry/Construction methodology		Material properties		Simulation Parameters		Results
Door Geometry		Thermo-Mechanical Material Properties		Model Mesh		Pressure
	Numbers of Doors		Density		Cell Size	Neutral Plane
	Door Structure		Thermal Conductivity		Number of Meshes	Furnace Pressure
	Span		Specific Heat Capacity	Heat Release Rate Curve		Outside pressure
	Thickness		Emissivity		Furnace Fire	Temperatures
	Door Insulation	Door Material Properties			Natural Fire	Exposed side of door
Door Gaps		Wood Doors		Duration of Simulation		Unexposed side of door
	Top Gap		Type of Wood		20 min	Door Gaps
	Latch Gap	Steel Door			1 hour	Thermocouple model in FDS
	Hinge Gap		Insulation	Fire Reaction Parameters		Flow
	Bottom Gap		Internal Structural elements		Heat of Combustion	Volume of smoke
Frame Geometry		Frame Material Properties			Soot Yield	Volume of fluid into furnace
	Rebate Size		Wood Frame		CO Yield	Volume of fluid out of gaps
	Frame Thickness		Steel Frame			Velocity
	Frame Insulation					Velocity out of door gaps
Wall						Visibility
	Materials					Radiative Heat flux
	Thickness					
Furnace						
	Size					
	Shape					

## 4.1 Overview of Modeling Effort

Using some of the model variables listed in Table 10 a modeling exercise was conducted to study the effects of gap size in a furnace. The models were designed in a computational fluid dynamics (CFD) program called fire dynamics simulator (FDS).

The model of a fire door in a furnace environment must replicate various thermo-mechanical processes, which are experienced by the fire door over the course of the test, including heat transfer to the door, heat conduction through the door, mass transfer of fluids, thermal expansion and shrinkage of the structure, and warping of the door structure. It is important to note that while these phenomena occur during a full-scale furnace test, any modeling conducted will focus on a limited number of these phenomena. There has been no complete computational modeling solution developed as of yet.

The models used in this context for this purpose have a number of limitations that restrict the results presented from being directly applicable to doors in a furnace.

1. These models do not capture the effects of shrinking or expansion that fire doors experience during full scale fire testing.
2. The performance criteria used to determine whether a door passes the NFPA 252 test, was not considered in these models. There are no performance criteria in NFPA 80 or NFPA 252 that address volume flow through the gaps or smoke flow through the gaps.
3. Modeling the gaps using a sub-grid scale empirical calculation does not take advantage of the 3D nature of the model and similar conclusions could be reached with basic thermodynamics and fluid mechanic calculations.

Beyond the limitations and difficulties in modeling there are additional difficulties with how a model results are used to judge whether door would pass or fail. The models that were used can output temperature, velocity, volume, and smoke levels, however the NFPA 252 test standard does not include quantified pass fail criteria. Because of this and lacking data from full scale testing these metrics cannot be used to identify whether a door would pass or fail without additional data that could relate a quantifiable metric with door failure.

An overview of the modeling effort is recorded in Appendix B.

## 5 Test Matrix

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The results of the literature review and the modeling exercises influence the type and number of tests that are recommended for further study. The literature review provides an overview of previously conducted testing and modeling.

Currently swinging fire doors with builder's hardware must be tested in compliance with NFPA 252. NFPA 252 provides the framework for the testing arrangement, setup, parameters, and performance pass/fail requirements. NFPA 252 specifies the maximum gap size for the bottom, side, top, and center gap (for double doors). As NFPA 252 is the standard by which swinging fire doors with builders hardware are tested, any testing conducted must be compliant with NFPA 252.

The purpose of this full scale testing is to determine the performance of swinging fire doors with builder's hardware in relation to the door gap sizes. The full scale testing program is influenced by the results of the literature review and the results of the modeling exercise.

### Influence From Research

The literature review included a number of testing reports and modeling studies, which illustrated the number of variables involved in the construction of fire doors such as the door fit (gap sizes), door thickness, the thermal insulation of door hardware, the door material, etc. (see Section **Error! Reference source not found.**). However, the focus of this research is to evaluate the effect of the door gap size has on fire development.

The modeling exercise sought to test a number of variables including the gap size in order to influence the full scale testing scenarios. The modeling approach utilized a CFD approach, providing information for the flow of soot and other gases, but does not account for any physical changes to the door (expansion, shrinking, etc) which will also influence the fluid flow. The results of the study demonstrated a simple thesis where larger gaps allowed for larger volume flow and vice-versa. The modeling did not present a strong influence on the performance of any test scenario over any other.

### Testing Approach

As a result, the testing approach that is recommended is a tiered approach that allows for feedback from the stakeholders so that the effectiveness of the testing regimen is considered at multiple points. Using the same variables as considered during the modeling exercise (see Table 12) would require 20 full scale test configurations. While this would be ideal, limited resources require a more efficient approach to testing. Figure 8 gives a representation of different test configuration options given that the variables are: the number of doors, the door material, and the gap size.

For example, to determine the effect of a 1 in. bottom gap in a single wood door the baseline test that is required is a single wood door with a bottom gap of 3/8 in. The door with a 1 in. bottom gap would then be tested to evaluate whether it passes or fails. It is not predictable at this time whether a positive result from one group variable (i.e. single wood doors) is applicable to other variables (i.e. single steel doors, double doors, etc). For this reason, it is recommended to test a subset of variables

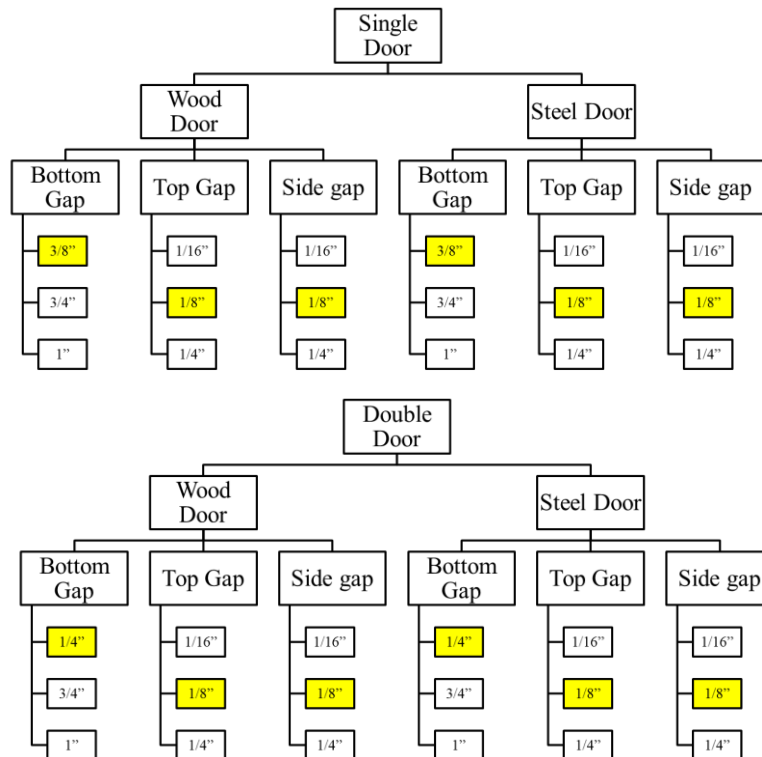


Figure 8: Representation of possible scenarios for a single swinging fire door with builder's hardware. The highlighted gap dimensions indicate what the baseline gaps sizes are. Note: Highlighted cells represent the maximum allowable gap size in NFPA 252.

To evaluate the effect of the gap size on fire development the door performance in the furnace test is compared to the baseline test to compare the performance of each.

For example, to evaluate the performance of a single steel door, a baseline test is conducted with NFPA 252-compliant door gaps. Then a single steel door with a larger gap size is conducted and compared to the baseline test. A second sub-group which may consist of a single wood door conducted in compliance with NFPA 252 establishes a baseline for single wood doors. This is then compared against test where only the gap is changed. The performance for each can then be compared. If the performance from the different sub-groups is similar for the different gap, then the gap is significant. If the performance is not similar either



the gap size is not significant or the performance metric is not significant (see Figure 9).

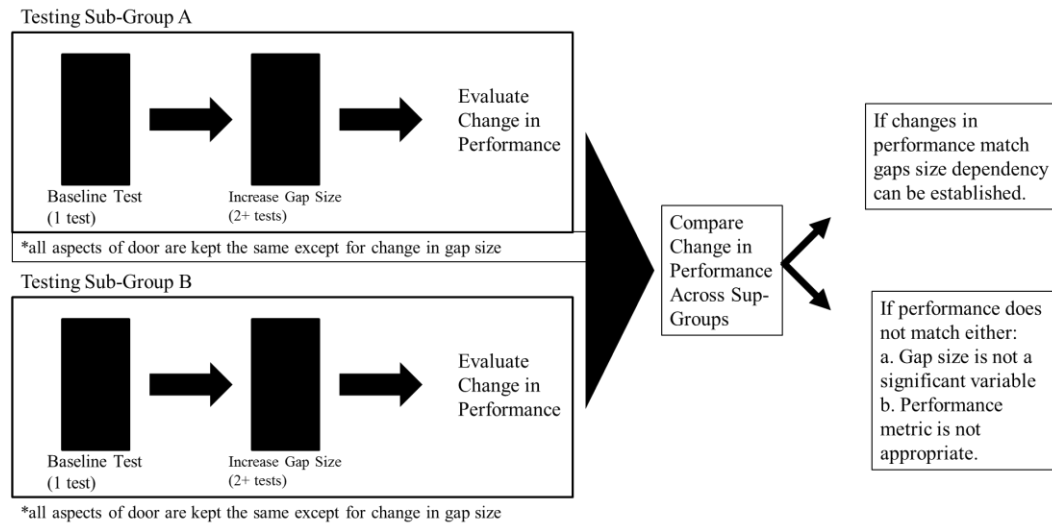


Figure 9: Representation of testing sub-groups that are compared to conclude the significance of the gaps size versus the baseline.

## Variable Selection

The number of variables that have been presented would result in approximately 4 baseline tests and approximately four tests per baseline that account for the bottom gap, top, and side gap variable.

- Single Wood Door (baseline)
  - Smaller bottom gap
  - Larger bottom gap
  - Smaller top/side gap
  - Larger top/side gap
- Single Steel Door (baseline)
  - Smaller bottom gap
  - Larger bottom gap
  - Smaller top/side gap
  - Larger top/side gap
- Double Wood Door (baseline)
  - Smaller bottom gap
  - Larger bottom gap
  - Smaller top/side gap
  - Larger top/side gap
- Double Steel Door (baseline)
  - Smaller bottom gap
  - Larger bottom gap
  - Smaller top/side gap
  - Larger top/side gap

The above list while not exhaustive represents that a large number of tests could be conducted, however in the interest of conducting a more efficient study. The challenge becomes determining the minimum number of tests that can be conducted which still achieving a viable study.

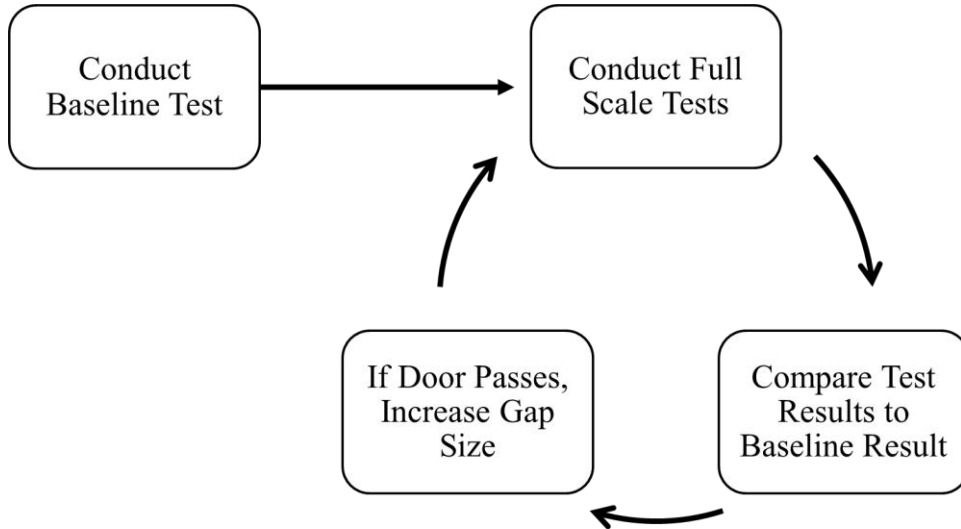


Figure 10: Representation of iteration procedure for each baseline test. The baseline is conducted, followed by tests that alter the gap size only. Those test are compared to the baseline, with the possibility of adding more due to acceptable door performance.

It is recommended that the initial study consider single steel doors. Single steel doors are designed for a longer fire duration and are therefore exposed to the furnace environment for longer. Table 12 provides a recommendation for initial tests that should be considered in a future testing program; options for testing multiple single doors assemblies with the same gap sizes should be explored in order to gain the most data out of each test as possible and to reduce testing costs.

In addition to collecting the data required by NFPA 252, significant consideration should also be given to recording the mass or volume flow rates of gas through the door assemblies since this will provide beneficial information with regard to fire propagation through the assemblies.

Table 11: Proposed Initial Full-Scale Testing Program

Test No.	Door Material	No. Doors	Bottom Gap	Side Gaps	Top Gap
1-1	Steel	Single	3/8"	1/8"	1/8"
1-2	Steel	Single	3/8"	1/8"	1/8"
1-3	Steel	Single	3/8"	1/8"	1/8"
2-1	Steel	Single	1"	1/8"	1/8"
2-2	Steel	Single	1"	1/8"	1/8"
2-3	Steel	Single	1"	1/8"	1/8"
3-1	Steel	Single	3/8"	1/4"	1/8"
3-2	Steel	Single	3/8"	1/4"	1/8"
3-3	Steel	Single	3/8"	1/4"	1/8"
4-1	Steel	Single	3/8"	1/8"	1/4"
4-2	Steel	Single	3/8"	1/8"	1/4"
4-3	Steel	Single	3/8"	1/8"	1/4"

With this initial series of tests, it should be possible to begin to assess which gap enlargements (bottom, side or top) performance most differently from the baseline NFPA 252 case. Each testing scenario (i.e. 1, 2, 3, 4) is repeated to confirm that each scenario has repeatable results, which will ultimately assist in quantifying the uncertainty and variability of the test itself. Once this information is available, then an assessment of additional testing needs for single steel doors can be made.

Secondarily, pending the outcome of the first testing study, another study looking at the double wood doors. From discussions with contacts in the industry, double wood doors present a particularly difficult challenge for maintaining their bottom gap.

Tertiary, pending the outcome of the above testing studies further testing can be conducted to determine the effect of gap sizes for the other door arrangements, namely single wood doors and double steel doors.

## Data Collection

The data that will be collected from this testing regimen will ultimately be used to quantify the door performance. In these custom tests the data collection will be the same as in NFPA 252 augmented with additional data collection devices.

- **Time:** The time duration is measured for the length of time that a fire door passes the performance criteria.
- **Furnace Temperature:** Temperature of the furnace should be measured as stated in NFPA 252 Section 4.2
- **Front and Back Face Door Temperatures:** Both front and back face temperatures of the door should be measured in accordance with Section 4.3 of NFPA 252. Including both back and front face temperatures will provide valuable data for post-test model validation.
- **Volume Flow through Gaps:** The volume flow through the door gaps should be measured. This will add an additional metric that may will provide information for post-test model validation.
- **Furnace Pressure:** The furnace pressure should be measured as stated in NFPA 252 Section 6.1.2.
- **FLIR Camera:**

In addition to quantifiable data NFPA 252 includes a number of criteria by which the door is judged that is qualitative as opposed to quantitative that can be categorized as:

- Opening Failures
- Staying Affixed to the Frame
- Flame Spread
- Gap Size Criteria

These criteria, stated in NFPA 252 Section 7, if failed result in the door failing the test. It is expected that the baseline door will be successful in passing these performance criteria and that changing the gap size may result in a failure of these performance criteria.

## Door Performance

Door performance is the main metric by which doors will be compared against each other and therefore it is important to reiterate how this is defined. Currently doors are rated by time duration of the test, which is typically pre-determined because the furnace tests will stop at that time and the doors are subjected to a hose test.

As time is the main determinant of door performance, given that the performance criteria in NFPA 252 Chapter 7 are satisfied, it is recommended to run the tests until failure as this will allow for a direct comparison of the time when failure is reached. It is to be noted that, to authors knowledge, NFPA 252 does not give any quantitative metric that could be used to determine whether a door passes or fails. Any future research effort should have a focus on identifying exactly how a door fails in test conditions as well as in actual fire events and attempt to attribute quantified metrics to door failure.

### **Expected Outcomes**

The testing regimen proposed will provide the industry with pass/fail results, in accordance with NFPA 252, on doors with non-compliant gap sizes. Additionally, the comparison to the baseline tests will allow for quantifiable difference, which can be used to determine the maximum gap sizes, which meet the intent of the code.

Testing doors with larger gap sizes demonstrating their performance in the furnace test will result in a demonstrable scientific basis for a code change to a larger bottom gap.

## 6 Conclusion

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Swinging fire doors with builders hardware are an important component of passive fire protection and they are subject to a strict regimen of testing to provide reasonable assurance that a fire which occurs in one part of a building will not spread to another part of the building. As a result, there are a number of standardized testing protocols developed to ensure that each door meets the required level of safety.

The literature review for the research project, Influence of Gap Sizes around Swinging Doors with Builders Hardware on Fire and Smoke Development, had two aims

- Conduct a thorough literature review and collect available data from fire door test results consisting of hollow metal frames with a 20-min fire-rated wood door and a 3-hour fire-rated steel door construction.
- Identify the critical variables involved to evaluate the effect of increased clearance under a fire door may have on pressure differentials across the opening.

The literature review was extremely thorough and identified almost 100 sources of information related to the topic of fire doors. These sources of information were discovered in several mediums including codes and standards, historical documents, journal articles, university publications, video lectures, etc. **From this information a great deal of information and data was collected that directly reveals that the gap sizes around swinging doors have a significant effect on the fire development.**

Research reports from the National Bureau of Standards (NBS) [USA] [29], the National Research Council of Canada (NRC) [Canada] [30], and Building Research Establishment (BRE) [United Kingdom] [35] contain the results of full scale testing on wood and steel doors, but more research is needed to look at the differences between US and UK door construction and most importantly the effect of the bottom gap size on door performance. Additionally, the reports clarify some of the failure mechanisms and mitigation options for doors.

Newer reports from Cheung [31], Wakili [36], Hugi [37], Tabaddor [38] that focus on computational modeling of fire and smoke doors also give insight into the critical variables needed for these models and the approaches that were taken. An important takeaway from these reports is that modeling a fire door in a furnace is a challenge with any approach and that the results are applicable to a specific set of input parameters and boundary conditions.

A significant amount of work was done to trace the historic record of the prescriptive gaps sizes included in NFPA 80. It was revealed that the first inclusion of these gaps sizes was added in 1959. Initially, requirements were based on the mounting of doors; however, in 1967 the requirements switched to

being based on the door construction. **There is no evidence to suggest that this was done from a fire performance perspective, however the test reports from that time period indicate that the prescriptive gap sizes are in the vicinity of what was found during full scale testing.**

The results of the literature review offer insight into the technical basis for the gap sizes and the testing that informed these gap sizes. However, it is also clear that the gaps sizes were also partially changed over the years as part of simplification processes. There is a great deal information on previous full scale testing, which is accessible to the public.

The modeling exercise to replicate the fire door performance in a furnace environment did not provide clear, actionable results. Additionally, the absence of guidance related to the volume flow through the door, from the standards make it challenging to suggest a limit on what the maximum flow through the gaps should be.

It is recommended that full scale testing be conducted to evaluate the effects of the gap size on fire development. A full scale test matrix has been described in Section 4.1. Conducting full scale testing using these recommendations will provide the fire community with the door gap's effect on the performance of the swinging fire doors with builders hardware. It is recommended that full scale testing be conducted before any change in policy or manufacturing processes is considered.

## 7 Next Steps

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The literature review and the computer modeling exercise revealed some important results; however, to develop a strong technical basis to understand the door gaps, more work is needed. Several next steps, including and in addition to the full scale test matrix described in Section 4.1, that should be considered to more fully understand the scientific and engineering principles related to swinging fire doors are listed below.

### 1. Full Scale Fire Testing

Full scale fire testing using the permutations of any set of doors varying only one variable (i.e. the bottom gap size) would provide the proper data for establishing the effect of the gap size. The full scale test matrix has been described in Section 4.1.

### 2. Thermo-Mechanical Model

A 3D structural thermo-mechanical model (e.g. LS Dyna) that can take into account thermal expansion of the door elements would allow for a better approximation of the way that the door changes during the test. An example of this type of testing can be seen in the works by Tabaddor [38]. However, this type of detailed finite element modeling is very detailed and highly specialized and is therefore relatively expensive.

