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U.S. DEPARTMENT OF COMMERCE
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Center for Fire Research
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# THE NEED AND AVAILABILITY OF TEST METHODS FOR MEASURING THE SMOKE LEAKAGE CHARACTERISTICS OF DOOR ASSEMBLIES

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Abstract

This paper identifies and places into perspective relevant information that would assist in focusing future research and development on test methods to measure the smoke leakage characteristics of door assemblies. The concept of smoke compartmentation is introduced and developed. The importance of cross-door pressure differential in establishing the performance of door assemblies in fire generated environments is discussed. Door assembly performance is then related to life safety, in general, and to the design of compartments of safe refuge, in particular. All of the discussion suggests a listing of required door assembly test methods, and, finally, leads to a review of the availability and development status of existing and potential future test method candidates.

Key words: compartmentation, compartment fires, door assemblies, high-rise buildings, leakage, life safety, pressure differential, pressurization, property protection, safe refuge, smoke control, smoke movement, stack effect, test methods.

## 1. INTRODUCTION AND OBJECTIVE OF THIS WORK

The fire stopping characteristics of door assemblies during certain practical fire scenarios can be estimated with some confidence by means of well-established test procedures. In contrast to this, the development of analogous test procedures for estimating a door assembly's smoke stopping characteristics are only now being fostered by appropriate institutions such as American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO), and the National Fire Protection Association (NFPA). Yet, it is well recognized that in real fire scenarios, contact with environments contaminated with a fire's gaseous and solid products of combustion (i.e., smoke), even though they are far from the fire's combustion zone (i.e., its flames), can pose as serious a threat to life and property as can with the fire itself [1-3]. It is the purpose of this paper to assemble and place into perspective relevant information that would assist in addressing facility design problems related to the latter situation.

The discussion to follow will focus attention on the relation between smoke leakage of door assemblies and smoke spread throughout a facility. However, smoke spread is a function of the leakage of all construction elements of a facility's partitions - leakage, for example, through joints, construction cracks, and penetrations around pipes, conduits and ducts, all of which are commonplace in floor/ceiling and wall assemblies. The relevance of the basic discussion to smoke leakage of generalized facility partions should, therefore, be emphasized here at the outset.

## 2. SMOKE COMPARTMENTATION

### 2.1 Clarification of the Term "Compartment"

To fix ideas it is useful to clarify the terms "fire compartment"and "smoke compartment", which will be used frequently in the discussion to follow. Here, a fire compartment is meant to denote a single facility space, or group of contiguous spaces (on the same, or even on different levels of the facility) which is/are bounded by a partition envelope assembly engineered and constructed to have significant, known, fire stopping characteristics. For a fire compartment of more than one facility space, the design fire-stopping performance of the compartment should be assured regardless of which compartment space(s) contain the fire.

A smoke compartment is analagous to a fire compartment. Its envelope is designed and constructed to have known smoke-stopping or smoke-leakage rather than fire-stopping characteristics. A smoke compartment of fire involvement is the smoke compartment which actually contains the fire. The smoke-stopping performance of a smoke compartment partition element would be assured independent of the location of the fire within the compartment.

By design, it is possible that a smoke or fire compartment of fire involvement will reliably maintain its integrity for only a specific, limited time interval into the fire. After this time interval, failure in a relatively weak component of the compartment envelope, say, onset of significant warpage of a compartment door or failure of seals due to high temperature exposure, could lead to a new, enlarged, smoke or fire compartment of fire involvement. Whereas the original compartment may have involved a relatively small portion of the facility, the new compartment could be much larger, possibly even encompassing all parts of the facility except for smoke compartments of safe refuge.

While it is possible for a smoke compartment and a fire compartment to be identical, this need not be the case. For example, a fire rated compartment envelope may be designed to provide reliable fire stopping during the course of likely hazardous fires for a one hour period. Yet, if the smoke leakage characteristics for all or part of the envelope, e.g., of the door assemblies, are unknown, and if the facility is not equipped with an appropriate system for pressurization, then it may be necessary to consider a much larger portion of the facility as the smoke compartment of fire involvement.