### 3. Develop steps for performance-based process for door approvals

From this research, there is evidence of many tests that have been conducted to look at fire doors, however there is not yet a NFPA 80 compliant way for building owners and managers to address inconsistencies involved with door gaps without completely replacing the door. It is recommended that additional testing is conducted to determine the performance change due to different gap sizes.

### 4. Develop verification and validation data sets for door models

Currently, there are a limited number of data sets that are complete enough to be used for validation of computer models. Developing a data set that can be used to validate models would be useful to establish models for steel doors and wood doors.

### 5. Develop round-robin type study for door model agreement

Modeling at its current state can be part science and part art and the decisions that the modeler can make affect the accuracy of the model. research organizations and universities to attempt to model the same configuration to realize how close the industry can get to reality and to have multiple points of reference to understand better how modeling can improve in the future.



## Appendix A

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- [42] UL, *UL 1784 Standard for Air Leakage Tests of Door Assemblies and Other Opening Protectives*, Northbrook, IL: Underwriters Laboratory, 2015.
- [43] A. Buchanan, Fire Engineering Design Guide, Christchurch, NZ: Centre for Advanced Engineering, April 2001.

## A2 Compendium of related resources

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This comprehensive list contains many of the resources that were reviewed over the course of this literature review. There was an effort made to collect information directly related to the research topic as well as other related resources. A challenging part of a literature review can be the absence of document availability, whether those documents are behind a paywall or not digitized or inaccessible for other reasons.

Our approach for locating and digesting useful and related literature starts with performing keyword search across different useful search engines, literature platforms, and reputable sources.

- Research Institutions
  - National Bureau of Standards (NBS)
  - National Institute of Standards and Technology (NIST)
  - BRANZ
  - BRE
  - SP
  - VTT
- Universities
  - Worcester Polytechnic Institute (WPI)
  - University of Maryland (UMD)
  - University of Edinburgh
  - University of Canterbury
- Organizations
  - International Association for Fire Safety Science (IAFSS)
  - National Fire Protection Association (NFPA)
  - Fire Protection Research Foundation (FPRF)
  - Society of Fire Protection Engineering (SFPE)
  - Healthcare Specific
    - Joint Commission
    - American Society for Healthcare Engineering (ASHE)

- American Hospital Association (AHA)
- Journals & Conferences
  - Fire & Materials Conference
  - Journal of Fire Protection Engineering
  - Fire Safety Journal
  - Journal of Building & Environment
  - Journal of Computers & Fluids

When looking through the specific sources above it is important to focus the study through appropriate keyword searches which will help to identify appropriate and related literature. A small list of keywords below demonstrates a small fraction of the keywords used for this work.

“door gap fire development”

“smoke leakage”

“door leakage”

“ISO 834”

“fire timber door”

“fire steel door”

Finally, from this list of sources there are some that are more directly related to this research topic than others. Many of those have been summarized and included in the body of the report. Those sources which were deemed important and required a more detailed review are highlighted in green in the table below.

	Date	ORG	Name	Document Availability	Link
1	2006	Fire Safety Journal	The influence of gaps of fire-resisting doors on the smoke spread in a building fire	Behind Paywall (\$35.95)	<a href="http://www.sciencedirect.com/science/article/pii/S0379711206000695">http://www.sciencedirect.com/science/article/pii/S0379711206000695</a>
2	2016	NFPA	NFPA 80: Standard for Fire Doors and Other Opening Protectives, 2016 Edition	Free through NFPA	<a href="http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code&amp;code=80">http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code&amp;code=80</a>
3	2017	NFPA	NFPA 252: Standard Methods of Fire Tests of Door Assemblies, 2017 Edition	Free through NFPA	<a href="http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code&amp;code=252">http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code&amp;code=252</a>
4	2013	UL	UL 10A: Standard for Safety for Tin-Clad Fire Doors, 21st Edition		
5	2015	UL	UL 10B: Standard for Safety for Fire Tests of Door Assemblies, 10th Edition		
6	2016	UL	UL 10C: Standard for Safety for Positive Pressure Fire Tests of Door Assemblies, 3rd Edition		
7	1984	Fire Safety Journal	Effect of Wind on Smoke Movement and Smoke Control Sysetms	Freely Available	<a href="http://www.sciencedirect.com/science/article/pii/0379711284900080">http://www.sciencedirect.com/science/article/pii/0379711284900080</a>
8	1984	Fire Safety Journal	The ASHRAE Design Manual for Smoke Control	Freely Available	<a href="http://www.sciencedirect.com/science/article/pii/0379711284900122">http://www.sciencedirect.com/science/article/pii/0379711284900122</a>

	Date	ORG	Name	Document Availability	Link
9	1984	Fire Safety Journal	Stairwell and Elevator Shaft Pressurization		
10	1978	NBS	A System for Fire Safety Evaluation of Health Care Facilities	Freely Available	<a href="http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir78-1555-1.pdf">http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir78-1555-1.pdf</a>
11	1984	NBS	The Need and Availability of Test Methods for Measuring the Smoke Leakage Characteristics of Door Assemblies	Freely Available	<a href="http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir84-2876.pdf">http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir84-2876.pdf</a>
12	1984	NBS	Field Tests of the Smoke Control System at the San Diego VA Hospital	Freely Available	<a href="http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir84-2948.pdf">http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir84-2948.pdf</a>
13	1981	NBS	Estimating Safe Available Egress Time From Fires	Freely Available	<a href="http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir80-2172.pdf">http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir80-2172.pdf</a>
14	1986	NBS	Smoke Control at Veterans Administration Hospitals	Freely Available	<a href="http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir85-3297.pdf">http://nvlpubs.nist.gov/nistpubs/Legacy/IR/nbsir85-3297.pdf</a>
15	1990	NIST	Estimating Air Leakage Through Doors for Smoke Control	Freely Available	<a href="http://fire.nist.gov/bfrlpubs/fire90/PDF/f90018.pdf">http://fire.nist.gov/bfrlpubs/fire90/PDF/f90018.pdf</a>
16	2009	UL	UL 1784: Air Leakage Tests of Door Assemblies		<a href="http://ulstandards.ul.com/standard/?id=1784_3">http://ulstandards.ul.com/standard/?id=1784_3</a>
17	2006	BRANZ	Study Report 151: Leakage of Smoke Control Door Assemblies	Freely Available	<a href="http://www.branz.co.nz/cms_show_download.php?id=fcf52ee7bc0b0dab18765fa99f90e32f27d380f6">http://www.branz.co.nz/cms_show_download.php?id=fcf52ee7bc0b0dab18765fa99f90e32f27d380f6</a>
18	2006	BRANZ	Study Report 148: Maintaining Tenability of Exitways in Buildings in the Even of Fire	Freely Available	<a href="http://www.branz.co.nz/cms_show_download.php?id=ed51425baaeccc5f8089bf3ce7e51d007856038c">http://www.branz.co.nz/cms_show_download.php?id=ed51425baaeccc5f8089bf3ce7e51d007856038c</a>
19	1993	BRANZ	Study Report 50: Smoke Control in Multi-Storey Buildings	Freely Available	<a href="http://www.branz.co.nz/cms_show_download.php?id=ce07dad44da7922244db5dfdd92af38ab75d2153">http://www.branz.co.nz/cms_show_download.php?id=ce07dad44da7922244db5dfdd92af38ab75d2153</a>



	Date	ORG	Name	Document Availability	Link
20	1994	BRANZ	Study Report 59: Report on the Effect of Passive Ventilation on the Rate of Fire Development in Dwellings	Freely Available	<a href="http://www.branz.co.nz/cms_show_download.php?id=fd492b3a904da9977da7a95da4c5248daa3e31af">http://www.branz.co.nz/cms_show_download.php?id=fd492b3a904da9977da7a95da4c5248daa3e31af</a>
21	1996	BRANZ	Study Report 66: Effectiveness of Smoke Management Systems	Freely Available	<a href="http://www.branz.co.nz/cms_show_download.php?id=6945c9a9512d6e2e74e6a53d021b76fa4603e903">http://www.branz.co.nz/cms_show_download.php?id=6945c9a9512d6e2e74e6a53d021b76fa4603e903</a>
22	2007	SS	SS 332: Specification for Fire Doors	Behind Paywall (\$93.40)	<a href="https://www.singaporestandardseshop.sg/product/product.aspx?id=ac292c2b-aca0-45f6-9257-1e6dd8b55135">https://www.singaporestandardseshop.sg/product/product.aspx?id=ac292c2b-aca0-45f6-9257-1e6dd8b55135</a>
23	2007	ISO	ISO 3008: Fire-resistance tests -- Door and shutter assemblies	Behind Paywall (CHF158)	<a href="http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=45472">http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=45472</a>
24	2014	ISO	ISO 3008-2: Fire-resistance tests -- Part 2: Lift landing door assemblies	Behind Paywall (CHF118)	<a href="http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=59989">http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=59989</a>
25	2016	ISO	ISO 3008-3: Fire resistance tests -- Part 3: Door and shutter assemblies horizontally oriented	Behind Paywall (CHF88)	<a href="http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=66756">http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=66756</a>
26	2007	ISO	ISO 5925-1: Fire tests -- Smoke-control door and shutter assemblies -- Part 1: Ambient- and medium-temperature leakage tests	Behind Paywall (CHF58)	<a href="http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=35264">http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=35264</a>

	Date	ORG	Name	Document Availability	Link
27	2006	ISO	ISO/TR 5925-2: Fire tests -- Smoke-control door and shutter assemblies -- Part 2: Commentary on test method and the applicability of test conditions and the use of test data in a smoke containment strategy	Behind Paywall (CHF58)	<a href="http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=39802">http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=39802</a>
28	2003	ISO	ISO 12472: Fire resistance of timber door assemblies - Method of determining the efficacy of intumescent seals	Behind Paywall (CHF58)	<a href="http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=37626">http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=37626</a>
29	2014	BS/EN	BS EN 1634-1: Fire resistance and smoke control tests for door and shutter assemblies, openable windows and elements of building hardware. Fire resistance test for door and shutter assemblies and openable windows	Behind Paywall (£234.00)	<a href="http://shop.bsigroup.com/ProductDetail/?pid=000000000030256881">http://shop.bsigroup.com/ProductDetail/?pid=000000000030256881</a>
30	2009	Joint Commission	The New "Life Safety" Chapter—What It Applies to and How Organizations Can Comply with It	Freely Available	<a href="https://www.jointcommission.org/assets/1/6/BHC_About_Life_Safety_Chapter.pdf">https://www.jointcommission.org/assets/1/6/BHC_About_Life_Safety_Chapter.pdf</a>
31	2016	Joint Commission	EC.02.03.05: FEATURES OF FIRE PROTECTION ASSOCIATED WITH THE FIRE ALARM SYSTEM		<a href="https://www.jointcommission.org/assets/1/6/Features_of_Fire_Protection_Related_to_Fire_Alarm_System.pdf">https://www.jointcommission.org/assets/1/6/Features_of_Fire_Protection_Related_to_Fire_Alarm_System.pdf</a>
32	2015	ICC	International Building Code (IBC), 2015 Edition	Freely Available	<a href="http://codes.iccsafe.org/app/book/toc/2015/I-Codes/2015%20IBC%20HTML/">http://codes.iccsafe.org/app/book/toc/2015/I-Codes/2015%20IBC%20HTML/</a>

	Date	ORG	Name	Document Availability	Link
33	2015	NFPA	NFPA 101: Life Safety Code, 2015 Edition	Freely Available	<a href="http://nfpa.org/101">nfpa.org/101</a>
34	2015	UL	UL 263: Standard for Safety Fire Tests of Building Construction and Materials, 14th Edition	Behind Paywall	
35	2016	ASTM	ASTM E119 - 16a: Standard Test Methods for Fire Tests of Building Construction and Materials	Behind Paywall (\$65)	<a href="https://www.astm.org/Standards/E119.htm">https://www.astm.org/Standards/E119.htm</a>
36	2016	NFPA	NFPA 105: Standard for Smoke Door Assemblies and Other Opening Protectives		
37	2000	ASTM	ASTM E2074 - 00:Standard Test Method for Fire Tests of Door Assemblies, Including Positive Pressure Testing of Side-Hinged and Pivoted Swinging Door Assemblies	Behind Paywall (\$61.20)	<a href="https://www.astm.org/Standards/E2074.htm">https://www.astm.org/Standards/E2074.htm</a>
38	2016	Doors and Hardware	Fire door certification and labeling: a retrospective	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA452584941&amp;it=r&amp;asid=51e0967e20f372109bb1a7a0502d99c3">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA452584941&amp;it=r&amp;asid=51e0967e20f372109bb1a7a0502d99c3</a>
39	2016	Doors and Hardware	Decoded: smoke door requirements of the 2015 international building code	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA439832541&amp;it=r&amp;asid=07c0eb3f0f74ae145d047ada017fac78">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA439832541&amp;it=r&amp;asid=07c0eb3f0f74ae145d047ada017fac78</a>

	Date	ORG	Name	Document Availability	Link
40	2016	Doors and Hardware	Fire-protection-rated versus fire-resistant-rated assemblies	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA447286463&amp;it=r&amp;asid=3b1148597a96faecec6d86950ac4356b">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA447286463&amp;it=r&amp;asid=3b1148597a96faecec6d86950ac4356b</a>
41	2014	Doors and Hardware	NFPA 80 considers annex note clearing up framing confusion	Freely Available	
42	2002	Doors and Hardware	Positive pressure: The basics	Freely Available	
43	2016	Doors and Hardware	Awareness of need for fire door inspections continues to grow	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA474660652&amp;it=r&amp;asid=3c07e9926fb6d205d78f9d9241ad97cb">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA474660652&amp;it=r&amp;asid=3c07e9926fb6d205d78f9d9241ad97cb</a>
44	2016	Doors and Hardware	Demand for fire door inspections expected to increase	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA462786866&amp;it=r&amp;asid=d5b7506582575a4f409784ffb19e7387">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA462786866&amp;it=r&amp;asid=d5b7506582575a4f409784ffb19e7387</a>
45	2016	Doors and Hardware	Inspecting Swinging Fire Doors with Builders Hardware	Freely Available	<a href="https://www.youtube.com/watch?v=-okkBNW7znE">https://www.youtube.com/watch?v=-okkBNW7znE</a>

	Date	ORG	Name	Document Availability	Link
46	2016	Doors and Hardware	Focus on Compliance: Fire door checklist	Freely Available	<a href="http://www.ashe.org/compliance/ls_02_01_10/pdfs/fire_door_checklist.pdf">http://www.ashe.org/compliance/ls_02_01_10/pdfs/fire_door_checklist.pdf</a>
47	2016	Doors and Hardware	Fire doors: compliance news and code requirements	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA452584943&amp;it=r&amp;asid=5556376fb3ced2d3a049b2e1d38617a1">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA452584943&amp;it=r&amp;asid=5556376fb3ced2d3a049b2e1d38617a1</a>
48	1999	Doors and Hardware	Fire door testing scenarios	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA54483295&amp;it=r&amp;asid=3f574eea3676ec70077a93dfbd738205">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA54483295&amp;it=r&amp;asid=3f574eea3676ec70077a93dfbd738205</a>
49	2013	Doors and Hardware	Manufacturers Directory	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA353136708&amp;it=r&amp;asid=89dd805cdd30dda17fc7f1f2a718e5bf">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA353136708&amp;it=r&amp;asid=89dd805cdd30dda17fc7f1f2a718e5bf</a>
50	2011	Doors and Hardware	Manufacturers directory	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA275577929&amp;it=r&amp;asid=60cdca699d8a86c3d1d59a2e02dd3a78">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA275577929&amp;it=r&amp;asid=60cdca699d8a86c3d1d59a2e02dd3a78</a>
51	2010	Doors and Hardware	2010 Manufacturers Buyer's Guide: twenty-second Edition	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA225075356&amp;it=r&amp;asid=41b4ecdda1716ae78b9362ee97200f53">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA225075356&amp;it=r&amp;asid=41b4ecdda1716ae78b9362ee97200f53</a>

	Date	ORG	Name	Document Availability	Link
52	2005	Doors and Hardware	Annual inspection for fire-rated door openings: why is it necessary?	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA144016574&amp;it=r&amp;asid=b1fcef5510078de7b56782f7d2d40dcb">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA144016574&amp;it=r&amp;asid=b1fcef5510078de7b56782f7d2d40dcb</a>
53	2006	Doors and Hardware	NFPA 80: Compartmentalization. Compartmentation. Containment. Protection. Preservation. Safety. Security	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA154334968&amp;it=r&amp;asid=c870d3c38a6e6927b8d82b553fea996a">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA154334968&amp;it=r&amp;asid=c870d3c38a6e6927b8d82b553fea996a</a>
54	2007	Doors and Hardware	Inspection of fire-rated door assemblies: this article will attempt to explain the new inspection requirements and allay these concerns	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA165445167&amp;it=r&amp;asid=100d6cb0a618beec53d3fa92ef0fd4d8">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA165445167&amp;it=r&amp;asid=100d6cb0a618beec53d3fa92ef0fd4d8</a>
55	2016	Doors and Hardware	Changes to NFPA 80, 2016 edition	Freely Available	<a href="http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA443130677&amp;it=r&amp;asid=c44d67ed32e736c3e911c4e40a8ecf42">http://go.galegroup.com/ps/i.do?p=ITOF&amp;sw=w&amp;u=mlin_c_worpoly&amp;v=2.1&amp;id=GALE%7CA443130677&amp;it=r&amp;asid=c44d67ed32e736c3e911c4e40a8ecf42</a>
56	2008	FDAI	Inspection Checklist 2008	Freely Available	<a href="https://www.dhi.org/shared/forms/PDFforms/FDAI/FDAI_NCRForms_Lots4a4bSAMPLE.pdf">https://www.dhi.org/shared/forms/PDFforms/FDAI/FDAI_NCRForms_Lots4a4bSAMPLE.pdf</a>
57	2016	NFPA	NFPA 80 Inspection, Testing, and Maintenance of Swinging Fire Doors Assemblies webinar	Freely Available	<a href="https://www.youtube.com/watch?v=RN_Ze9Js3E0&amp;t=329s">https://www.youtube.com/watch?v=RN_Ze9Js3E0&amp;t=329s</a>
58	2016	NFPA	Overview of the Installation and Maintenance Requirements for Fire Door Assemblies Webinar	Freely Available	<a href="https://www.youtube.com/watch?v=9iqZURtlfzQ">https://www.youtube.com/watch?v=9iqZURtlfzQ</a>
59	2016	NFPA	TIA - Standard for Fire Doors and Other Opening Protectives	Freely Available	<a href="http://www.nfpa.org/Assets/files/AboutTheCodes/80/TIA_80_16_1.pdf">http://www.nfpa.org/Assets/files/AboutTheCodes/80/TIA_80_16_1.pdf</a>

	Date	ORG	Name	Document Availability	Link
60	2005	AAMA	AAMA/WDMA/CSA 101/I.S.2/A440-05	Freely Available	<a href="http://www.aamanet.org/upload/file/CMB-5-05_Excerpt.pdf">http://www.aamanet.org/upload/file/CMB-5-05_Excerpt.pdf</a>
61	2008	AAMA	AAMA/WDMA/CSA 101/I.S.2/A440-08	Freely Available	<a href="http://www.aamanet.org/upload/file/CMB-5-08.pdf">http://www.aamanet.org/upload/file/CMB-5-08.pdf</a>
62	2011	AAMA	AAMA/WDMA/CSA 101/I.S.2/A440-11	Freely Available	<a href="http://www.aamanet.org/upload/file/CMB-5-11.pdf">http://www.aamanet.org/upload/file/CMB-5-11.pdf</a>
63	2011	SDI	ANSI/SDI A250.4-2011 Test Procedure and Acceptance Criteria for – Physical Endurance for Steel Doors, Frames and Frame Anchors	Freely Available	<a href="https://www.steeldoor.org/res/A250_4.pdf">https://www.steeldoor.org/res/A250_4.pdf</a>
64	2014	SDI	ANSI/SDI A250.8-2014 Specifications for Standard Steel Doors and Frames (SDI-100)	Freely Available	<a href="https://www.steeldoor.org/res/A250_8.pdf">https://www.steeldoor.org/res/A250_8.pdf</a>
65	2015	SDI	Fixing Uneven Gaps Between a Door and Frame (Improper Clearance)	Freely Available	<a href="https://www.youtube.com/watch?v=2KyBALzRRCw">https://www.youtube.com/watch?v=2KyBALzRRCw</a>
66	2014	SDI	Fire Rated Doors	Freely Available	<a href="https://www.youtube.com/watch?v=1TgxQB1w0Zo">https://www.youtube.com/watch?v=1TgxQB1w0Zo</a>
67	2016	SDI	Compilation of SDI Technical Documents and ANSI/SDI Standards and Test Methods	Freely Available	<a href="https://www.steeldoor.org/pdf/SDI%20Fact%20File.pdf">https://www.steeldoor.org/pdf/SDI%20Fact%20File.pdf</a>
68	1999	Australia	Report of the performance of a solid core timber door in a fire test using a standard heating regime	Freely Available	<a href="http://www.vba.vic.gov.au/_data/assets/pdf_file/0007/19555/Performance-of-a-solid-core-timber-door-in-a-fire-test-using-a-standard-heating-regime.pdf">http://www.vba.vic.gov.au/_data/assets/pdf_file/0007/19555/Performance-of-a-solid-core-timber-door-in-a-fire-test-using-a-standard-heating-regime.pdf</a>