### 2.2 Test Methods for Implementing Fire Compartmentation

In the design of facilities, fire compartmentation has been classically used to impede the spread of fires from one space to another. In this regard, several test methods [4-10] have been developed to measure the time that a particular construction element will reach agreed-upon criteria of failure when exposed to a standard, fully developed fire. Thus, by proper choice of rated construction elements, which include door assemblies, one can, under certain limited circumstances, anticipate containment of a fire to the compartment of fire origin for a time interval of, for example, one, two, or more hours. The limited circumstances referred to include those where wind loading, stack effect and/or facility ventilation would not lead to significant positive pressures (relative to adjacent compartments) in fire compartments of fire involvement.

While compartment constructions might predictably contain the spread of fire to adjacent spaces, they may or may not necessarily abate the spread of smoke to any significant degree. Yet, most would probably agree that with care in design, construction, and installation, significant reduction in typical smoke leakage from a smoke compartment of fire involvement to an adjacent compartment can indeed be achieved. If compartment envelopes could be so implemented, and, just as important, if meaningful characterizations of the smoke leakage performance of such envelopes during real fire scenarios could be established, then, as in the case of fire compartmentation, smoke compartmentation would be an important concept. Smoke compartmentation would be convenient and useful for understanding, developing and implementing methods of controlling smoke spread.

### 2.3 Mechanisms of Intracompartment Smoke Migration - Two Types of Smoke Compartments

It is useful to identify characteristics of the two basic types of smoke migration mechanisms which are depicted in Figure 1. One of these would be associated with the smoke compartment of fire involvement, and the other with all other smoke compartments of a facility.

Because of relatively high smoke temperatures and associated large temperature differences, the buoyancy forces which lead to strong intracompartment stratification will dominate the dynamics of smoke migration within one or all spaces of a smoke compartment of fire involvement. However, once smoke has been transported from this compartment through penetrations (e.g., leaks in a doorway assembly) in its boundaries, and into an adjacent smoke compartment, different primary mechanisms of further smoke migration can come into play. If the rate of smoke leakage into adjacent compartments is limited by well-designed partition assemblies, then it is reasonable to expect* success in a model of further smoke spread which assumes that entering smoke is continuously and uniformly mixed throughout adjacent compartment environments. Such mixing would be driven, for example, by forced ventilation-generated air currents, and by buoyancy-driven wall flows [12,13]. This suggests a second, "tracer-gas migration" type of mechanism or the smoke's continued transport throughout the facility. The term "tracer-gas migration" is meant to indicate a mechanism of intrafacility smoke movement, outside the smoke compartment of fire involvement, which is characterized by time-dependent, compartment-to-compartment, migration and dilution of relatively cool smoke. The intrafacility smoke migration and dilution is driven by pressure differences between uniform environment compartments, which are generated by forced ventilation systems, wind effects, stack effects, or a combination of these driving forces.

### 2.4 A Key to Successful Smoke Compartmentation

If one accepts the above description, successful smoke compartmentation can be achieved if, by design, there is a switchover from strong and rapid smoke spread, due to significant and unavoidable stratification on the fire side of a smoke compartment barrier, to a conceptually simpler and more easily analyzed tracer-gas migration smoke spread, on the other side of the barrier.

The designed switchover to the tracer-gas migration mechanism of smoke spread outside the smoke compartment of fire origin is key in that it would allow an achievable and practical method of analysis of total intrafacility hazard development. The method of analysis referred to would involve an

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* There is an important exception to this expectation. This has to do with the movement and mixing of smoke in tall, narrow spaces such as shafts, stairwells and tall, narrow atriums. The dynamics of smoke introduced into such spaces, even if at a temperature only moderately above the local ambient will tend to bear strong similarities with the aforementioned smoke dynamics of the fire compartment. Thus, for better or for worse, strong stratification of the smoke may develop, and an analysis or design based on the assumption of a uniform, fully mixed environment throughout the shaft, stairwell or atrium can lead to significant error. Modeling of the dynamic environment within such high aspect ratio spaces (i.e., large ratio of height to compartment width) is an important and relevant problem whose solution is only now in the research stage[11].

enclosure fire model of appropriate detail (e.g., like one of those of references 14-18) for predicting events in the smoke compartment of fire involvement, and a facility infiltration and ventilation model (e.g., like one of those of references 19-21) for all other smoke compartments of a facility. To specify or evaluate fire safety, requirements of safe available egress time [22] would be established for the different types of smoke compartments of the facility. Criteria for a safe compartment environment would be established, where these would be based on predictable fire environment descriptors (e.g., the level of smoke dilution relative to concentrations in the smoke compartment of fire fire involvement).