	Date	ORG	Name	Document Availability	Link
69	2008	Fire Safety Journal	Thermal behaviour of a steel door frame subjected to the standard fire of ISO 834: Measurements, numerical simulation and parameter study	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/j.firesaf.2007.11.003">http://dx.doi.org/10.1016/j.firesaf.2007.11.003</a>
70	2002	Fire Safety Journal	Experimental investigation of fire door behaviour during a natural fire	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/S0379-7112(02)00003-6">http://dx.doi.org/10.1016/S0379-7112(02)00003-6</a>
71	2009	Fire Safety Journal	Measured and calculated temperature evolution on the room side of a butted steel door frame subjected to the standard fire of ISO 834	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/j.firesaf.2009.02.003">http://dx.doi.org/10.1016/j.firesaf.2009.02.003</a>
72	2008	Journal of constructional Steel Research	Survivability of steel frame structures subject to blast and fire	Behind Paywall (\$39.95)	<a href="http://dx.doi.org/10.1016/j.jcsr.2007.12.013">http://dx.doi.org/10.1016/j.jcsr.2007.12.013</a>
73	2005	Energy and Buildings	Thermal analysis of a wooden door system with integrated vacuum insulation panels	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/j.enbuild.2004.11.002">http://dx.doi.org/10.1016/j.enbuild.2004.11.002</a>



	Date	ORG	Name	Document Availability	Link
74	1996	Construction and Building Materials	Computer simulation of the thermal fire resistance of building materials and structural elements	Behind Paywall (\$39.95)	<a href="http://dx.doi.org/10.1016/0950-0618(95)00053-4">http://dx.doi.org/10.1016/0950-0618(95)00053-4</a>
75	2008	IAFSS	The Effect of Model Parameters on the Simulation of Fire Dynamics	Freely Available	<a href="http://dx.doi.org/10.3801/IAFSS.FSS.9-1341">http://dx.doi.org/10.3801/IAFSS.FSS.9-1341</a>
76	2011	IAFSS	Forecasting Fire Growth using an Inverse CFD Modelling Approach in a Real-Scale Fire Test	Freely Available	<a href="http://dx.doi.org/10.3801/IAFSS.FSS.10-1349">http://dx.doi.org/10.3801/IAFSS.FSS.10-1349</a>
77	2012	Procedia Engineering	Study of the Fire Resistance Performance of a Kind of Steel Fire Door	Freely Available	<a href="http://dx.doi.org/10.1016/j.proeng.2013.02.166">http://dx.doi.org/10.1016/j.proeng.2013.02.166</a>
78	1994	Applied Mathematical Modelling	Fire risk in linear segregated structures—fire door determination	Freely Available	<a href="http://dx.doi.org/10.1016/0307-904X(94)90141-4">http://dx.doi.org/10.1016/0307-904X(94)90141-4</a>

	Date	ORG	Name	Document Availability	Link
79	2004	Nuclear Engineering and Design	An evaluation of risk methods for prioritizing fire protection features: a procedure for fire barrier penetration seals	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/j.nucengdes.2003.11.035">http://dx.doi.org/10.1016/j.nucengdes.2003.11.035</a>
80	2009	Fire Safety Journal	An analysis of compartment fire doorway flows	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/j.firesaf.2009.02.001">http://dx.doi.org/10.1016/j.firesaf.2009.02.001</a>
81	2012	Proceedia Engineering	Air Flow through the Door Opening Induced by a Room Fire under Different Ventilation Factors	Freely Available	<a href="http://dx.doi.org/10.1016/j.proeng.2012.08.022">http://dx.doi.org/10.1016/j.proeng.2012.08.022</a>
82	1986	Fire Safety Journal	Doorway flow induced by a propane fire	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/0379-7112(86)90015-9">http://dx.doi.org/10.1016/0379-7112(86)90015-9</a>
83	1999	International Journal of Heat and Mass Transfer	Measurement of doorway flow field in multi-enclosure building fires	Behind Paywall (\$39.95)	<a href="http://dx.doi.org/10.1016/S0017-9310(98)00385-8">http://dx.doi.org/10.1016/S0017-9310(98)00385-8</a>
84	2012	Fire Technology	Assessment of Physical Phenomena Associated to Fire Doors During Standard Tests	Behind Paywall (\$39.95)	<a href="http://link.springer.com/article/10.1007/s10694-012-0270-0">http://link.springer.com/article/10.1007/s10694-012-0270-0</a>

	Date	ORG	Name	Document Availability	Link
85	1984	Combustion Institute	Fire Induced Flows Through Room Openings - Flow Coefficients	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/S0082-0784(85)80654-8">http://dx.doi.org/10.1016/S0082-0784(85)80654-8</a>
86	2012	Fire Technology	Fire Behaviour of Tropical and European Wood and Fire Resistance of Fire Doors Made of this Wood	Behind Paywall (\$39.95)	<a href="http://link.springer.com/article/10.1007%2Fs10694-010-0207-4">http://link.springer.com/article/10.1007%2Fs10694-010-0207-4</a>
87	2009	Journal of Fire Protection Engineering	Thermo-mechanical Analysis of Fire Doors Subjected to a Fire Endurance Test	Freely Available	<a href="http://journals.sagepub.com/doi/abs/10.1177/1042391508098899">http://journals.sagepub.com/doi/abs/10.1177/1042391508098899</a>
88	1975	NRC	Fire tests of wood door assemblies	Freely Available	<a href="http://nparc.cisti-icist.nrc-cnrc.gc.ca/eng/view/object/?id=1993fe0d-30fa-460f-9c5e-a2d5167b4921">http://nparc.cisti-icist.nrc-cnrc.gc.ca/eng/view/object/?id=1993fe0d-30fa-460f-9c5e-a2d5167b4921</a>
89	1966	NBS	Doors as Barriers to Fire and Smoke	Freely Available	<a href="http://nvlpubs.nist.gov/nistpubs/Legacy/BSS/nbsbuilding science3.pdf">http://nvlpubs.nist.gov/nistpubs/Legacy/BSS/nbsbuilding science3.pdf</a>
90	1966	NFPA	Report of Committee on Fire Doors and Windows	Freely Available	<a href="http://www.nfpa.org/Assets/files/AboutTheCodes/80/1966_TCR-80.pdf">http://www.nfpa.org/Assets/files/AboutTheCodes/80/1966_TCR-80.pdf</a>
91	2015	Journal of Fire Sciences	Thermo-mechanical analysis of a fire door for naval applications	Freely Available	<a href="http://journals.sagepub.com/doi/full/10.1177/0734904114564955">http://journals.sagepub.com/doi/full/10.1177/0734904114564955</a>

	Date	ORG	Name	Document Availability	Link
92	2014	Doors and Hardware	The Effect of Oversized Clearances on Fire Door Tests	Freely Available	<a href="http://www.nfpa.org/Assets/files/AboutTheCodes/80/August%20article%20from%20Doors%20and%20Hardware%20.pdf">http://www.nfpa.org/Assets/files/AboutTheCodes/80/August%20article%20from%20Doors%20and%20Hardware%20.pdf</a>
93	2013	Case Studies in Fire Safety	Assessment of fire protection systems in proscenium theaters	Freely Available	<a href="http://dx.doi.org/10.1016/j.csfs.2014.07.001">http://dx.doi.org/10.1016/j.csfs.2014.07.001</a>
94	2009	Fire Safety Journal	Round-robin study of a priori modelling predictions of the Dalmarnock Fire Test One	Behind Paywall (\$35.95)	<a href="http://dx.doi.org/10.1016/j.firesaf.2008.12.008">http://dx.doi.org/10.1016/j.firesaf.2008.12.008</a>
95	1971	BRE	An Investigation into the Fire Resistance of Timber Doors	Freely Available	<a href="https://www.era.lib.ed.ac.uk/bitstream/handle/1842/2404/DFT11%20A%20Posteriori%20Modelling.pdf?sequence=1&amp;isAllowed=y">https://www.era.lib.ed.ac.uk/bitstream/handle/1842/2404/DFT11%20A%20Posteriori%20Modelling.pdf?sequence=1&amp;isAllowed=y</a>
96	1967	USFS	Charring Rate of Selected Woods -- Transverse to Grain	Freely Available	<a href="https://www.fpl.fs.fed.us/documnts/fplrp/fplrp69.pdf">https://www.fpl.fs.fed.us/documnts/fplrp/fplrp69.pdf</a>
97	2016	Fire and Materials	Thermal and mechanical transient behaviour of steel doors installed in non-load-bearing partition wall assemblies during exposure to the standard fire test	Behind Paywall (\$38.00)	<a href="http://onlinelibrary.wiley.com/doi/10.1002/fam.2365/abstract">http://onlinelibrary.wiley.com/doi/10.1002/fam.2365/abstract</a>
98	2002	Journal of Building Physics	Experimental Investigation of the Effect of Natural Convection on Heat Transfer in Mineral Wool	Freely Available	<a href="http://journals.sagepub.com/doi/abs/10.1177/0075424202026002930">http://journals.sagepub.com/doi/abs/10.1177/0075424202026002930</a>

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99	2006	ICC	Resource A Guidelines on Fire Ratings of Archaic Materials and Assemblies	Freely Available	<a href="http://www2.iccsafe.org/states/seattle2006/seattle_existing/PDFs_existing/Resource%20A_Guidelines%20on%20Fire%20Ratings%20of%20Archaic%20Materials%20and%20Assemblies.pdf">http://www2.iccsafe.org/states/seattle2006/seattle_existing/PDFs_existing/Resource%20A_Guidelines%20on%20Fire%20Ratings%20of%20Archaic%20Materials%20and%20Assemblies.pdf</a>
100	2014	ASTM	ASTM A36 Standard Specification for Carbon Structural Steel		
101	2016	ASTM	ASTM E289: Standard Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry	Behind Paywall	
102	2015	ASTM	ASTM D6745: Standard Test Method for Linear Thermal Expansion of Electrode Carbons		
103	1997	IAFSS	Three-dimensional Simulation of a Fire-Resistance Furnace		<a href="http://www.iafss.org/publications/fss/5/1009">http://www.iafss.org/publications/fss/5/1009</a>
104	1997	IAFSS	A Theoretical Consideration On Heat Transfer In Fire Resistance Furnaces For Furnace Harmonization		<a href="http://www.iafss.org/publications/fss/5/1033">http://www.iafss.org/publications/fss/5/1033</a>
105	1997	IAFSS	Harmonization Of The Fire Severity In Standard Fire Resistance Test Furnaces		<a href="http://www.iafss.org/publications/fss/5/1045">http://www.iafss.org/publications/fss/5/1045</a>
106	1970	ASTM	Fire Test Performance	Behind Paywall	<a href="https://www.astm.org/DIGITAL_LIBRARY/STP/PAGES/STP44711S.htm">https://www.astm.org/DIGITAL_LIBRARY/STP/PAGES/STP44711S.htm</a>
107	2007	FPRF	Fire Resistance Testing For Performance-based Fire Design of Buildings	Freely Available	<a href="http://www.nfpa.org/~media/files/news-and-research/resources/research-foundation/research-foundation-reports/building-and-life-safety/fireresistancetesting.pdf?la=en">http://www.nfpa.org/~media/files/news-and-research/resources/research-foundation/research-foundation-reports/building-and-life-safety/fireresistancetesting.pdf?la=en</a>

	Date	ORG	Name	Document Availability	Link
108	1956	USFS	The Coefficients of Thermal Expansion of wood and Wood products	Freely Available	<a href="http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/1597/FPL_1487ocr.pdf">http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/1597/FPL_1487ocr.pdf</a>
109	2010	UoE	Fire Resistance of Structures 5	Freely Available	<a href="http://civil.iisc.ernet.in/~manohar/Fire/Part-23_Materials.pdf">http://civil.iisc.ernet.in/~manohar/Fire/Part-23_Materials.pdf</a>
110	2003	IAFSS	Thermal Expansion of Wood and timber-concrete composite members under ISO-Fire Exposure	Freely Available	<a href="http://www.iafss.org/publications/fss/7/1111/view/fss_7-1111.pdf">http://www.iafss.org/publications/fss/7/1111/view/fss_7-1111.pdf</a>
111	2012	European Commission	Fire Resistance Assessment of Steel Structures	Freely Available	<a href="http://eurocodes.jrc.ec.europa.eu/doc/2012_11_WS_fire/presentations/04-ZHAO-EC-FireDesign-WS.pdf">http://eurocodes.jrc.ec.europa.eu/doc/2012_11_WS_fire/presentations/04-ZHAO-EC-FireDesign-WS.pdf</a>
112	2010	NIST	Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings	Freely Available	<a href="http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1681.pdf">http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1681.pdf</a>
113	1941	USFS	Thermal Conductivity of Wood	Freely Available	<a href="https://www.fpl.fs.fed.us/documnts/pdf1941/macle41a.pdf">https://www.fpl.fs.fed.us/documnts/pdf1941/macle41a.pdf</a>
114	2009	USFS	Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species found in North America	Freely Available	<a href="https://www.nrs.fs.fed.us/pubs/rn/rn_nrs38.pdf">https://www.nrs.fs.fed.us/pubs/rn/rn_nrs38.pdf</a>
115	1999	USFS	Wood Handbook: Wood as an Engineering Material	Freely Available	<a href="https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.pdf">https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.pdf</a>

## Appendix B

### Discussion of Modeling Effort

**DISCLAIMER:** The details of the modeling exercise conducted during this research are detailed in this section below. The inputs and outputs of the model resulted in inconclusive results for the reasons listed in Section 4.1 as well as the reasons listed below. Because of this we suggest that any readers reviewing these results have a critical eye and use them at your own discursion and judgment.



## B1 Modeling Exercise

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To model a fire door in a furnace environment it is first necessary to understand the physical phenomena that occur. Various thermo-mechanical processes are experienced by the fire door over the course of the test, including heat transfer to the door, heat conduction through the door, mass transfer of fluids, thermal expansion and shrinkage of the structure, and warping of the door structure. It is important to note that while these phenomena occur during a full-scale furnace test, any modeling conducted will focus on a limited number of these phenomena, as there has been no complete computational modeling solution developed as of yet. Therefore the boundary conditions, model inputs, and limitations of the modeling exercise are described below.

### B1.1 Model Elements

#### B1.1.1 Furnace

An important component to consider is the construction of the furnace and the thermal environment in which the door will be tested. To properly assess both the heat transfer and mass transfer across the door gaps, the furnace needs to be replicated so that these phenomena are both accurate. It is important that the below physical attributes are replicated in the model of a furnace:

- Thermal environment
- Fuel mass flow rate

The thermal environment is important for this modeling exercise, as it is how fire doors are tested (i.e. time-temperature curve). NFPA 252 references the time-temperature curve depicted in Figure 11. The thermal environment created by the furnace will impact the fire door through convection heat transfer and radiative heat transfer; conduction will also occur through the door.

The conservation of mass is an important consideration when modeling a furnace environment. In the furnace, the flow of fuel and the flow of oxygen combine to create combustion. In the context of a physical furnace, the fuel is pre-mixed, meaning that combustion is nearly complete combustion.

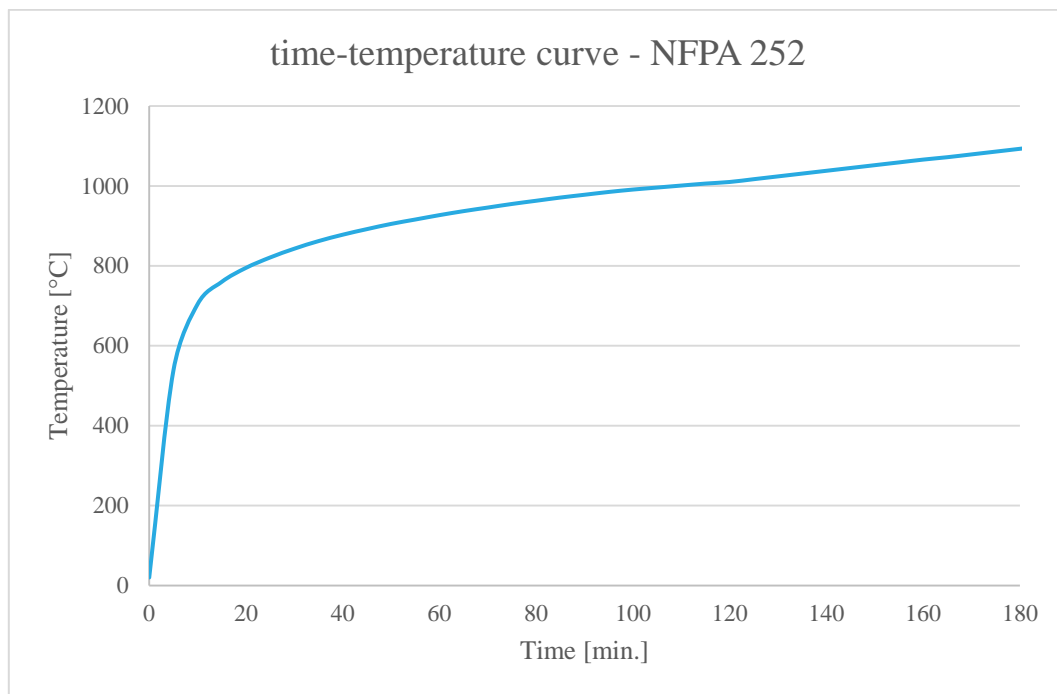


Figure 11: NFPA 252 time-temperature curve graph

#### B1.1.1.1 Implementation into FDS

Fire Dynamics Simulator (FDS) includes many features that are beneficial for implementing the modeling exercises, however it presents a few modeling challenges, which are described below. FDS is a CFD model specifically designed to model fire-driven fluid flows. FDS divides the computational domain (i.e. the furnace, door, and ambient environment) into rectilinear cells. The smaller the cells are, the more resolved the computational domain is; however, as the mesh becomes finer it becomes more computationally expensive. The list of items below are the components of the furnace which were implemented into the FDS model

1. **Combustion:** FDS includes a combustion sub-routine that was used to model a premixed furnace environment using propane as the fuel. FDS requires the modeler to specify the mass flux of fuel and air. To determine the mass flux of fuel to air provided into the furnace was a modeling challenge that was resolved by trial and error. The ratio of fuel to air is based upon stoichiometric values. Several trials were conducted, varying the mass flux of fuel and air into the furnace to find which mass flux of propane and air resulted in the time temperature curve dictated by NFPA 252.
2. **Conservation of Mass:** The CFD study focused on how fluids flow in the furnace environment and especially through the door gaps, so it was important to have fluids be transferred only through the door gaps. The conservation of mass was checked by measuring the flow into the furnace

(i.e. air and fuel) and measuring the flow out of the furnace through the door gaps. The net flows into the furnace were confirmed to be equal to the net flows out of the furnace.

3. **Temperatures:** The NFPA 252 standard specifies the furnace environment in terms of a time temperature curve. A difficulty in FDS is that a temperature cannot be an input, rather the appropriate combination of fuel and air was the input. A trial and error process was used to find the mass flows for propane and air that were injected into the model to achieve the correct temperature profile.
4. **Model Mesh Size:** The size of the mesh cells used and the duration of the models (i.e. 20 min and 180min) required efficient use of available computational resources and the associated simulation time. A mesh size of 100 mm (4 in.) was selected for this study.

The actual physical dimensions of the furnace in FDS are 4.8 meters (15.7 feet) in length by 1.6 meters (5.2 feet) in depth, and 3.0 meters (9.8 feet) in height. The model matched the descriptions in NFPA 252 as closely as possible (see Figure 12).

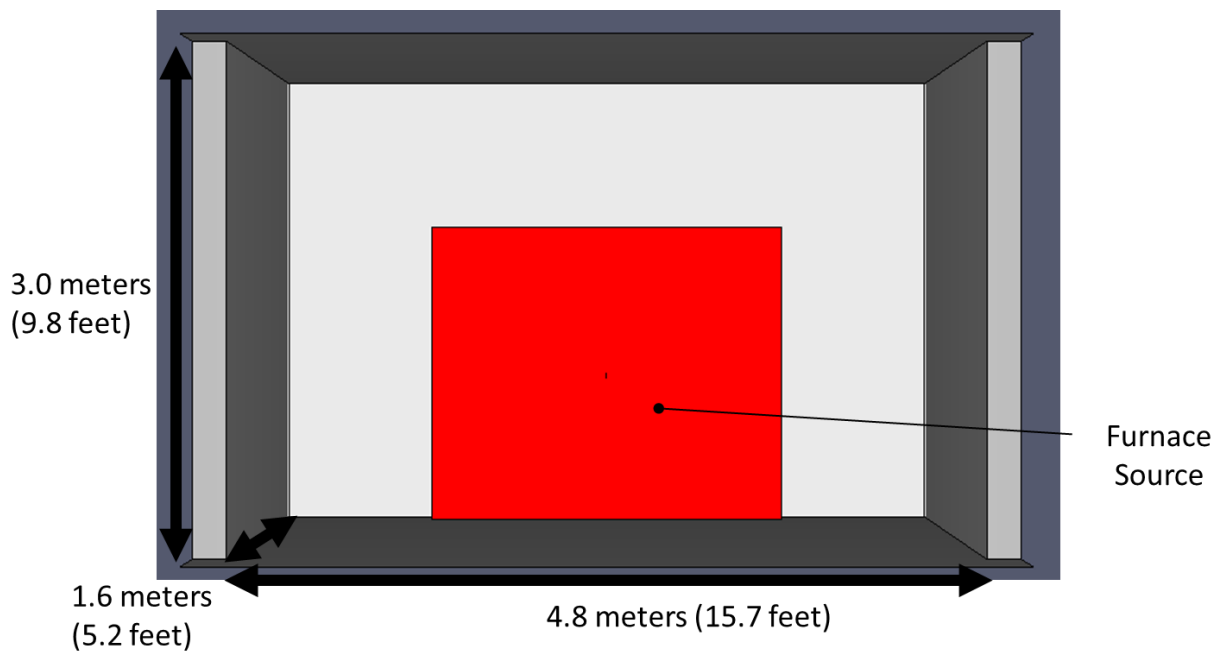


Figure 12: Representation of the furnace design implemented in the FDS model.

### B1.1.2 Fire Doors

Fire doors are complex objects made up of multiple different materials that are installed to provide a way for occupants to get from one compartment to another, while not significantly decreasing the safety provided by the surrounding passive fire protection.

The modeling of fire doors involves the tracking of many different physical phenomena (i.e. flows through door cracks, heat transfer through the door, structural response, etc.).

#### **B1.1.2.1 Flow through door**

One of the items of concern for a fire door is the flow of smoke through any holes or gaps that are present. Because of this, the flows through the gaps at the bottom, sides, top and middle of the door are important to characterize accurately. This is a somewhat challenging problem as the gap sizes compared to the total door size are small.

The flow through the gap is very important to capture for the relevance to smoke and mass transfer through the door. Equally as important are the pressures across the doors, as they are indicative of whether the fire door is able to maintain a pressure differential in the event of a fire, where smoke migration can decrease the tenable environment.

#### **B1.1.2.2 Door Components**

A fire door is a complicated assembly that is designed to resist the spread of fire and smoke for an extended period of time. To capture the dimensions of a door, and not following exactly a specific manufacturer's design, a generic door design which could be used as the baseline for the study was assumed (see Figure 13). The door as implemented in the model includes:

- Door Leaf (both single and double doors were studied)
- Door Frame
- Door Hardware

The different components of the door are made up of different materials. In this study doors made of steel and wood were studied, however only the heat transfer properties assigned to the components were included, so the differences in the model between wood and steel doors are minimal.

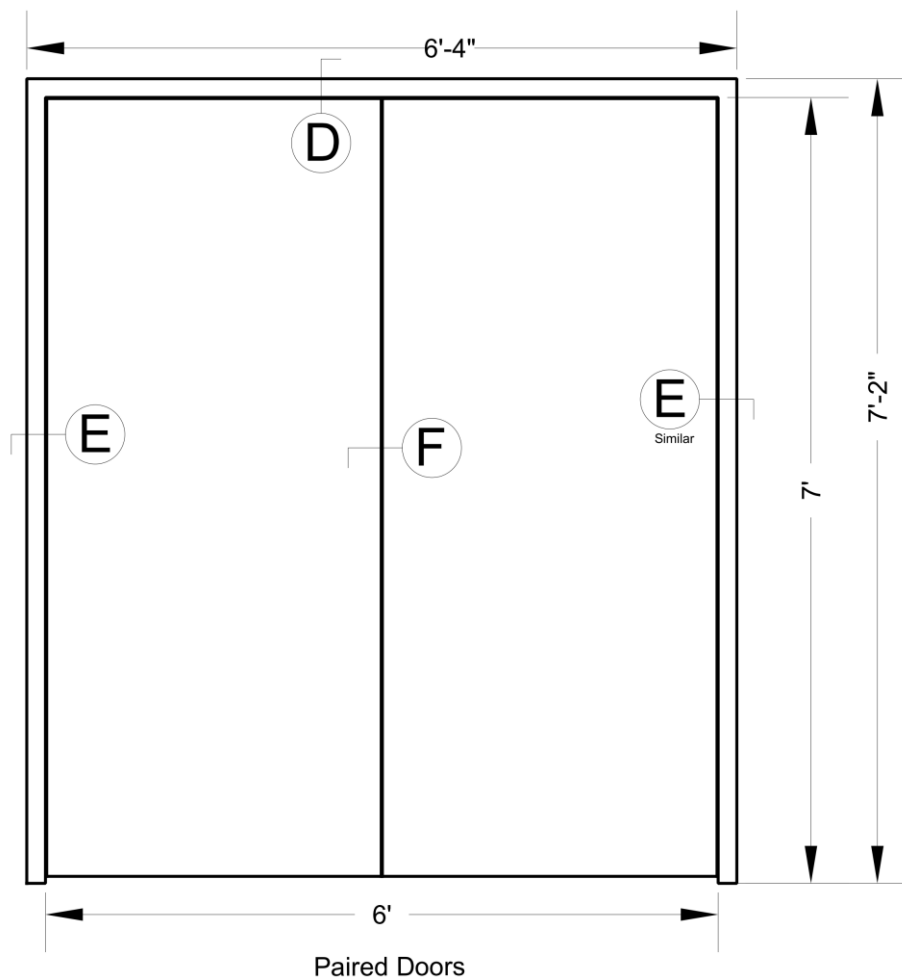


Figure 13: Generic door model. The letters seen indicate sections that look at different portions of the door. F is extending across the centerline of the door. E is a section looking at the side gaps. D is looking at the top gap.

### B1.1.2.3 Neutral Plane

The neutral plane is an important concept when studying compartment fires. It is commonly found where there is a pressure differential over a certain height [39]. For the furnace test the pressure over the height of the compartment varies. In accordance with the requirements of NFPA 252 the neutral plane height was established at 1,016 mm (40 inches) above the sill.

### B1.1.2.4 Door Gaps in FDS

To model the door gaps, the HVAC sub-model is used to model sub-grid scale air flow between the furnace and ambient environment through the door gaps, while maintaining the efficiency of the larger grid. The specific feature used is called the

pressure leak function and it helps to model flows that develop in the gaps of doors. Because it was important to get data from each of the different gaps, as well as assign the gap size, each gap was modeled individually. The gap sizes according to Table 12, were then implemented into each of the FDS scenarios (see Figure 14).

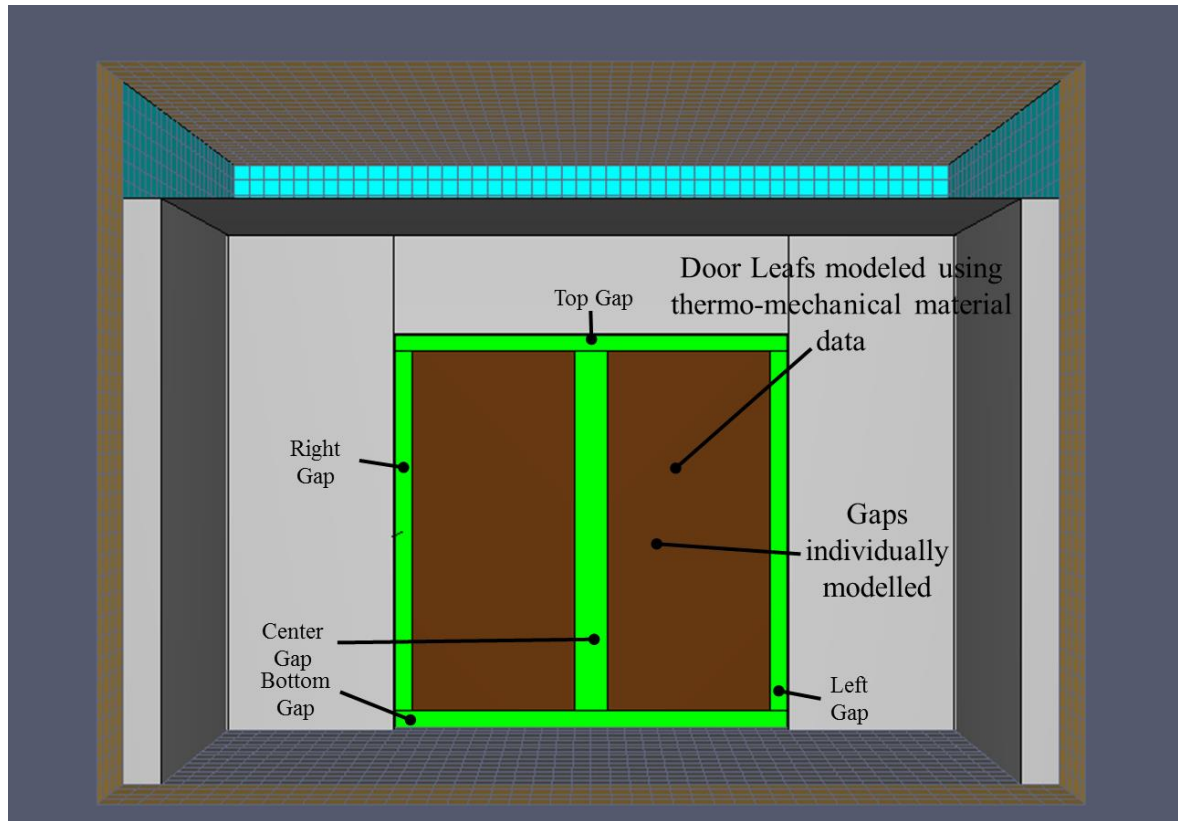


Figure 14: Representation of the doors implemented in the FDS model

## B1.2 Scenarios

The scope of this research exercise is relatively narrow, with the main goal being to answer the question: Are the prescribed gaps around swinging fire doors currently required in NFPA 80 and NFPA 252 equivalent to the code and standard required level of safety?

To this end, a series of simulations were proposed that included the maximum gap sizes allowed by the standard with variations from those maximums to determine the effect of gap sizes that are smaller and larger than the maximums (see Table 12). Additionally, other variables were also considered for inclusion; the door material (i.e. wood or steel), the door fire rating (i.e. 20 minutes or 3 hours), and the door configuration (i.e. single door or double egress door).

**As part of this research the findings from the modeling are expected to be incorporated into a full-scale testing regimen to validate the results of the**

**modeling exercise.** As a result, it was decided that the modeling will be based on NFPA 252 and include the insult from the furnace as well as the establishment of the neutral plane as well as the other requirements indicated in the standard.

Table 12: Overview of doors analyzed

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap	
#1	Single Door	Wood	1/3 hr.	3/4"	1/8"	1/8"	*Allowed By NFPA 80
#2	Single Door	Wood	1/3 hr.	3/8"	1/8"	1/8"	*Smaller Bottom Gap
#3	Single Door	Wood	1/3 hr.	1"	1/8"	1/8"	*Larger Bottom Gap
#4	Single Door	Wood	1/3 hr.	3/4"	1/16"	1/16"	*Smaller Side Gaps
#5	Single Door	Wood	1/3 hr.	3/4"	1/4"	1/4"	*Larger Side & Top Gaps
#6	Single Door	Steel	3 hr.	3/4"	1/8"	1/8"	*Allowed By NFPA 80
#7	Single Door	Steel	3 hr.	3/8"	1/8"	1/8"	*Smaller Bottom Gap
#8	Single Door	Steel	3 hr.	1"	1/8"	1/8"	*Larger Bottom Gap
#9	Single Door	Steel	3 hr.	3/4"	1/16"	1/16"	*Smaller Side Gaps
#10	Single Door	Steel	3 hr.	3/4"	1/4"	1/4"	*Larger Side & Top Gaps
#11	Double Door	Wood	1/3 hr.	3/4"	1/8"	1/8"	*Allowed By NFPA 80
#12	Double Door	Wood	1/3 hr.	3/8"	1/8"	1/8"	*Smaller Bottom Gap
#13	Double Door	Wood	1/3 hr.	1"	1/8"	1/8"	*Larger Bottom Gap
#14	Double Door	Wood	1/3 hr.	3/4"	1/16"	1/16"	*Smaller Side Gaps
#15	Double Door	Wood	1/3 hr.	3/4"	1/4"	1/4"	*Larger Side & Top Gaps
#16	Double Door	Steel	3 hr.	3/4"	1/8"	1/8"	*Allowed By NFPA 80
#17	Double Door	Steel	3 hr.	3/8"	1/8"	1/8"	*Smaller Bottom Gap
#18	Double Door	Steel	3 hr.	1"	1/8"	1/8"	*Larger Bottom Gap
#19	Double Door	Steel	3 hr.	3/4"	1/16"	1/16"	*Smaller Side Gaps
#20	Double Door	Steel	3 hr.	3/4"	1/4"	1/4"	*Larger Side & Top Gaps

### B1.2.1 Simulation Plan

From the literature review, there are two distinct hazards which fire doors prevent; (a.) the transmission of smoke, and (b.) the spread of fire, from one location in a building to another. While these two hazards are typically thought of together (when there is smoke there is fire) this is not necessarily straightforward to model. The codes and standards do not consider a link between smoke and fire as NFPA 80 & NFPA 252 are concerned with a severe fire, whereas NFPA 105 & UL 1784 are concerned with smoke.

The goals of these models are to assist with the development of the technical basis to the degree to which the gap size influences the fire development and then use that knowledge to develop a full scale testing matrix.

Fire Dynamics Simulator (FDS) was used to model the furnace fire and the resulting fluid flow through the door. The advantage to using an FDS model is that it is a three dimensional computational fluid dynamics model that is validated for fire-driven fluid flows.

A particular challenge with CFD programs in general, and FDS in particular, is their reliance on a uniform computational mesh. With the size of a door being on the order 2,500 mm (8 feet) wide for a double door and the interest in a gap size on the order of 3 mm (1/8 in.), it is not simple to define a mesh that can directly model the flow through the gaps. To resolve this issue FDS has a sub-model that incorporates an empirical correlation to estimate sub-grid flow in a specified location for a given area.

## **B1.3 Output and Results**

### **B1.3.1 FDS Devices**

To get data from the FDS CFD model, devices are placed in the model. Data is recorded to each of these devices based on its location in the model. The volume flow, pressure, temperature, and velocity were measured in the model as indicated in Figure 15, Figure 16, and Figure 17.

### **B1.3.2 Results**

The modeling exercise to replicate the fire door performance in a furnace environment did not provide clear, actionable results. The goal of this project was to identify a performance difference between gaps of different sizes, however it was not clear from the output data that there was a significant performance difference that was seen across all of the simulations.



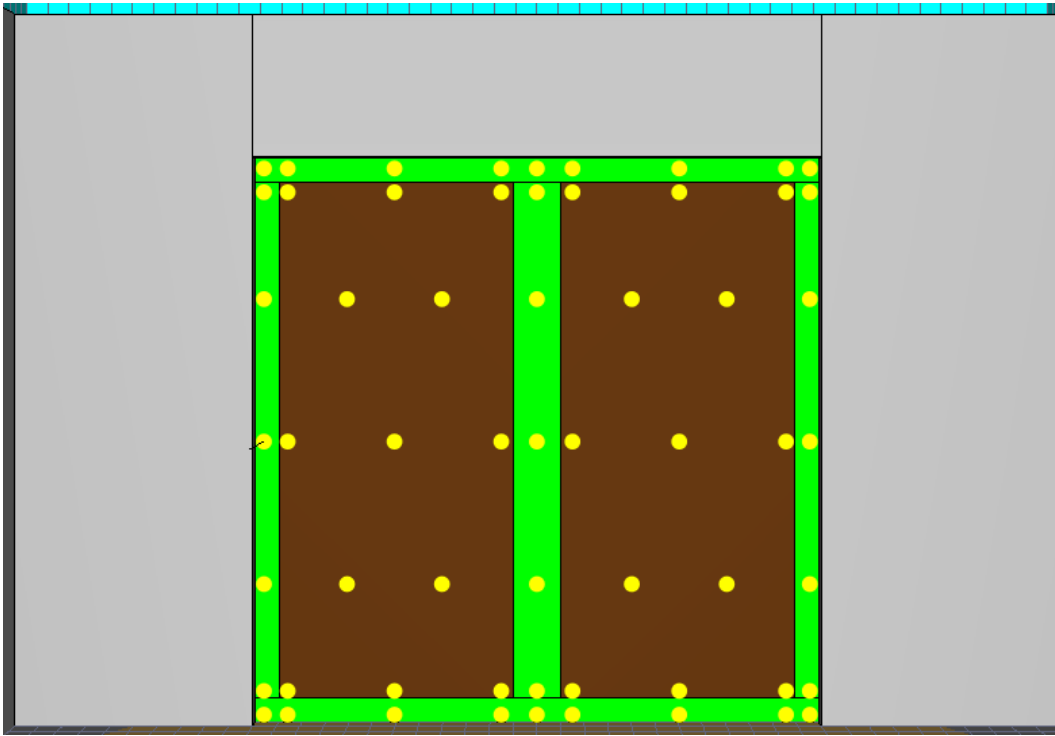


Figure 15: Devices located around door on the furnace side of the door

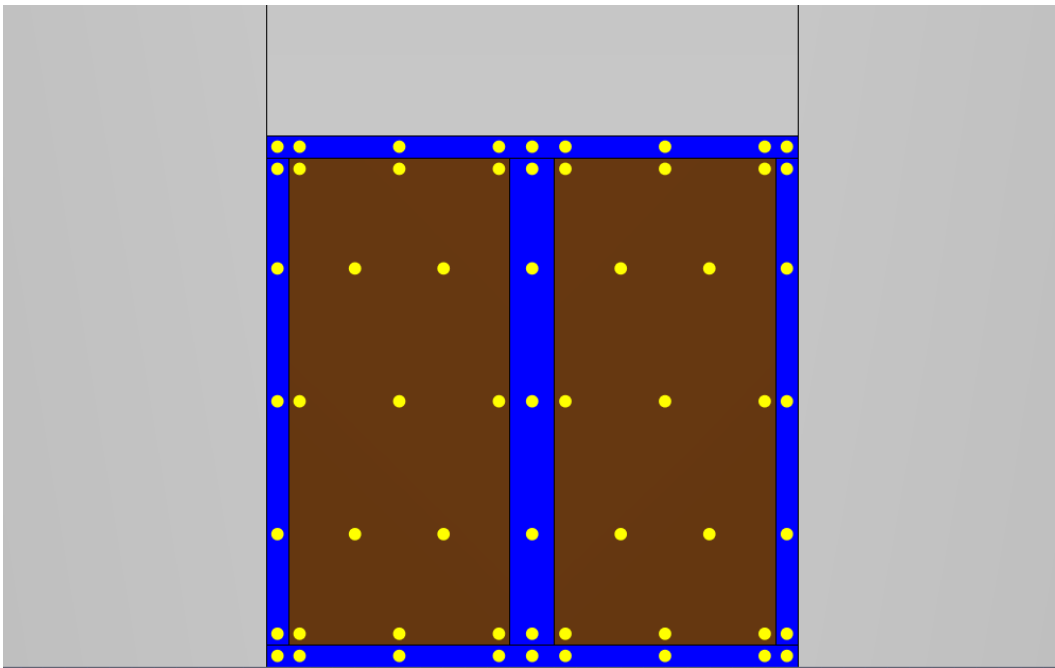


Figure 16: Devices located around door on the ambient side of the door

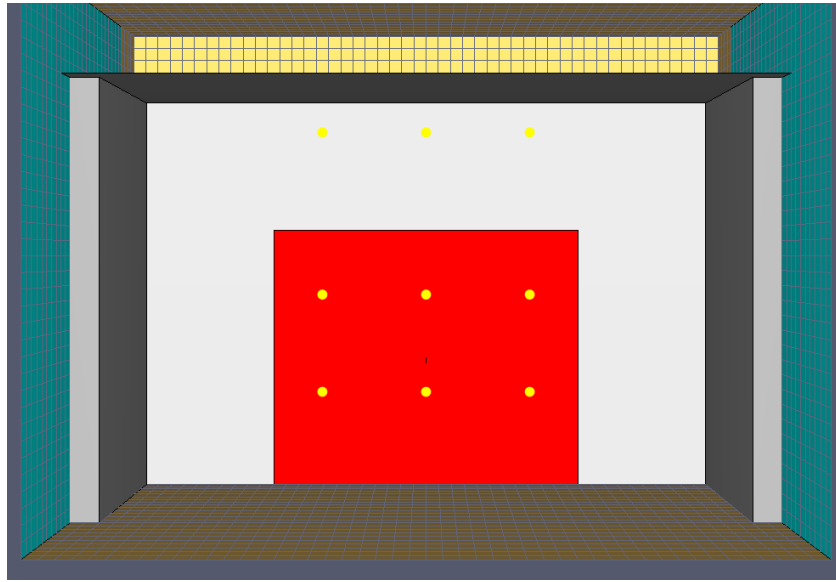


Figure 17: Devices located in front of the furnace, located 152 mm (6 inches) away from the fire door assembly as per NFPA 252 Section 4.2.1.3

## B1.4 Model Limitations

The models used in this context for this purpose have a number of limitations that restrict the results presented from being directly applicable to doors in a furnace.