In the above type of facility fire safety evaluation, it would not necessarily be the role of the fire test community to establish requirements of safe available egress time and criteria for a safe environment (a task partially attempted, for example, in reference 23). However, this community would clearly have a role in the development of door assembly, smoke leakage, test methods. Indeed, the ability to carry out the indicated type of analysis of hazard development at any level of sophistication is totally dependent on a quantitative description of the leakage characteristics of door assemblies.

## 3. THE IMPORTANCE OF CROSS-DOOR PRESSURE DIFFERENTIAL IN ESTABLISHING A RATING FOR A FIRE COMPARTMENT DOOR ASSEMBLY

### 3.1 Pressure Differential and the Smoke Leakage of Fire Compartment Door Assemblies

The last section discussed mechanisms for smoke migration both inside and outside the compartment of fire involvement. As depicted in Figure 1, the physical and operational link between these two spaces, the fire compartment and the rest of the facility, are the actual compartment boundary components, e.g., connecting door assemblies, and their leakage characteristics. In the context of a compartment containing a fire, we specifically refer to the leakage of smoke across door assemblies which are potentially exposed on one side to developing and fully developed fire environments, and where the smoke is driven by a cross-door pressure differential.

The existence of a cross-door pressure differential is key to the evaluation of a door assembly design! In particular, a variety of possible pressure differential magnitudes and directions (higher or lower pressure in the compartment relative to the adjacent space) can occur in practice. For example, stack effect alone can lead to (relatively) uniform, positive or negative, cross-door pressure differentials of the order of several tens of pascals or higher when compartments of fire involvement are exposed to the outside environment through broken windows [24]. Steady wind velocities of, say, 25 mph would add or subtract up to 75 Pa [25,26], and this value is proportional to the square of the wind velocity. Over and above these uniform pressures, fire-generated cross-door pressure differentials can vary from top to bottom of a doorway on the order of ± 5-10 Pa [24]. Depending on which pressure conditions can be anticipated for a particular compartment in a given facility, totally different quantities of smoke could be transferred across door assemblies of identical design.

### 3.2 Pressure Differentials and the Fire Stopping Characteristics of Door Assemblies

Not enough attention has been paid in the past to the potential impact of cross-door pressure differentials on the actual fire stopping capabilities of door assemblies. Thus, with unknown consequences, a fire door assembly may be subjected to the above-mentioned type of fire scenario involving positive, cross-door, pressure differentials of several tens of pascals. For example, a door assembly may receive a one hour fire endurance rating in an ASTM E152 [6] or ISO 3008 [8] test, where the test conditions involved a relatively modest, cross-door, pressure differential condition of, say, ±10 Pa. But, when similarly tested under a pressure condition which simulated a realistic, high-overpressure fire scenario, it is possible that the same door assembly would receive a significantly reduced fire endurance rating. Alternatively, consider a facility which includes an automatic smoke control system which is designed to maintain a negative pressure (relative to all adjacent compartments) in any potential compartment of fire origin. Then, depending on the magnitude of the designed cross-door pressure differential, it is reasonable to speculate that a desired one hour of protection against the spread of fire may be achievable with a door assembly having an ASTM E152 or ISO 3008 rating (obtained, say, under modest positive over-pressure conditions) significantly less than one hour. Safety and cost tradeoffs implicit in the above examples are obvious.

The point of the above discussion is that there may be good reason to rate and take account of the fire-stopping capability of door assemblies relative to, and as a function of cross-door pressure differential. To obtain such ratings a revised ASTM E152 or ISO 3008 with a significant furnace pressure control capability and/or with other means of achieving a cross-door pressure differential control capability (e.g., by the method proposed in reference 24) would be required.

### 3.3 Some Naturally Occurring Pressure Differentials During High-Rise Building Fire Scenarios

In order to place the cross-door pressure differential question into perspective, and as a case in point, it is instructive to consider the use of door assemblies in high-rise buildings or, more directly, in buildings where stack effects are significant. (Even in low facilities, steady winds could lead to the type of pressure loadings to be discussed here.) Assume, for example, that cross-exterior-wall pressure differences during normal winter days in a building of interest are of the order of several tens of pascals at the lower floors (higher pressure outdoors) and at the upper floors (higher pressure indoors). Now consider the following scenario:

Fire breaks out in a compartment on a low floor of the building during the winter. The compartment flashes over, and a ventilation controlled fire develops, where ventilation is from broken windows on exterior walls. Once the windows break, the pressure in the fire compartment is substantially maintained at the (relatively high) outdoor pressure. The fire compartment is connected to adjacent compartments by partitions with relatively small penetrations, e.g., (closed) door assemblies. The pressure in these adjacent compartments is substantially maintained at a (relatively low) indoor pressure which is characteristic of the low floor under consideration. The pressure drop across the partitions is therefore maintained at levels which are of the order of magnitude of several tens of pascals, i.e., at levels which are of the order of magnitude of indoor-to-outdoor, stack-effect-generated pressure differentials.

Note that in the above scenario it is reasonable to anticipate rates of smoke leakage across fire compartment door assemblies which could be significant. (This would depend, of course, on the actual in situ leakage characteristics of the door assemblies involved.) It is also noteworthy that if the fire compartment was on a high floor, it would be maintained at a smaller pressure than adjacent compartments, and smoke leakage to the rest of the building would be substantially eliminated.

## 4. DOOR ASSEMBLIES, COMPARTMENTS OF SAFE REFUGE, AND LIFE SAFETY

### 4.1 General Considerations

Outside of a fire compartment, and by virtue of the existence of closed door assemblies and other barriers to fire and smoke spread, every compartment of a facility through which occupant egress could occur will be maintained at safe conditions at least for some limited time into the fire. However, in order to achieve facility designs which are compatible with life safety, it is desirable to designate and design certain specific spaces as compartments of safe refuge. The environment in such compartments would be maintained under tenable conditions for significant (although, not necessarily indefinite), specified time intervals.

Three types of information are required to design compartments of safe refuge with confidence. First is some knowledge of the leakage characteristics of candidate door assemblies. Second are estimates of the likely smoke conditions which will occur in those smoke compartments adjacent to a smoke compartment of safe refuge. As suggested by the discussion in the previous section, a third and final type of input is the anticipated level of pressure differential between potential smoke-laden adjacent smoke compartments and the protected compartment itself.

Pressurized stairwells are examples of smoke compartments of safe refuge. A discussion of these kinds of compartments will now be presented to illustrate the type of inputs required for their successful design. This discussion is presented here mainly for the purpose of highlighting the general types of door assembly leakage measurements that a facility designer might require. For specific design information about pressurized stairwells and other smoke control systems the reader is referred to reference 26.

## 4.2 The Pressurized Stairwell — An Example of a Compartment of Safe Refuge

It would clearly enhance the safety of a facility if stairwells were designed as smoke compartments of safe refuge for time intervals required to evacuate all occupants to other, more secure compartments or to the outside. Toward this end, the pressurized stairwell design concept has been developed [1,3]. By introducing fresh air into a stairwell with the use of appropriate blower hardware and control, it is possible to maintain the stairwell at a practical positive pressure relative to all adjacent compartments during <u>many</u> realistic fire scenarios and related stairwell door usage. Provided the stairwell door to the floor of fire involvement is closed, such stairwell designs would lead to a positive flow of fresh air across door assemblies from the stairwell compartment to all adjacent spaces (including those on the fire floor). Thus, the fully successful pressurized stairwell will "never" allow leakage of smoke (or air) into the stairwell compartment from adjacent building spaces. In particular, all smoke infiltration into the stairwell is eliminated so long as the doors and other partition construction elements of the stairwell maintain their integrity.

The design of the stairwell pressurization system clearly requires knowledge of the leakage characteristics of entry/exit door assemblies. Except for the fire floor, we are talking here about leakage of unheated air across a(n unheated) door assembly under design conditions of cross-door pressure difference. Leakage characteristics of this type could be acquired with ASTM E 283, [27] or with the proposed ISO 5925 Part 1 [28] test method. For the fire floor (assuming no protected lobby on the other side of the door) one also requires knowledge of the leakage characteristics of the door assembly as it is exposed to fully developed fire conditions. Here we are talking about leakage rates that would be measured, for example, in a door assembly fire endurance test (such as ASTM E152 or ISO 3008, appropriately revised to allow for leakage measurements) where the test laboratory furnace was maintained at such a level of negative pressure, relative to the pressure at the unexposed side of the door, as to simulate the stairwell-to-fire compartment pressure differential.