4. These models do not capture the effects of shrinking or expansion that fire doors experience during full scale fire testing.
5. The performance criteria used to determine whether a door passes the NFPA 252 test, was not considered in these models. There are no performance criteria in NFPA 80 or NFPA 252 that address volume flow through the gaps or smoke flow through the gaps.
6. Modeling the gaps using a sub-grid scale empirical calculation does not take advantage of the 3D nature of the model and similar conclusions could be reached with basic thermodynamics and fluid mechanic calculations.
7. The absence of guidance related to the volume flow from the standards make it impossible to suggest a limit on what the maximum flow through the gaps should be, other than to suggest any flows out of the furnace higher than the NFPA 80 compliant doors would not be acceptable and any flows lower than the NFPA 80 compliant doors would be acceptable.

These models can provide insight to some phenomena in the physical world, but it is recommended that full scale testing be conducted before any change in policy or manufacturing processes is considered.

## B2 Trials conducted

As part of the modeling exercise there were many trials conducted to match the different physical parameters that were required as per the NFPA 252 Test. These included looking at single or double doors, changing the leakage area encompassed in the door. Note that this is the total leakage area across all the doors. The creation of the furnace was also attempted in different ways that ranged from a typical burner configuration to just a temperature surface. A mesh resolution study was also conducted to find an optimal cell size that provided a reasonable computation time without sacrificing results.

Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_004	double	103 in2	1000	0.04		
trial_005	double	103 in2	750	0.04		
trial_006	double	103 in2	500	0.04		
trial_007	double	103 in2	250	0.04		
trial_008	double	103 in2	-	0.4		failed - hole in furnace
trial_009	double	103 in2	-	0.2		failed - hole in furnace
trial_010	double	103 in2	-	0.1		failed - hole in furnace
trial_011	double	103 in2	-	0.04		failed - hole in furnace
trial_012	double	120 in2	-	0.2		testing to check the leakage for double and single doors
trial_013	double	120 in2	-	0.1		
trial_014	double	120 in2	-	0.04		
trial_015	double	120 in2	-	0.02		
trial_016	single	52.5 in2	-	0.2		

Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_017	single	52.5 in2	-	0.1		
trial_018	single	52.5 in2	-	0.04		
trial_019	single	52.5 in2	-	0.02		
trial_020	double	120 in2	1000	0.04		testing to determine the appropriate furnace hrr
trial_021	double	120 in3	750	0.04		
trial_022	single	120 in4	500	0.04		
trial_023	single	120 in5	250	0.04		
trial_024	double	120 in2	-	0.2		testing heat source as opposed to a burner
trial_025	double	120 in2	-	0.1		
trial_026	double	120 in2	-	0.04		
trial_027	double	120 in2	-	0.02		
trial_028	single	52.5 in2	-	0.2		
trial_029	single	52.5 in2	-	0.1		
trial_030	single	52.5 in2	-	0.04		
trial_031	single	52.5 in2	-	0.02		
trial_032	double	120 in2	1000	0.04		Checking to see whether the 'SUPPRESSION=.FALSE.' command will allow for the furnace to not go out. If works then we can check temperatures to see whether a ratio of the max will work to replicate curve
trial_033	single	hvac	1000	0.03		Testing HVAC Approach to ventilation crack, only using bottom crack
trial_034						
trial_035	single	52.5 in2		0.04		test pressure zone leakage for heat transfer
trial_036	single	52.5 in2	1 m/s	0.04		test pressure zone leakage for mass transfer

Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_037	single	52.5 in2	1000	0.04		test pressure zone leakage for furnace (heat transfer, mass transfer)
trial_038	single	39 in2		0.04		test pressure zone leakage for heat transfer
trial_039	single	39 in2	1 m/s	0.04		test pressure zone leakage for mass transfer
trial_040	single	39 in2	1000	0.04		test pressure zone leakage for furnace (heat transfer, mass transfer)
trial_041	single	52.5 in2	1000	0.04		test for HVAC in furnace
trial_042	single	61.5 in2	1000	0.04		test for hvac in furnace
trial_043	none	-----	1000	0.04		door removed, furnace test
trial_044	none	-----	1000	0.04		door in place hole below vent
trial_045	none	-----	1000	0.04		door in place hole above vent
trial_046	none	-----	1000	0.04		using model with now geometry to measure air flow required and max temperature achieved.
trial_047	single	52.5 in2	250	0.04		testing different hrrpua with the new ventilation configuration. (200degC)
trial_048	single	52.5 in2	500	0.04		testing different hrrpua with the new ventilation configuration (300degC)
trial_049	single	52.5 in2	1000	0.04		testing different hrrpua with the new ventilation configuration
trial_050	single	52.5 in3	1500	0.04		testing different hrrpua with the new ventilation configuration
trial_051	single	52.5 in4	2500	0.04		testing different hrrpua with the new ventilation configuration
trial_052	single	52.5 in5	5000	0.04		testing different hrrpua with the new ventilation configuration
trial_053						tryng furnace with open boundaries

Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_054						trying furnace with 1.8 m3/s of supply
trial_055	single	52.5 in2	250	0.04		vents supplying 10m3/s with open vents at bottom
trial_056	single	52.5 in2	500	0.04		vents supplying 10m3/s with open vents at bottom
trial_057	single	52.5 in2	1000	0.04		vents supplying 10m3/s with open vents at bottom
trial_058	single	52.5 in2	1500	0.04		vents supplying 10m3/s with open vents at bottom
trial_059	single	52.5 in2	2500	0.04		vents supplying 10m3/s with open vents at bottom
trial_060	single	52.5 in2	t(fnt)=100	0.04		trying same ventlation as 55-59 but with t(fnt) at differen temps and furnace hrrpua at 1000
trial_061	single	52.5 in2	t(fnt)=250	0.04		trying same ventlation as 55-59 but with t(fnt) at differen temps and furnace hrrpua at 1000
trial_062	single	52.5 in2	t(fnt)=500	0.04		trying same ventlation as 55-59 but with t(fnt) at differen temps and furnace hrrpua at 1000
trial_063	single	52.5 in2	t(fnt)=750	0.04		trying same ventlation as 55-59 but with t(fnt) at differen temps and furnace hrrpua at 1000
trial_064	single	52.5 in2	t(fnt)=1000	0.04		trying same ventlation as 55-59 but with t(fnt) at differen temps and furnace hrrpua at 1000
trial_065	single	52.5 in2	t(fnt)=1000	0.1		trying different mesh arrangement to test timing
trial_066	single	52.5 in2	0.0m3/s	0.1		different ventilation flows to differentiate pressure effect
trial_067	single	52.5 in2	1.0m3/s	0.1		different ventilation flows to differentiate pressure effect

Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_068	single	52.5 in2	2.5 m3/s	0.1		different ventilation flows to differentiate pressure effect
trial_069	single	52.5 in2	5.0 m3/s	0.1		different ventilation flows to differentiate pressure effect
trial_070	single	52.5 in2	-1.0 m3/s	0.1		different ventilation flows to differentiate pressure effect
trial_071	single	52.5 in2	-2.5 m3/s	0.1		different ventilation flows to differentiate pressure effect
trial_072	single	52.5 in2	-5.0 m3/s	0.1		different ventilation flows to differentiate pressure effect
trial_073	single	52.5 in2	0.0 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures
trial_074	single	52.5 in2	-0.5 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures
trial_075	single	52.5 in2	-1.0 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures
trial_076	single	52.5 in2	-1.5 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures
trial_077	single	52.5 in2	-2.0 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures
trial_078	single	52.5 in2	-2.5 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures
trial_079	single	52.5 in2	-3.0 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures
trial_080	single	52.5 in2	-3.5 m3/s	0.1	t(fnt)=100	testing different ventilation flows at different temperatures

Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_081	single	52.5 in2	0.0 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_082	single	52.5 in2	-0.5 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_083	single	52.5 in2	-1.0 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_084	single	52.5 in2	-1.5 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_085	single	52.5 in2	-2.0 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_086	single	52.5 in2	-2.5 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_087	single	52.5 in2	-3.0 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_088	single	52.5 in2	-3.5 m3/s	0.1	t(fnt)=795	testing different ventilation flows at different temperatures
trial_089	single	52.5 in2	0.0 m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures
trial_090	single	52.5 in2	-0.5 m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures
trial_091	single	52.5 in2	-1.0 m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures
trial_092	single	52.5 in2	-1.5 m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures
trial_093	single	52.5 in2	-2.0 m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures



Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_094	single	52.5 in2	-2.5m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures
trial_095	single	52.5 in2	-3.0m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures
trial_096	single	52.5 in2	-3.5m3/s	0.1	t(fnt)=1093	testing different ventilation flows at different temperatures
trial_097	single	52.5 in2	hrrpua=500	0.1		
trial_098	single	52.5 in2	hrrpua=750	0.1		
trial_099	single	52.5 in2	hrrpua=1000	0.1		
trial_100	single	52.5 in2	hrrpua=2500	0.1		
trial_101	single	52.5 in2	hrrpua=5000	0.1		
trial_102	single	52.5 in2	hrrpua=10000	0.1		
trial_103	single	52.5 in2	hrrpua=1	0.1		wood door with updated material and surface properties
trial_104	single	52.5 in2	hrrpua=50	0.1		wood door with updated material and surface properties
trial_105	single	52.5 in2	hrrpua=100	0.1		wood door with updated material and surface properties
trial_106	single	52.5 in2	hrrpua=200	0.1		wood door with updated material and surface properties
trial_107	single	52.5 in2	hrrpua=250	0.1		1200
trial_108	single	52.5 in2	hrrpua=300	0.1		1440
trial_109	single	52.5 in2	hrrpua=350	0.1		1680
trial_110	single	52.5 in2	hrrpua=400	0.1		1920
trial_111	single	52.5 in2	hrrpua=450	0.1		2160
trial_112	single	52.5 in2	hrrpua=500	0.1		2400

Name	Single/double	leakage	variable	mesh size	Temperature input	notes
trial_113	single	52.5 in2	hrrpua=550	0.1		2640
trial_114	single	52.5 in2	hrrpua=600	0.1		2880
trial_115	single	52.5 in2	hrrpua=600	0.1		New ventilation (open walls and hole in ceiling)
trial_116	double	120 in2	----	0.1		Just making sure devices work for double door

## B3 Detailed Model Results

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This section will expand upon the outcomes of the model with particular attention to:

- Providing comprehensive results from the models
- Providing more quantitative results
- Addressing the impacts of gaps allowed by NFPA 80 [40]

The results of the CFD model are designed to demonstrate the effects of fluid transfer from a furnace environment through gaps around a swinging fire door as listed in Table 13. The model takes advantage of an empirical formula to derive the sub-grid door gaps. This modeling effort provides insight into the fluid flow across a door that would be experienced in a severe fire. This modeling study seeks to shed light on how the flow across a fire door is affected by static door gaps.

### B3.1 Limitations

These models do not capture the effects of shrinking or expansion that fire doors experience during full scale fire testing. The performance criteria which is used to determine whether a door passes the NFPA 252 test, was not able to be considered in these models (see Section 4.1). A fire door is tested to evaluate its ability to withstand the effects of a severe fire, and degradation of door materials such that would predict the formation of holes or openings are not presently available.

These models can provide insight to some phenomena in the physical world, but it is recommended that full scale testing be conducted before any change in policy or manufacture.

### B3.2 Evaluation

To evaluate the effects of the door gaps 20 simulations were conducted that allow each variable to be considered independently. In this study the variables considered were the number of doors {single or double}, the door material {wood or steel}, the bottom gap dimension {3/8 in., 3/4 in., 1 in.}, and the top / side gap dimensions {1/16 in., 1/8 in., 1/4 in.}. Table 13 summarizes the CFD simulations performed.

The simulations are grouped to isolate each variable individually. A short discussion is provided within each section to discuss the results and to provide a short conclusion on the qualitative effects of that variable.

#### B3.2.1 Performance Criteria

As discussed in the limitations section, the type of modeling performed does not directly provide feedback to any of the pass/fail criteria in NFPA 252 [41]. In addition, there is no guidance in NFPA 252 on the volume of air and smoke that are allowed through the gaps. In general, the requirements governing fluid flow through a door are specifically for smoke-leakage rated door assemblies in

accordance with UL 1784 [42]. For life safety codes in the US (i.e. NFPA 101 and IBC) the maximum air leakage rate of a door assembly is  $3.0 \text{ ft}^3/\text{min}/\text{ft}^2$  ( $0.9 \text{ m}^3/\text{min}/\text{m}^2$ ) for  $0.1 \text{ inH}_2\text{O}$ . [2] [4]

Table 13: CFD simulations

Sim	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap	Noted Difference
#1	Single Door	Wood	1/3 hr	3/4"	1/8"	1/8"	Wood Door Control Test
#2	Single Door	Wood	1/3 hr	3/8"	1/8"	1/8"	Smaller Bottom Gap
#3	Single Door	Wood	1/3 hr	1"	1/8"	1/8"	Larger Bottom Gap
#4	Single Door	Wood	1/3 hr	3/4"	1/16"	1/16"	Smaller Side & Top Gaps
#5	Single Door	Wood	1/3 hr	3/4"	1/4"	1/4"	*Larger Side & Top Gaps
#6	Single Door	Steel	3 hr	3/4"	1/8"	1/8"	Steel Door Control Test
#7	Single Door	Steel	3 hr	3/8"	1/8"	1/8"	Smaller Bottom Gap
#8	Single Door	Steel	3 hr	1"	1/8"	1/8"	Larger Bottom Gap
#9	Single Door	Steel	3 hr	3/4"	1/16"	1/16"	Smaller Side & Top Gaps
#10	Single Door	Steel	3 hr	3/4"	1/4"	1/4"	Larger Side & Top Gaps
#11	Double Door	Wood	1/3 hr	3/4"	1/8"	1/8"	Wood Double Door Control Test
#12	Double Door	Wood	1/3 hr	3/8"	1/8"	1/8"	Smaller Bottom Gap
#13	Double Door	Wood	1/3 hr	1"	1/8"	1/8"	Larger Bottom Gap
#14	Double Door	Wood	1/3 hr	3/4"	1/16"	1/16"	Smaller Side & Top Gaps
#15	Double Door	Wood	1/3 hr	3/4"	1/4"	1/4"	Larger Side & Top Gaps
#16	Double Door	Steel	3 hr	3/4"	1/8"	1/8"	Steel Double Door Control Test
#17	Double Door	Steel	3 hr	3/8"	1/8"	1/8"	Smaller Bottom Gap
#18	Double Door	Steel	3 hr	1"	1/8"	1/8"	Larger Bottom Gap
#19	Double Door	Steel	3 hr	3/4"	1/16"	1/16"	Smaller Side & Top Gaps
#20	Double Door	Steel	3 hr	3/4"	1/4"	1/4"	Larger Side & Top Gaps

B4    Model Results

B4.1    Group A (#s01,s02,s03)

# Single Wood Door Comparing Effects of Bottom Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#01	Single Door	Wood	1/3 hr	0.7500	0.1250	0.1250
#02	Single Door	Wood	1/3 hr	0.3750	0.1250	0.1250
#03	Single Door	Wood	1/3 hr	1.0000	0.1250	0.1250

This section compares the effects of changing the bottom gap for single wood doors with top and side gaps in compliance with the requirements of NFPA 80. The bottom gaps considered include the maximum allowable bottom gap as required by NFPA 252 fire test (3/8 in.), the maximum gap allowed by NFPA 80 (3/4 in.), and a 1 in. gap to evaluate the effects of a non-compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

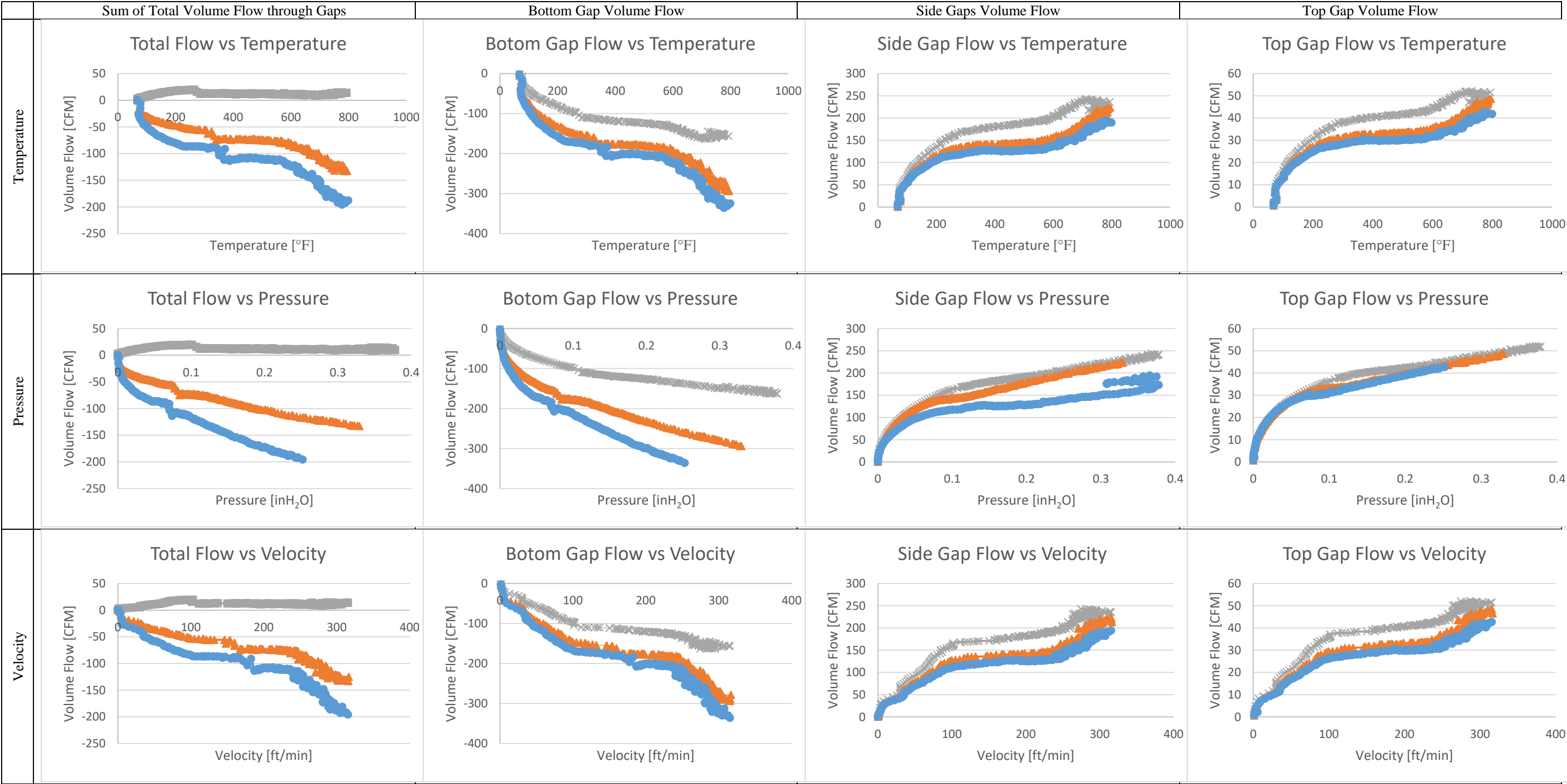
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 3/8 in., orange is 3/4 in., and blue is 1 in..