There is at least one class of realistic fire scenario, and stairwell door usage where the latter pressurized stairwell design considerations may not be adequate (unless the most up-to-date pressurization design technology is used) [26]. Reference is made to the use of doors during high-rise building evacuation at times of cold winter conditions. Under such circumstances, it may not be practical to maintain a positive pressure difference between the stairwell and the outside at the elevation of the lower floors of the building (see, for example, the building measurements reported in Figure 10 of reference 29). Thus, with a fire in a lower floor which is vented directly to the outside through broken windows (as in the fire scenario referred to in an earlier section), the smoke compartment (floor) of fire origin will be at a positive pressure relative to the stairwell. Under this circumstance there will be unavoidable continuous smoke leakage into the stairwell. But it is clear that the stairwell pressurization system could accept some limited smoke intake without leading to any serious degradation in the stairwell environment during the required time interval for safe refuge. Therefore, one design task would be to choose a candidate door assembly whose leakage characteristics were such that this established design limit would not be exceeded. Such leakage characteristics could only be established by carrying out a test (such as the one recommended in reference 24, depicted here in Figure 2 and, as yet to be developed) which measured the leakage rate of a door assembly while it was undergoing a fire endurance test exposure with positive furnace-to-unexposed-side pressure differential.

## 5. GENERAL PREDICTION AND CONTROL OF THE DEVELOPMENT OF THREATENING CONDITIONS THROUGHOUT A FACILITY

Door assembly leakage characteristics are required to describe a facility's fire-generated environment, in general, and to design smoke compartments of safe refuge, in particular. As suggested in earlier discussion, by implementing an appropriately conservative design concept like the "perfectly" pressurized compartment of safe refuge, (i.e., no smoke entry under design conditions), it is often possible to simplify the latter design task, and to do this in a manner which requires only the most approximate door leakage characteristics. Indeed, it is with the use of "perfect" pressurization that the safe egress path problem is now being solved [26]. However, if facility designs are to be responsive to more flexible fire safety performance criteria, it is evident that approaches for solving the inherently coupled problems of compartment-to-compartment smoke spread are required. Such approaches would be based on tools for predicting or mathematically simulating the fire-generated smoke environments which develop throughout a facility subsequent to the ignition of a potentially threatening fire. These would include mathematical models for predicting fire growth phenomena in multiroom spaces of a compartment of fire involvement, and the migration of smoke to all other compartments of the facility (e.g., to compartments of designed safe refuge), whether as a result of forced ventilation, stack effect, wind-generated pressure differences, smoke buoyancy, or a combination of these.

Key to overcoming the challenges in developing fire environment simulation models are the compromises which must be made between accuracy and detail in simulation of physical phenomena, on the one hand and practicality of implementation on the other (i.e., to be successful, the analytic tools to be developed will have to be both reliable and "user friendly"). Once developed, dynamic fire environment prediction models will be used together with models which predict the response of people and property to such environments. It will then be possible to systematically establish the life or property safety performance of a facility on a fully integrated, economical and rational basis [11].

# 6. REQUIRED NEW AND/OR REVISED DOOR ASSEMBLY TEST METHODS

## 6.1 Required Measurements

Based on all of the previous discussion it follows that test methods are required to evaluate the following performance characteristics of door assemblies used in the partitions of smoke compartments:

1. Rate of leakage under ambient temperature conditions, as a function of cross-door pressure differential.

2. Fire endurance time (according to criteria similar to those set forth in ASTM E152) of an interior door assembly under conditions where one side is exposed to a fully developed (flashed-over) fire simulation, the other side is exposed to an ambient environment, and where the assembly is subjected to a cross-door pressure differential between, say, ± 100 pascals.

3. Rate of leakage as a function of time (up to the assembly's fire endurance time, as established in measurement 2, above) under conditions where one side is exposed to a fully developed (flashed-over) fire simulation, the other side is exposed to an ambient environment, and where the assembly is subjected to cross-door pressure differential between, say, +100 pascals and values that are (slightly) negative enough as to lead to zero leakage conditions.

It has been suggested [23,30] that another test method is required to evaluate leakage characteristics under medium temperature (100°C-250°C) exposure conditions. Such a test method would be used to estimate the leakage characteristics of door assemblies which were not (yet) exposed to flashover conditions, but which, by reason of proximity to a smoke compartment of fire involvement, were exposed to significantly elevated temperature environments (as might be eventually anticipated in an "intermediate" compartment between the fire compartment and a compartment of safe refuge).

A test method developed to acquire and report any of the above measurements on a particular door assembly would likely include a shorthand means of summarizing the test results. Such a summary would take the form of a rating or classification system (as, e.g., suggested in reference 23) which could be used as a convenient means of reference between facility design guides, standards, codes, etc.

## 6.2 Leakage Under Ambient Conditions

The ambient leakage measurements under item 1 above could be acquired by implementing ISO 5925, Part 1 (Figure 3), or ASTM E283 (Figure 4).

The measurements obtained by one of these test methods would provide door assembly leakage characteristics required in the analysis of pressurized stairwell designs, in the early time analysis of smoke leakage from fire compartments to the rest of a facility, and, generally, in analyses of total intrafacility smoke migration.

Besides actual laboratory evaluations of ambient temperature leakage, a method of carrying out insitu testing of door assemblies would also be of interest. The results of such tests, on insitu elevator and stair shaft doors, are reported, for example, in reference 31, and ASTM E783 [32] is an existing field test method for exterior doors.

For an indepth discussion on measurements, calculations and specifications of door assembly leakage under ambient conditions the reader is referred to reference 25.

## 6.3 Testing for Fire Endurance

As discussed in an earlier section, the fire endurance of a door assembly may be very sensitive to the magnitude and direction of cross-door pressure differentials. To obtain fire endurance ratings under practical, nonzero, cross-door pressure differentials a significantly revised ASTM E152 or similar type furnace driven test method would be required. The major aspect of the revision would be in the operation of the furnace at pressures significantly higher or lower (say, between ± 100 pascals) than the pressure on the unexposed side of a subject door assembly. Short of actually operating the furnace at such positive or negative pressures relative to the test laboratory (i.e., relative to the ambient), one possible alternate means of achieving such cross-door pressure differentials would be by use of a door enclosure box (as in the tentative ISO 5925, Part 3 test method [33], depicted in Figure 5). The door box would be attached to the wall in which the door assembly was mounted, and it would enclose the entire subject door assembly on its unexposed side. By appropriate ventilation and surface cooling of the box, as recommended in reference 24 (Figure 2), the unexposed door surface would be continuously subjected to a simulated ambient environment. Further, the box would be operated at such a negative or positive pressure, relative to the (ambient pressure) furnace, as to achieve the desired cross-door pressure differential.

### 6.4 Leakage Under Fully Developed Fire Conditions

During the last decade much attention has been focused on the development of test methods to measure the leakage of door assemblies under fully developed fire exposures. The first of these test methods, which was limited to near zero cross-door pressure differentials, was developed in Finland [34-36] in the early 1970's and proposed to a working group of ISO. The working group documented the test method [33] with the anticipation that, if acceptable, it would eventually be issued by ISO as the third of a three part series of tests for measuring the leakage of door assemblies under ambient temperature [27,36] (DP5925, Part 1), medium temperature [37] (DP5925, Part 2), and high temperature [33] (DP5925, Part 3). Also planned for this series is an introductory or commentary document [23,30] (DP5925, Part 0). An annotated sketch of the high temperature, DP5925, Part 3 test method is presented in Figure 5.

An indepth experimental [37] and theoretical analysis of the DP5925, Part 3 test method was carried out in the U.S. A report of this study [24] indicated that, for a variety of reasons, the test method is generally unreliable. The report went on to recommend an alternate test concept which would hopefully remove the problems as well as the significant limitation of a near-zero, cross-door pressure differential. The proposed test concept, which is depicted in Figure 2 (and has yet to be implemented), involves the use of a ventilated enclosure box referred to earlier.

Independent of the latter analysis, experimental studies on an improved DP5925, Part 3 test method were carried out in the Netherlands [39-42]. The hardware of this revised test method is illustrated in Figure 6. As can be seen, it also makes use of a ventilated enclosure box. While this test method may finally prove to be reliable, it does not address the issue of elevated, cross-door pressure differentials.