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the bottom gap does affect the total flow across the door. When the total flows are summed the smallest gaps size (3/8 in. bottom gap) results in a net positive flow out of the compartment and correspondingly higher pressures within the compartment. The 3/4 in. gaps and 1 in. gap both result in a net negative flow, meaning that flow through the bottom gap is greater than flow through the top and side gaps.

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the 1 in. gap (blue) allows for the highest flow and the 3/8 in.. gap (grey) allows for the smallest flow. On average the 1 in. gap allows 1.8 times the flow of the 3/8 in. gap. On average the 3/4 in. gap allows 1.6 times the flow of the 3/8 in. gap. This trend is reversed for the flow through the top and side gaps with higher flow rates vs temperature measured from the 3/8 in. bottom gap than the 3/4 in. or 1 in. gap models. This is to be expected as mass will be conserved in the model.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1 in. gap (blue) has higher flows than a door with 3/4 in. or 3/8 in. gaps at the same pressure. A larger opening will require less pressure to move an equivalent amount of air through a small gap. The top gap flow vs pressure graphs demonstrate that for the same gap size and pressure, the flow should be the same.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. It would be expected that the 3/8 in. door gap model would present the highest velocity. In the bottom gap flow vs velocity graph the 3/8 in. door gap model presents the highest velocity for a given volume flow. This trend is reversed (as is seen in volume flow vs temperature graphs) for the side and top gap flows.



—■— 3/8" Bottom Gap    —▲— 3/4" Bottom Gap    —●— 1" Bottom Gap

B4.2    Group B (#s01,s04,s05)

# Single Wood Door

## Comparing Effects of Side/Top Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#01	Single Door	Wood	1/3 hr	0.7500	0.1250	0.1250
#04	Single Door	Wood	1/3 hr	0.7500	0.0625	0.0625
#05	Single Door	Wood	1/3 hr	0.7500	0.2500	0.2500

This section compares the effects of changing the top and side gaps in a single wood door with the bottom gap in compliance with the requirements of NFPA 80. The top and side gaps considered include the maximum allowable top/side gap, as allowed by NFPA 80 (1/8 in., orange), a smaller gap size (1/16 in., grey), and a larger gap size (1/4 in., blue). This will evaluate the effects of a non-compliant door compared to a compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

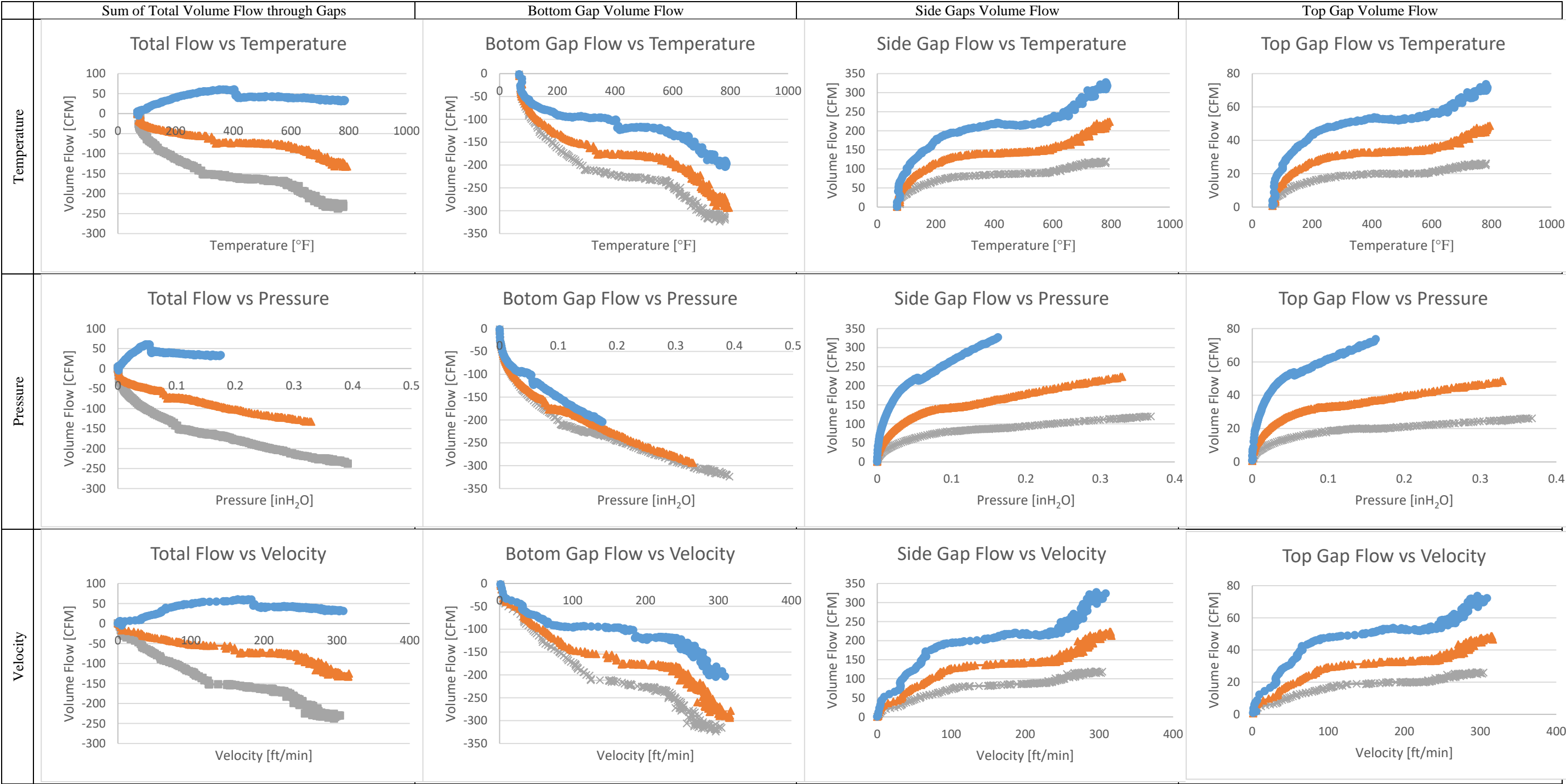
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top row), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom row). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 1/16 in., orange is 1/8 in., and blue is 1/4 in..

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the top/side gap size does affect the total flow across the door. When the total flows are summed the smaller gaps sizes (1/16 in. & 1/8 in. side/top gap) results in a net negative flow (i.e. flow into the furnace) and correspondingly higher pressures within the furnace. The largest top/side gap (1/4 in., blue) results in a net positive flow (i.e. net flow out of the furnace). This demonstrates that the flow is governed by the bottom gap size, but when the top/side gaps are large enough, the flow out of the top/side gaps will be greater than the flow through the bottom gap. It is unclear what the inconsistency in the results of 1/4 in. scenario at approximately 400 F, but there looks to be a jump in the bottom gap velocity flow at this temperature.

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the smallest top/side gap (1/16 in. gap, grey) allows for the highest flow and the largest top/side gap (1/4 in. gap, blue) allows for the smallest flow. This trend is reversed for the flow through the top and side gaps with the largest top/side gap (1/4 in., blue) resulting in the largest volume flow and the smallest top/side gap (1/16 in.) resulting in the smallest volume flow through the top and side gaps, respectively.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1/4 in. top/side gap (blue) results in net flow out of the furnace and correspondingly lower pressures as the flows into and out of the furnace are closer to being equivalent. The bottom gap flow vs pressure graph shows that for the same bottom gap size (3/4 in.) the trend is consistent for all scenarios and what changes is the maximum pressure. It is clear that there is a distinction between the smaller gap sizes (1/16 in. & 1/8 in., grey & orange) and 1/4 in. top gap where there is a tipping point between 1/4 in. and 1/8 in. that changes the flow and pressure relationship.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. There is somewhat more of a spread at the upper velocity margins between the different scenarios. In the bottom gap flow vs velocity graph the 3/8 in. door gap model presents the highest velocity for a given volume flow. This trend is reversed (as is seen in volume flow vs temperature graphs) for the side and top gap flows.



—■— 1/16" Side/Top Gap —▲— 1/8" Side/Top Gap —●— 1/4" Top/Side Gap



B4.3    Group C (#d11,d12,d13)

# Double Wood Doors

## Comparing Effects of Bottom Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#11	Double Door	Wood	1/3 hr	0.7500	0.1250	0.1250
#12	Double Door	Wood	1/3 hr	0.3750	0.1250	0.1250
#13	Double Door	Wood	1/3 hr	1.0000	0.1250	0.1250

This section compares the effects of changing the bottom gap for double wood doors with top and side gaps in compliance with the requirements of NFPA 80. The bottom gaps considered include the maximum allowable bottom gap as required by NFPA 252 fire test (3/8 in.), the maximum gap allowed by NFPA 80 (3/4 in.), and a 1 in. gap to evaluate the effects of a non-compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

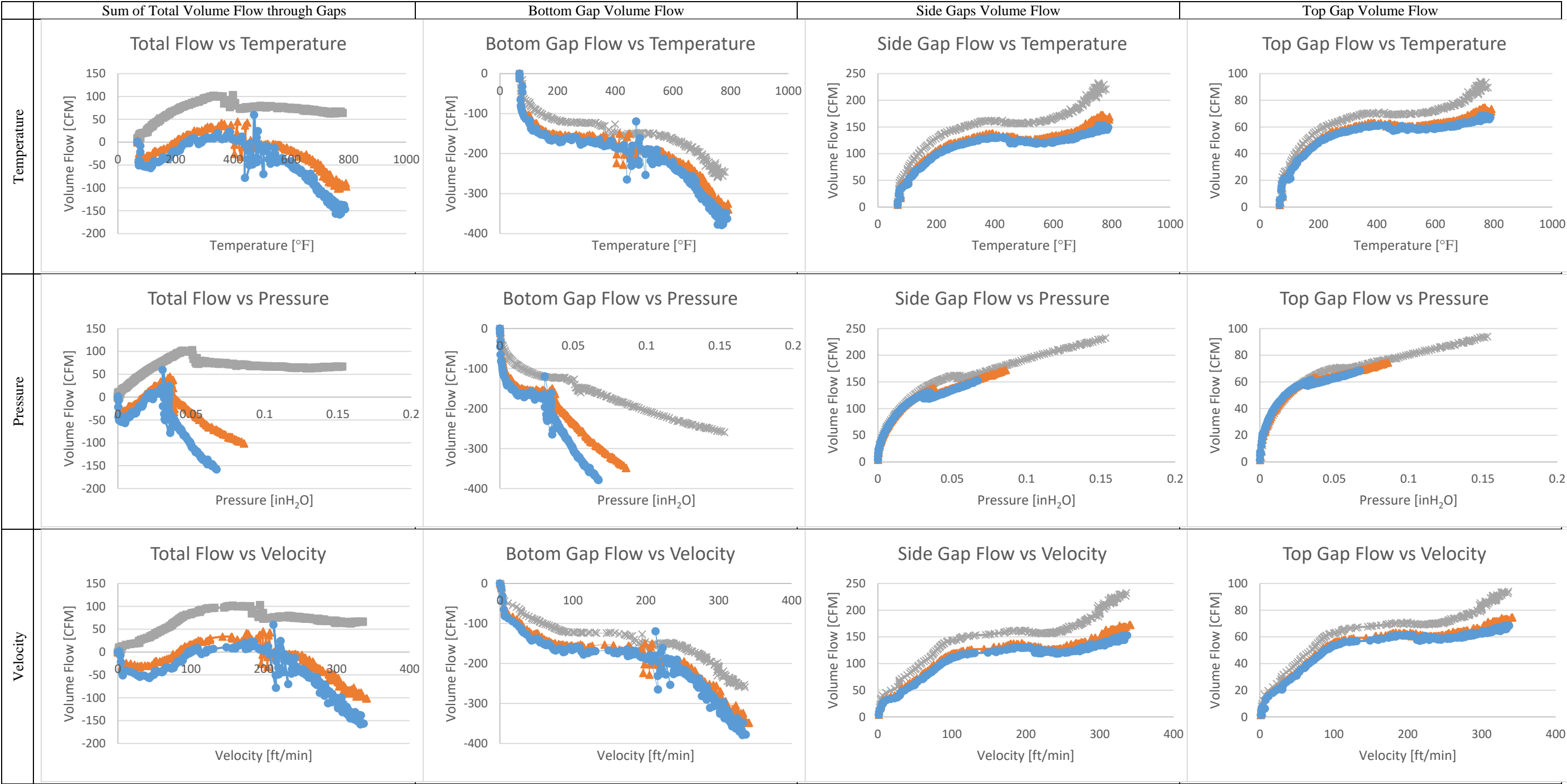
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 3/8 in., orange is 3/4 in., and blue is 1 in..

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the bottom gap does affect the total flow across the door. These graphs again display inconsistencies at approximately the 400 F temperature range, where the flow shows more variability and fluctuation than in other scenarios. Of note is the switch for the total flow from positive to negative. Consistent with other groups the smallest bottom gap (3/8 in., grey) results in a positive flow (i.e. net flow out of the compartment). The larger gap sizes (1 in. & 3/4 in.) volume flow changes between positive and negative flow, where flow below 200 F is into the furnace, between 200 F and 500 F is out of the furnace, and above 500 F the flow is into the furnace. It is unknown what the mechanism for this change is. This does not mean that flow through the bottom gap changes from flow into the furnace to out of the furnace, but that comparatively the flow into the furnace through the bottom gap is sometimes greater than the flow out of the furnace through the top/side gaps and sometimes not.

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the 1 in. gap (blue) and 3/4 in. (orange) gap are relatively similar and the 3/8 in. gap (grey) allows for the smallest flow.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1 in. gap (blue) has higher flows than a door with 3/4 in. or 3/8 in. gaps at the same pressure, especially at pressures greater than 0.05 inH<sub>2</sub>O. The inconsistencies associated with the total volume flow vs pressure are also evident in the pressure results, however it seems that this is a result of a temperature relationship rather than a pressure relationship.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. In the relationship between velocity and volume flow, again it can be seen that the larger gap sizes (i.e. 1 in. and 3/4 in.) are more similar and the smallest gap size (3/8 in., grey) has a higher volume flow for a given velocity, for the side and top gap flows.



—■— 3/8" Bottom Gap    —▲— 3/4" Bottom Gap    —●— 1" Bottom Gap

B4.4    Group D (#d11,d14,d15)

# Double Wood Doors

## Comparing Effects of Side/Top Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#11	Double Door	Wood	1/3 hr	0.7500	0.1250	0.1250
#14	Double Door	Wood	1/3 hr	0.7500	0.0625	0.0625
#15	Double Door	Wood	1/3 hr	0.7500	0.2500	0.2500

This section compares the effects of changing the top and side gaps in a double wood door with the bottom gap in compliance with the requirements of NFPA 80. The top and side gaps considered include the maximum allowable top/side gap, as allowed by NFPA 80 (1/8 in., orange), a smaller gap size (1/16 in., grey), and a larger gap size (1/4 in., blue). This will evaluate the effects of a non-compliant door compared to a compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

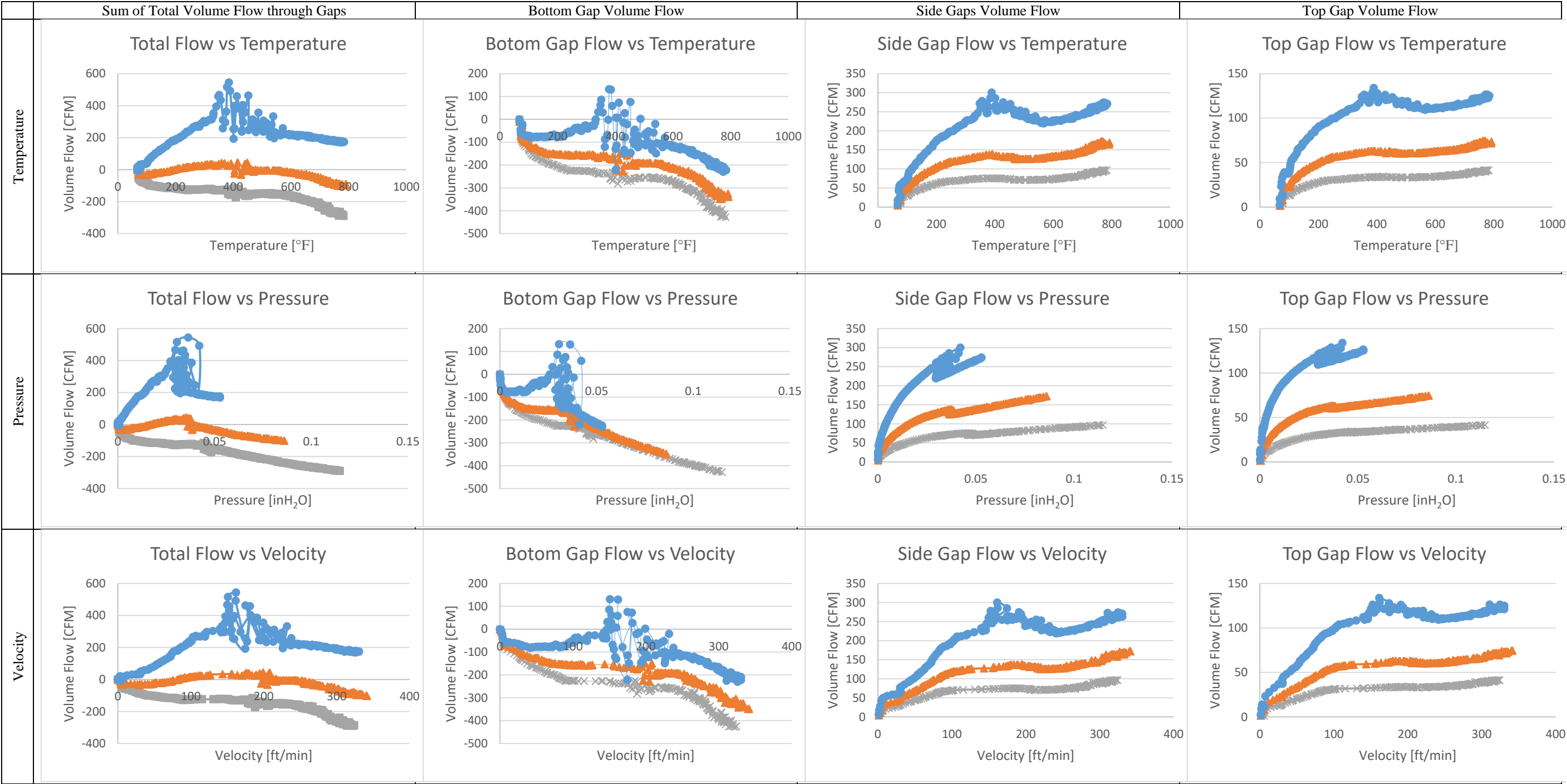
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top row), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom row). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 1/16 in., orange is 1/8 in., and blue is 1/4 in.

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the top/side gap size does affect the total flow across the door. When the total flows are summed the smallest gaps sizes (1/16 in., grey) results in a net negative flow (i.e. net flow into the furnace) and correspondingly higher pressures within the furnace. The largest top/side gap (1/4 in., blue) results in a net positive flow (i.e. net flow out of the furnace). The largest top/side gap (1/4 in., blue) shows inconsistencies around 400 F, similar to previous groups. Interestingly the NFPA 80 compliant top/side gap size (1/8 in., orange) results in almost equivalent flow into the furnace as out of the furnace.

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the smallest top/side gap (1/16 in. gap, grey) allows for the highest flow and the largest top/side gap (1/4 in. gap, blue) allows for the smallest flow. The flow through the bottom gap for the largest top/side gap (1/4 in., orange) shows that the flow around 400 F is inconsistent, changing from positive to negative flow. The mechanism for this inconsistency is not known. The scenario through the top and side gaps with the largest top/side gap (1/4 in., blue) resulted in the largest volume flow and the scenario with the smallest top/side gap (1/16 in.) resulted in the smallest volume flow through the top and side gaps.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1/4 in. top/side gap (blue) results in net flow out of the furnace and correspondingly lower pressures. Curiously the largest top/side gap (1/4 in., blue) shows clumping around 0.05 inH2O, meaning that the pressure never exceeds this value. This is curious still as the bottom gap is the same for this group and a similar trend was expected. For the same bottom gap size (3/4 in.) the trend is consistent only at the margins (i.e. greater than 0.05 inH2O) for all scenarios and what changes is the maximum pressure. It is clear that there is a distinction between the smaller gap sizes (1/16 in. & 1/8 in., grey & orange) and 1/4 in. top gap where there is a tipping point between 1/4 in. and 1/8 in. that changes the flow and pressure relationship.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. There is somewhat more of a spread at the upper velocity margins between the different scenarios. In the bottom gap flow vs velocity graph the 3/8 in. door gap model presents the highest velocity for a given volume flow. This trend is reversed (as is seen in volume flow vs temperature graphs) for the side and top gap flows.



—■— 1/16" Side/Top Gap —▲— 1/8" Side/Top Gap —●— 1/4" Top/Side Gap

B4.5    Group E (#s06,s07,s08)

# Single Steel Door

## Comparing Effects of Bottom Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#06	Single Door	Steel	3 hr	0.7500	0.1250	0.1250
#07	Single Door	Steel	3 hr	0.3750	0.1250	0.1250
#08	Single Door	Steel	3 hr	1.0000	0.1250	0.1250

This section compares the effects of changing the bottom gap for a single steel door with top and side gaps in compliance with the requirements of NFPA 80. The bottom gaps considered include the maximum allowable bottom gap as required by NFPA 252 fire test (3/8 in.), the maximum gap allowed by NFPA 80 (3/4 in.), and a 1 in. gap to evaluate the effects of a non-compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

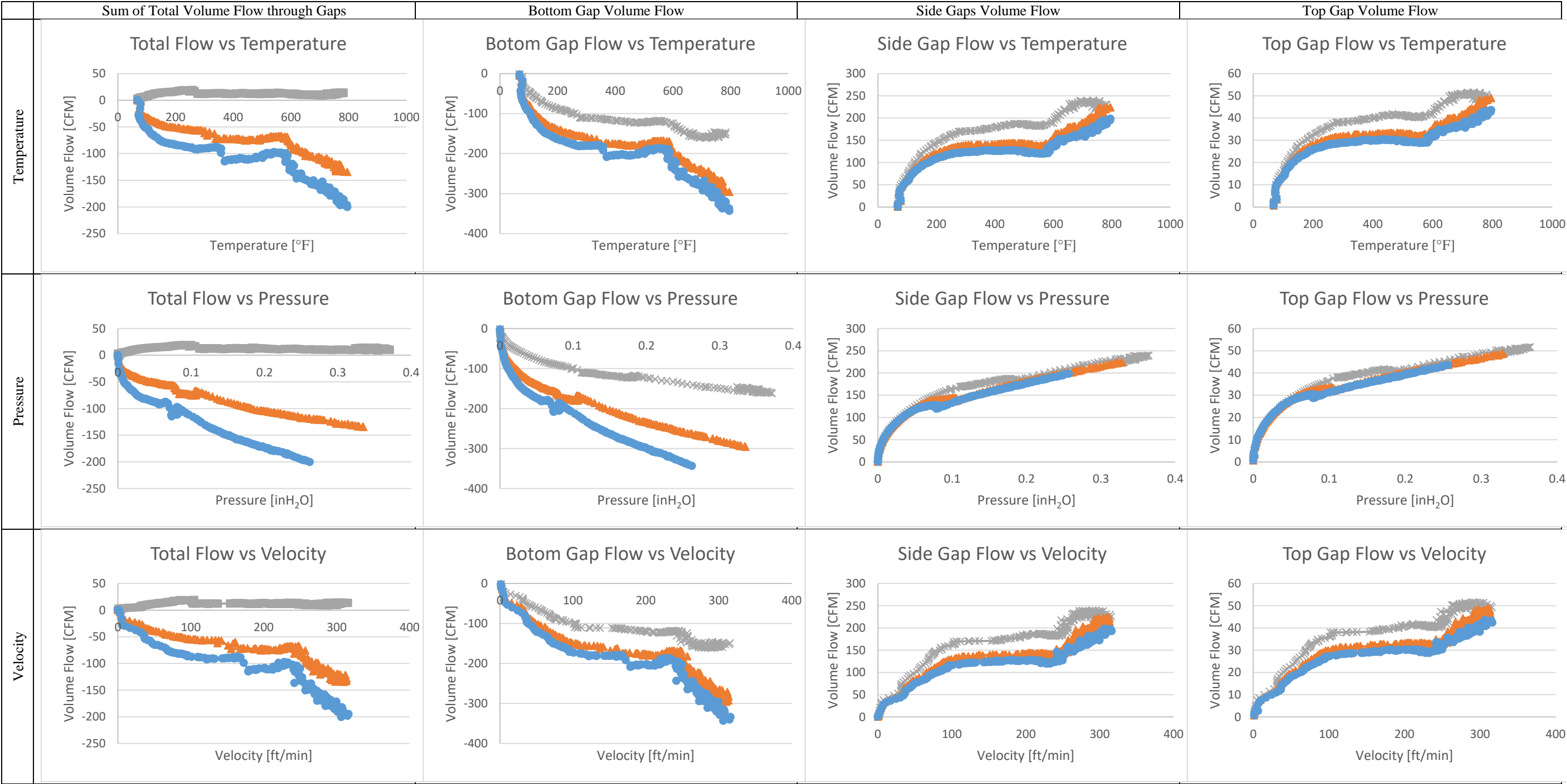
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 3/8 in., orange is 3/4 in., and blue is 1 in..

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the bottom gap does affect the total flow across the door. The total flow vs temperature shows that the smallest bottom gap size (3/8 in., grey) is almost equal so the flow out of the compartment is equivalent to the flow in. The larger bottom gap sizes (3/4 in. & 1 in.) both show net negative flow (i.e. flow into the furnace). Additionally, there are two interesting trends first around 400 F there is an increase in the volume flow, and second around 600 F there is another increase in volume flow. These changes in flow rate are especially emphasized in the largest bottom gap size (1 in., blue).

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the 1 in. gap (blue) and 3/4 in. (orange) gap are relatively similar and the 3/8 in. gap (grey) allows for the smallest flow.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1 in. gap (blue) has higher flows than a door with 3/4 in. or 3/8 in. gaps at the same pressure. The inconsistencies associated with the total volume flow vs pressure are also evident in the pressure results, however it seems that this is a result of a temperature relationship rather than a pressure relationship.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. In the relationship between velocity and volume flow, again it can be seen that the larger gap sizes (i.e. 1 in. and 3/4 in.) are more similar and the smallest gap size (3/8 in., grey) has a higher volume flow for a given velocity, for the side and top gap flows.



—■— 3/8" Bottom Gap    —▲— 3/4" Bottom Gap    —●— 1" Bottom Gap



B4.6    Group F (#s06,s09,s10)

# Single Steel Door

## Comparing Effects of Side/Top Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#06	Single Door	Steel	3 hr	0.7500	0.1250	0.1250
#09	Single Door	Steel	3 hr	0.7500	0.0625	0.0625
#10	Single Door	Steel	3 hr	0.7500	0.2500	0.2500

This section compares the effects of changing the top and side gaps in a single wood door with the bottom gap in compliance with the requirements of NFPA 80. The top and side gaps considered include the maximum allowable top/side gap, as allowed by NFPA 80 (1/8 in., orange), a smaller gap size (1/16 in., grey), and a larger gap size (1/4 in., blue). This will evaluate the effects of a non-compliant door compared to a compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

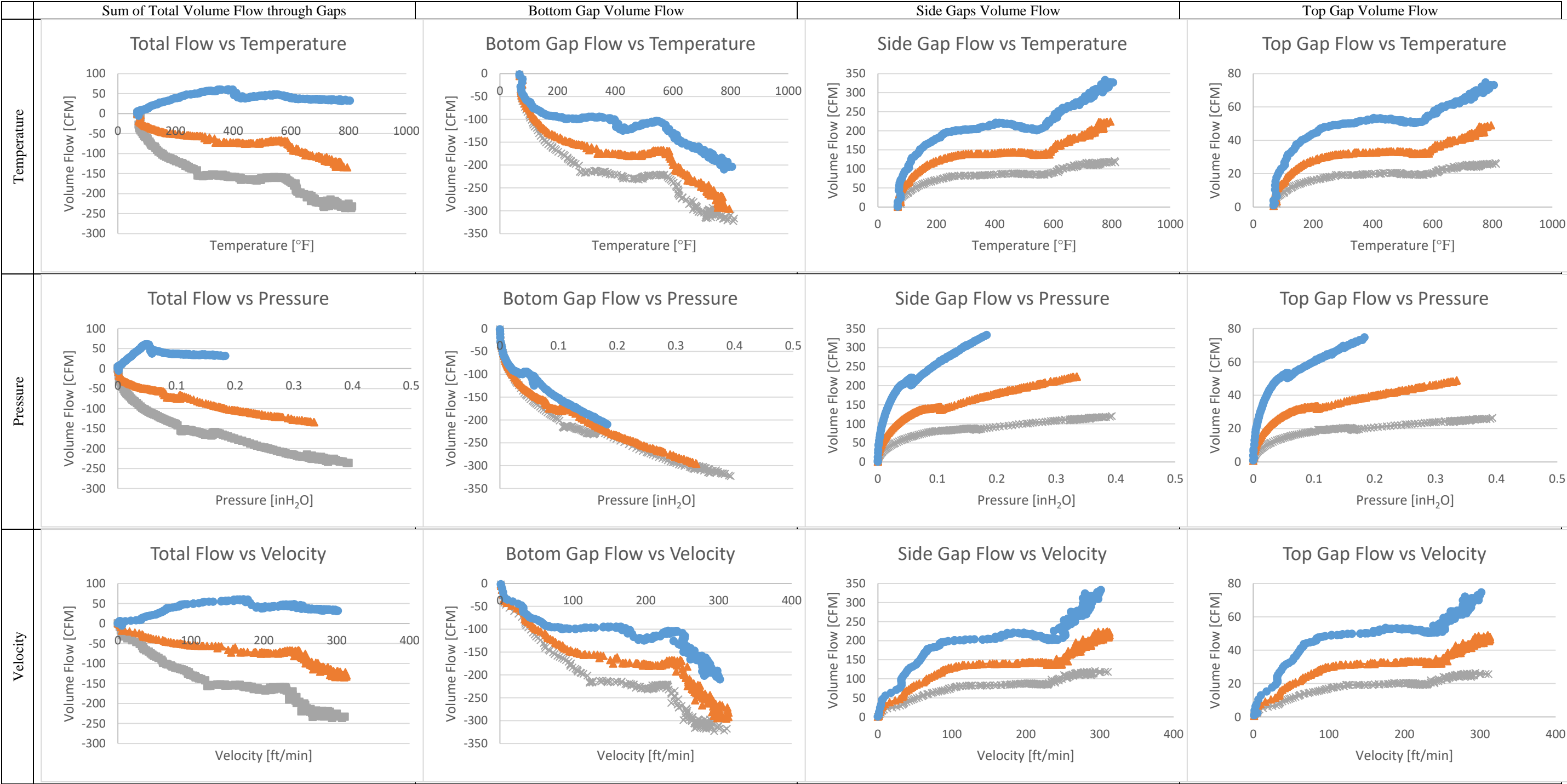
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top row), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom row). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 1/16 in., orange is 1/8 in., and blue is 1/4 in..

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the top/side gap size does affect the total flow across the door. When the total flows are summed the smallest gaps sizes (1/16 in., grey & 1/8 in., orange) result in a net negative flow (i.e. net flow into the furnace) and correspondingly higher pressures within the furnace. The largest top/side gap (1/4 in., blue) results in a net positive flow (i.e. net flow out of the furnace). The largest top/side gap (1/4 in., blue) shows inconsistencies around 600 F, similar to previous groups, but at a higher temperature.

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the smallest top/side gap (1/16 in. gap, grey) allows for the highest flow and the largest top/side gap (1/4 in. gap, blue) allows for the smallest flow. The scenario through the top and side gaps with the largest top/side gap (1/4 in., blue) resulted in the largest volume flow and the scenario with the smallest top/side gap (1/16 in.) resulted in the smallest volume flow through the top and side gaps.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1/4 in. top/side gap (blue) results in net flow out of the furnace and correspondingly lower pressures. For the same bottom gap size (3/4 in.) the trend of the volume flow vs pressure similar for all scenarios and what changes is the maximum pressure. It is clear that there is a distinction between the smaller gap sizes (1/16 in. & 1/8 in., grey & orange) and 1/4 in. top gap where there is a tipping point between 1/4 in. and 1/8 in. that changes the flow and pressure relationship.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. There is somewhat more of a spread at the upper velocity margins between the different scenarios. In the bottom gap flow vs velocity graph the 3/8 in. door gap model presents the highest velocity for a given volume flow. This trend is reversed (as is seen in volume flow vs temperature graphs) for the side and top gap flows.



—■— 1/16" Side/Top Gap —▲— 1/8" Side/Top Gap —●— 1/4" Top/Side Gap



B4.7    Group G (#d16,d17,d18)

# Double Steel Doors

## Comparing Effects of Bottom Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#16	Double Door	Steel	3 hr	0.7500	0.1250	0.1250
#17	Double Door	Steel	3 hr	0.3750	0.1250	0.1250
#18	Double Door	Steel	3 hr	1.0000	0.1250	0.1250

This section compares the effects of changing the bottom gap for double steel doors with top and side gaps in compliance with the requirements of NFPA 80. The bottom gaps considered include the maximum allowable bottom gap as required by NFPA 252 fire test (3/8 in.), the maximum gap allowed by NFPA 80 (3/4 in.), and a 1 in. gap to evaluate the effects of a non-compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

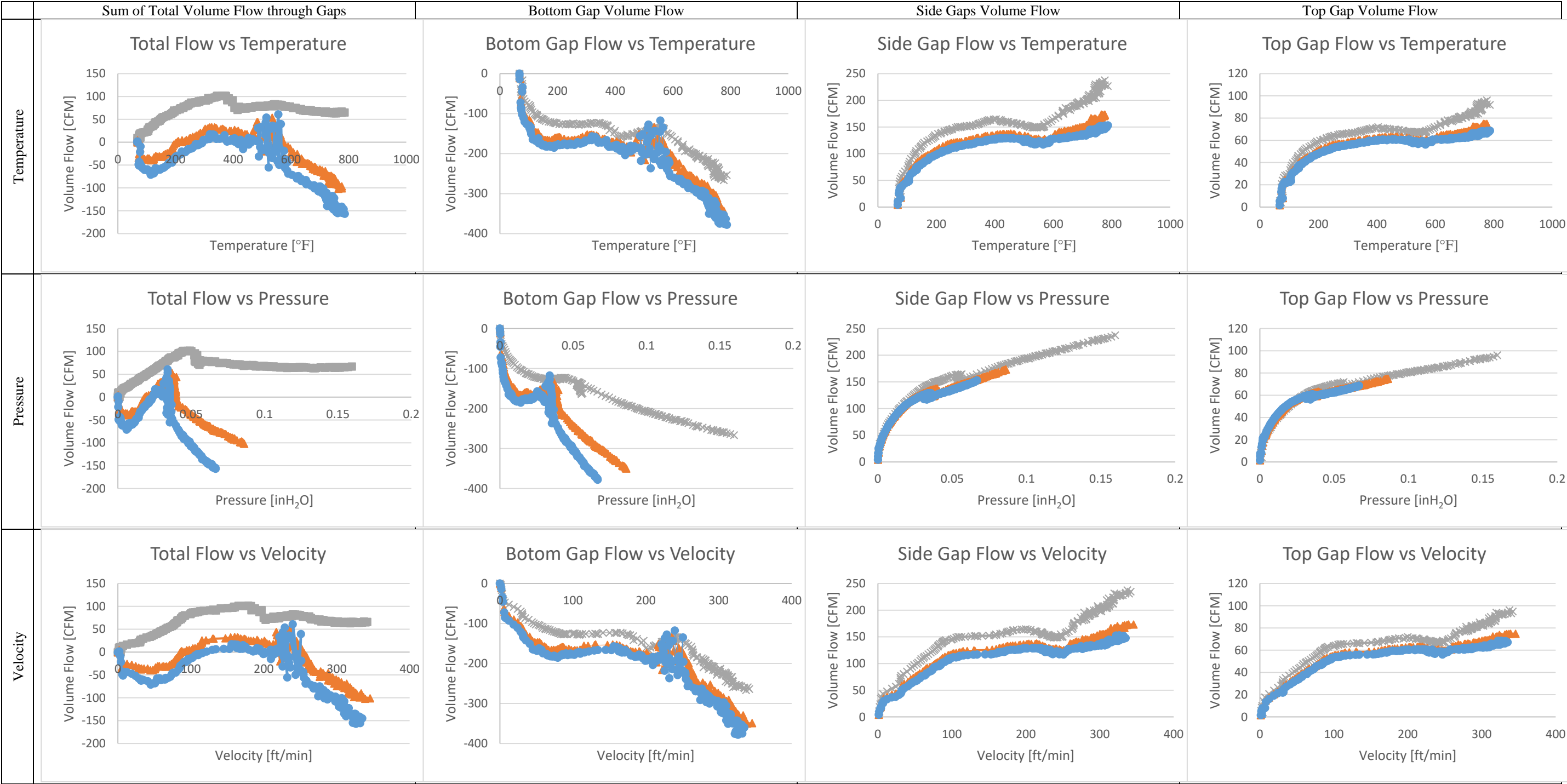
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 3/8 in., orange is 3/4 in., and blue is 1 in.

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the bottom gap does affect the total flow across the door. These graphs again display inconsistencies at approximately 600 F, where the flow shows more variability and fluctuation, especially for the larger bottom gap sizes (3/4 in., orange & 1 in., blue). Of note is the fluctuation of the total flow from positive to negative. Consistent with other groups the smallest bottom gap (3/8 in., grey) results in a positive flow (i.e. net flow out of the compartment). The larger gap sizes (1 in. & 3/4 in.) volume flow changes between positive and negative flow, where flow below 300 F is into the furnace, between 300 F and 600 F is out of the furnace, and above 600 F the flow is into the furnace. It is unknown what the mechanism for this change is. This does not mean that flow through the bottom gap changes from flow into the furnace to out of the furnace, but that comparatively the flow into the furnace through the bottom gap is sometimes greater than the flow out of the furnace through the top/side gaps and sometimes not.

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the 1 in. gap (blue) and 3/4 in. (orange) gap are relatively similar and the 3/8 in. gap (grey) allows for the smallest flow.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1 in. gap (blue) has higher flows than a door with 3/4 in. or 3/8 in. gaps at the same pressure, especially at pressures greater than 0.05 inH2O. The inconsistencies associated with the total volume flow vs pressure are also evident in the pressure results, however it seems that this is a result of a temperature relationship rather than a pressure relationship.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. In the relationship between velocity and volume flow, again it can be seen that the larger gap sizes (i.e. 1 in. and 3/4 in.) are more similar and the smallest gap size (3/8 in., grey) has a higher volume flow for a given velocity, for the side and top gap flows.



—■— 3/8" Bottom Gap    —▲— 3/4" Bottom Gap    —●— 1" Bottom Gap

B4.8    Group H (#d16,d19,d20)

# Double Steel Doors

## Comparing Effects of Side/Top Gap

Simulation	Type	Material	Rating	Bottom Gap	Top Gap	Side Gap
#16	Double Door	Steel	3 hr	0.7500	0.1250	0.1250
#19	Double Door	Steel	3 hr	0.7500	0.0625	0.0625
#20	Double Door	Steel	3 hr	0.7500	0.2500	0.2500

This section compares the effects of changing the top and side gaps in a double steel door with the bottom gap in compliance with the requirements of NFPA 80. The top and side gaps considered include the maximum allowable top/side gap, as allowed by NFPA 80 (1/8 in., orange), a smaller gap size (1/16 in., grey), and a larger gap size (1/4 in., blue). This will evaluate the effects of a non compliant door compared to a compliant door. Flow into the furnace is negative, flow out of the compartment is positive. All data is expressed in English units.

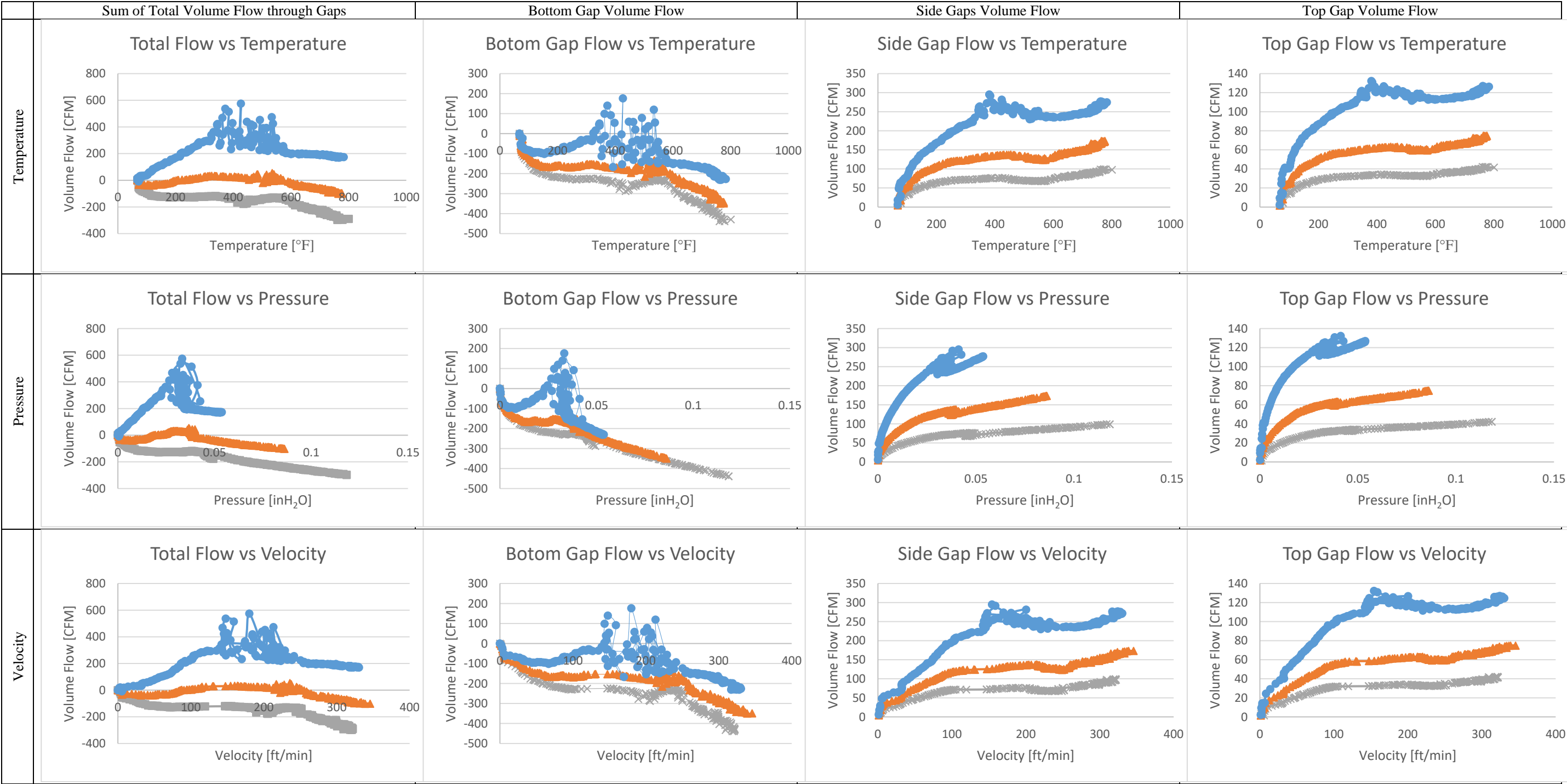
The graphs from left to right show the sum of the total volumetric flow through all gaps, the bottom gap flow, the sum of the flow through the side gaps, and the flow through the top gap. From top to bottom the flow rate is compared to furnace temperature (top row), average pressure in the furnace (middle row), and the average velocity at the gaps (bottom row). The key at the bottom of the page indicates which colors correspond to which gap size, where grey is 1/16 in., orange is 1/8 in., and blue is 1/4 in..

Looking at the temperature vs volume flow graphs, the total flow vs the temperature indicates that the change in the top/side gap size does affect the total flow across the door. When the total flows are summed the smallest gaps sizes (1/16 in., grey) results in a net negative flow (i.e. net flow into the furnace) and correspondingly higher pressures within the furnace. The largest top/side gap (1/4 in., blue) results in a net positive flow (i.e. net flow out of the furnace). The largest top/side gap (1/4 in., blue) shows inconsistencies between 400 F and 600 F, similar to previous groups. Interestingly the NFPA 80 compliant top/side gap size (1/8 in., orange) results in almost equivalent flow into the furnace as out of the furnace.

When the flow through the individual components is broken down it is observable in the bottom gap vs temperature graph that the smallest top/side gap (1/16 in. gap, grey) allows for the highest flow and the largest top/side gap (1/4 in. gap, blue) allows for the smallest flow. The flow through the bottom gap for the largest top/side gap (1/4 in., orange) shows that the flow around 400 F is inconsistent, changing from positive to negative flow. The mechanism for this inconsistency is not known. The scenario through the top and side gaps with the largest top/side gap (1/4 in., blue) resulted in the largest volume flow and the scenario with the smallest top/side gap (1/16 in.) resulted in the smallest volume flow through the top and side gaps.

The pressure vs volume flow results are consistent with the temperature vs flow results. The 1/4 in. top/side gap (blue) results in net flow out of the furnace and correspondingly lower pressures. Curiously the largest top/side gap (1/4 in., blue) shows clumping around 0.05 inH2O, meaning that the pressure never exceeds this value. This is curious still as the bottom gap is the same for this group and a similar trend was expected. For the same bottom gap size (3/4 in.) the trend is consistent only at the margins (i.e. greater than 0.05 inH2O) for all scenarios and what changes is the maximum pressure. It is clear that there is a distinction between the smaller gap sizes (1/16 in. & 1/8 in., grey & orange) and 1/4 in. top gap where there is a tipping point between 1/4 in. and 1/8 in. that changes the flow and pressure relationship.

The velocity graphs show that total flow versus velocity through the doors is consistent with the volume flow vs temperature graphs. There is somewhat more of a spread at the upper velocity margins between the different scenarios. In the bottom gap flow vs velocity graph the 3/8 in. door gap model presents the highest velocity for a given volume flow. This trend is reversed (as is seen in volume flow vs temperature graphs) for the side and top gap flows.



—■— 1/16" Side/Top Gap —▲— 1/8" Side/Top Gap —●— 1/4" Top/Side Gap

## B5 Conclusion

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In conclusion there are several trends that were noted in the different groups, but in general the trends within the groups were consistent with expectations.

### 1.NFPA Compliant Simulations:

Scenario #01, #06, #11, #16 all were designed to be compliant with the maximum allowable gaps in NFPA 80, with those being 3/4 in. bottom gaps and 1/8 in. top and side gaps. Figure 18 shows only those scenarios. It is noteworthy that the single door scenarios (#01 & #06) both follow the same general trend and feature net negative flows (i.e. flow into the furnace). The double door scenarios (#11 & #16) also follow similar trends, with the flow positive from approximately 200 F to 500 F.

### 2.Net Positive Flows:

Figure 19 shows those scenarios with net positive flows (i.e. flows out of the furnace). Not surprisingly these scenarios either have a 3/8 in. bottom gap (i.e. smallest bottom gap tested) or a 1/4 in. side gap (i.e. largest side gaps tested). This indicates that for the smallest bottom gap the pressure in the furnace was sufficient to force more air out of the top/side gaps than was able to enter through the bottom gap.

The highest flows are from scenario #15 and #20 (seen going out of the graph in red and green) which both feature double doors with 1/4 in. side/top gaps, indicating that the total surface area for volume flow exchange is very large and can all for significant air exchange.

For the purposes of this summary the graph in Figure 19 was limited to 120 cfm to show there are relationships between the steel and wood doors scenarios. The lowest volume flow (seen in pink) are those single doors with 3/8 in. bottom gaps (#02 & #07). The middle line (seen in green) are those single doors with 1/4 in. top and side gaps (#05 & #10). The top line that can be seen (seen in purple) are those double door scenarios with a bottom gap of 3/8 in. (#12 & #17).

### 3.Large Fluctuations in Volume Flow:

Figure 20 displays those graphs with noticeably fluctuations in volume flow where the flow fluctuates from negative to positive to negative. The scenarios where this occurred are #11, #13, #16, #18. What links these scenarios are the fact that they include double doors with either a 1/8 in. side gap (NFPA 80 compliant side gap) or 1 in. bottom gap (largest bottom gap tested).

### 4.Net Zero Volume Flow

Figure 21 includes those scenarios which resulted in almost equivalent volume flow between the bottom gap (fluid in) and the top and side gaps (fluid out). Scenarios #02 and #07 are both single door scenarios with 3/8 in. bottom gap and 1/8 in. top and side gaps. Scenarios #11 and #16 are both double door scenarios with 3/4 in. bottom gap and 1/8 in. side gaps.

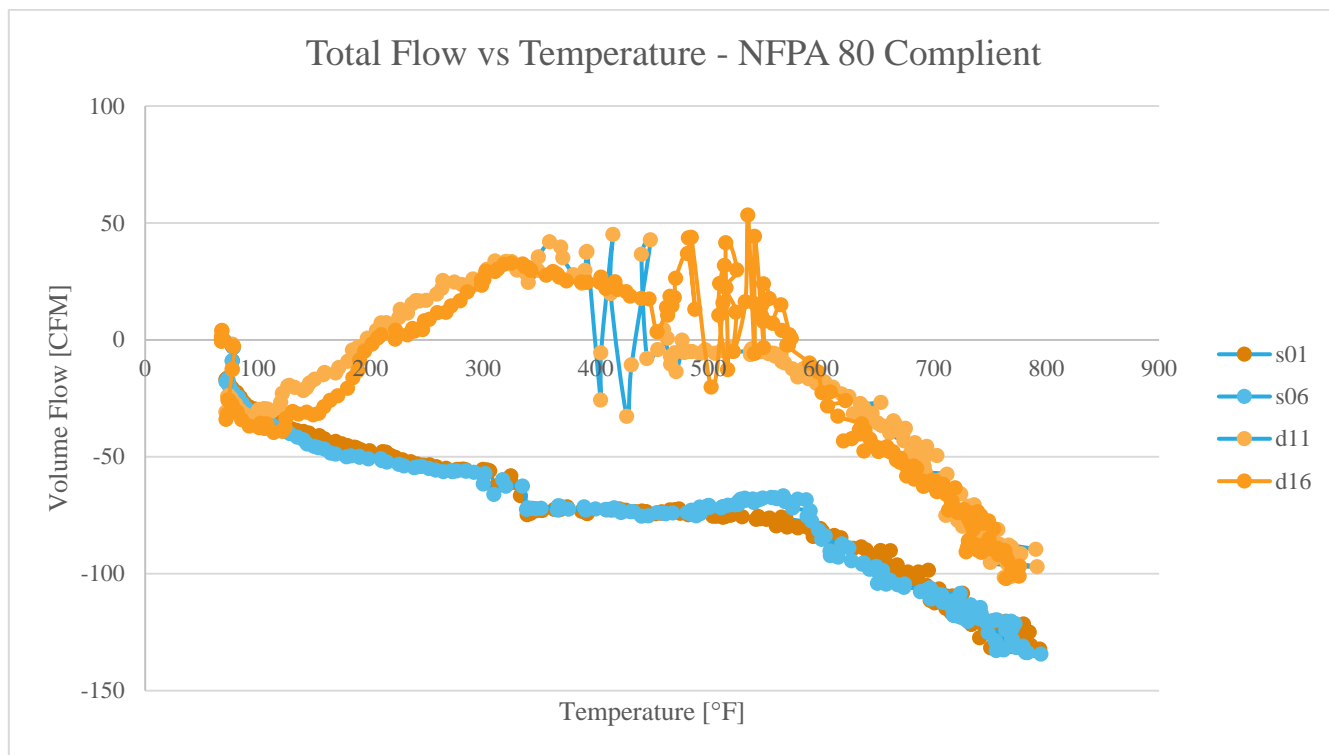


Figure 18: Total Flow vs Temperature - NFPA 80 Compliant

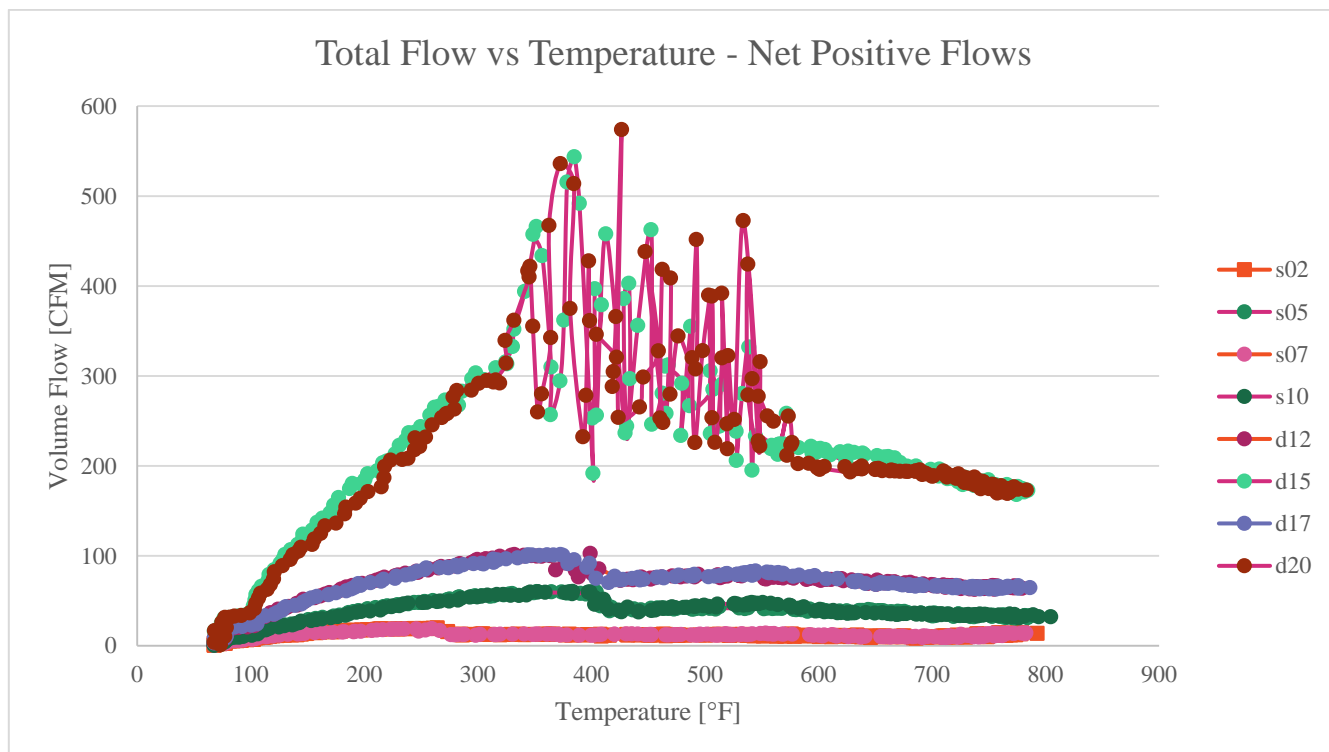


Figure 19: Total Flow vs Temperature - Net Positive Flows

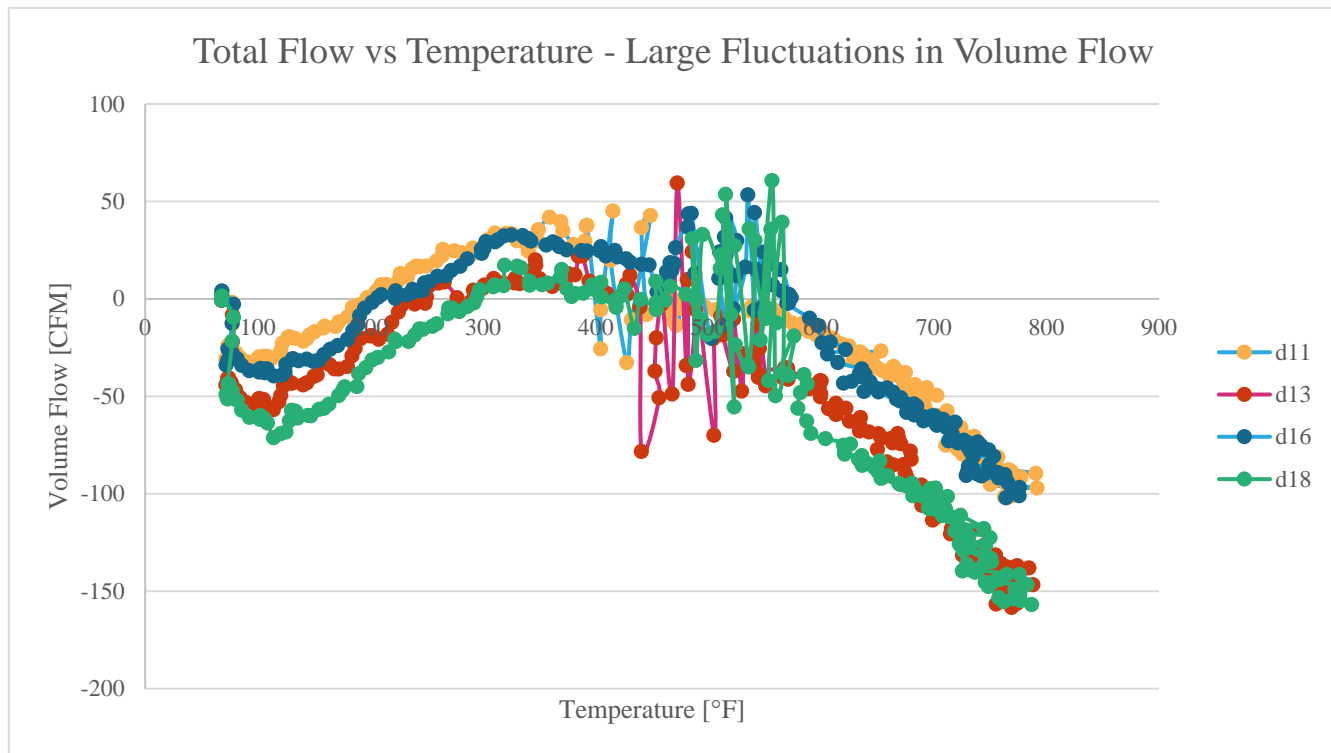


Figure 20: Total Flow vs Temperature - Large Fluctuations in Volume Flow

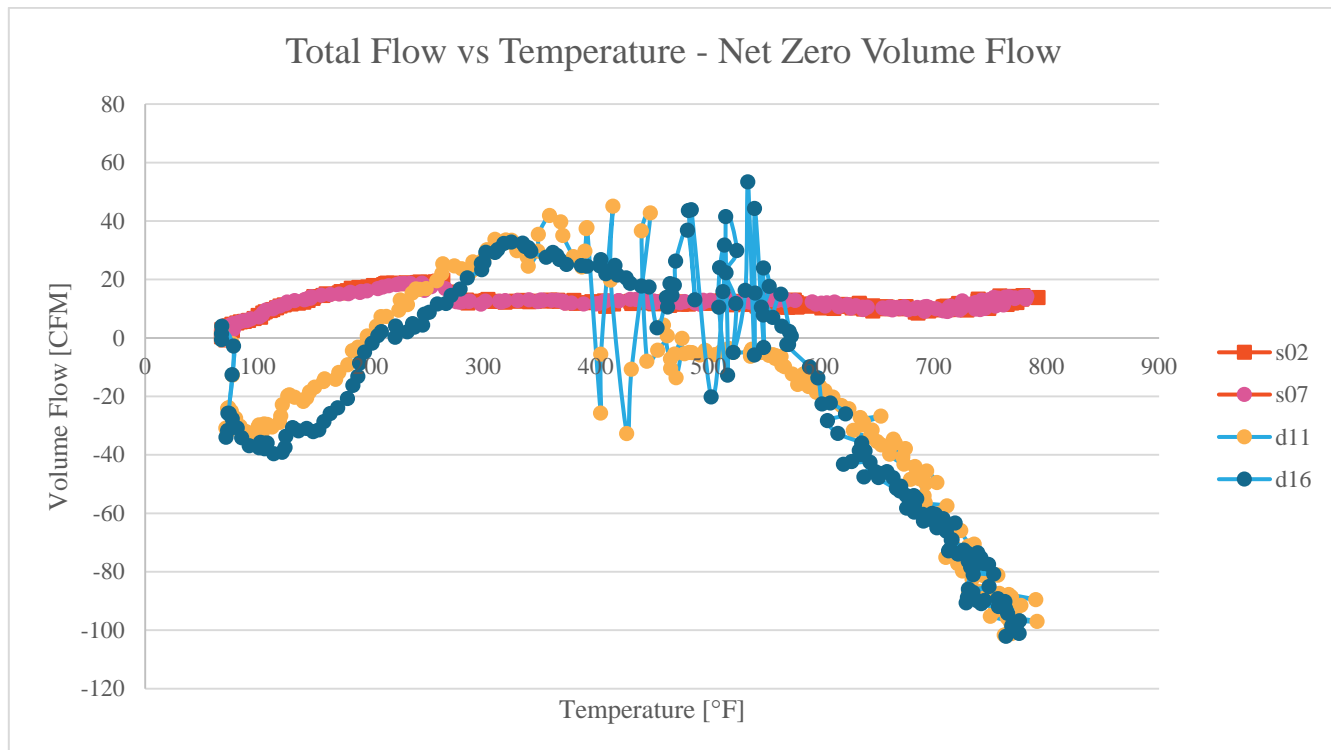


Figure 21: Total Flow vs Temperature - Net Zero Volume Flow