The above test methods all make use of structures which enclose the subject door assembly and which collect and measure the total rate of leakage of furnace gases. Another method for measuring the rate of leakage under fully developed fire exposures, which does not involve the use of a cumbersome enclosure box, is now under development in Finland [43,44]. This method, depicted in Figure 7, makes use of carbon dioxide ($CO_2$) as a tracer gas of known (measured) concentration within the furnace. The tracer gas, uniformly mixed with other furnace gases, leaks past the door assembly. On the unexposed side of the door all leaked gases rise due to buoyancy, and they are collected in an open, ventilated canopy (reminiscent of the canopy smoke collection used in reference 45). The rate of tracer gas flow is measured and related to the total leakage rate of the door assembly.

Two criticisms of the latter test method have been raised and partially refuted [44]. The first has to do with the strong variation of $CO_2$, tracer gas concentration within the furnace, and the second has to do with the fact that unknown amounts of $CO_2$ may be introduced at burning surfaces near leakage gaps of the door assembly, thereby leading to spurious estimates of total leakage rate.

Short of pressurizing the furnace relative to the laboratory ambient, or using the ventilated enclosure box idea, it does not appear that the above, tracer gas test method will provide leakage rates of door assemblies under significant cross-door pressure differentials.

### 6.5 Combined Tests

Under significant cross-door pressure differentials it is likely that successful methods to measure fire endurance and leakage under fully developed fire exposures will require substantial research and development activity. Furthermore, to implement such test methods and obtain ratings for a particular door assembly design will clearly require resource commitments which will be even greater than those presently required under ASTM E152. (For example, to obtain a leakage classification under two different cross-door pressure differentials would likely require destructive tests on each of two separate door assemblies.) For this reason it would be a particularly attractive feature of the test methods if both types of evaluations, fire endurance and leakage, could be carried out during the course of a single test procedure. Thus, for example, if the leakage test concept of reference 24 (Figure 2) proved to be practical, then (except for the possible difficulty of carrying out a hose stream test) there is no particular reason why fire endurance and leakage rate could not be established simultaneously.

### 6.6 Leakage Under Medium Temperature Conditions

Leakage of door assemblies under both ambient and medium temperature (up to 200°C) conditions, and with cross-door pressure differentials of up to ± 100 pascals have been successfully carried out in Germany with a single test apparatus [37]. The apparatus, which is depicted in Figure 8, uses a 60 kW electric heating device. The elevated temperature tests were initiated at ambient conditions and required from 25 to 30 minutes to reach maximum temperature.

## 7. SUMMARY AND CONCLUDING REMARKS

Key to the protection of life and property during fires is the control of smoke migration. Such control can be designed into a facility to the degree that the structural integrity and leakage characteristics of compartment partitions are known during real fire conditions. One parameter of real fire conditions which will have a great impact on these characteristics is the cross-partition pressure differential. In practical fire scenarios such pressure differentials can be sustained by steady wind loadings, stack effect, and/or ventilation systems at amplitudes which could easily be of the order of several tens of pascals.

The measurement of the structural integrity and leakage characteristics of compartment partition elements require test methods which are at various stages of development. Required measurement capabilities for door assemblies, in particular, include leakage rate under ambient temperature conditions (insitu as well as laboratory testing), fully developed fire conditions, and, possibly, under intermediate temperature exposures, for fixed cross-door pressure differentials within some range to be determined. Also required is a capability to evaluate door assembly fire endurance under a similar range of fixed, cross-door pressure loadings. At a given pressure loading there is reason to expect that with a carefully designed test method the latter fire endurance evaluation could be successfully carried out together with leakage measurements during a single test procedure.

A method of reporting summary results of test evaluations, basically a rating or classification system, has to be developed. For example, summary results presented in a shorthand form might include: cross-door pressure differential, test exposure (e.g., ambient or fully developed fire temperatures), and characteristic rates of leakage (in the case of elevated temperature exposure, e.g., maximum leakage during the first 30 minutes, second 30 minutes, etc., up to the fire endurance rating of the assembly). Such a rating or classification system would be used in performance or specification guides, standards, and codes for selecting door assemblies to be used in different applications within different types of facilities. In the future, such use documents will have to be prepared by appropriate organizations.

Institutions such as ASTM, ISO, and NFPA clearly have a role to play in establishing, improving, promulgating, and in encouraging the development of the above test methods, reporting procedures, and use documents.

## 8. ACKNOWLEDGMENTS

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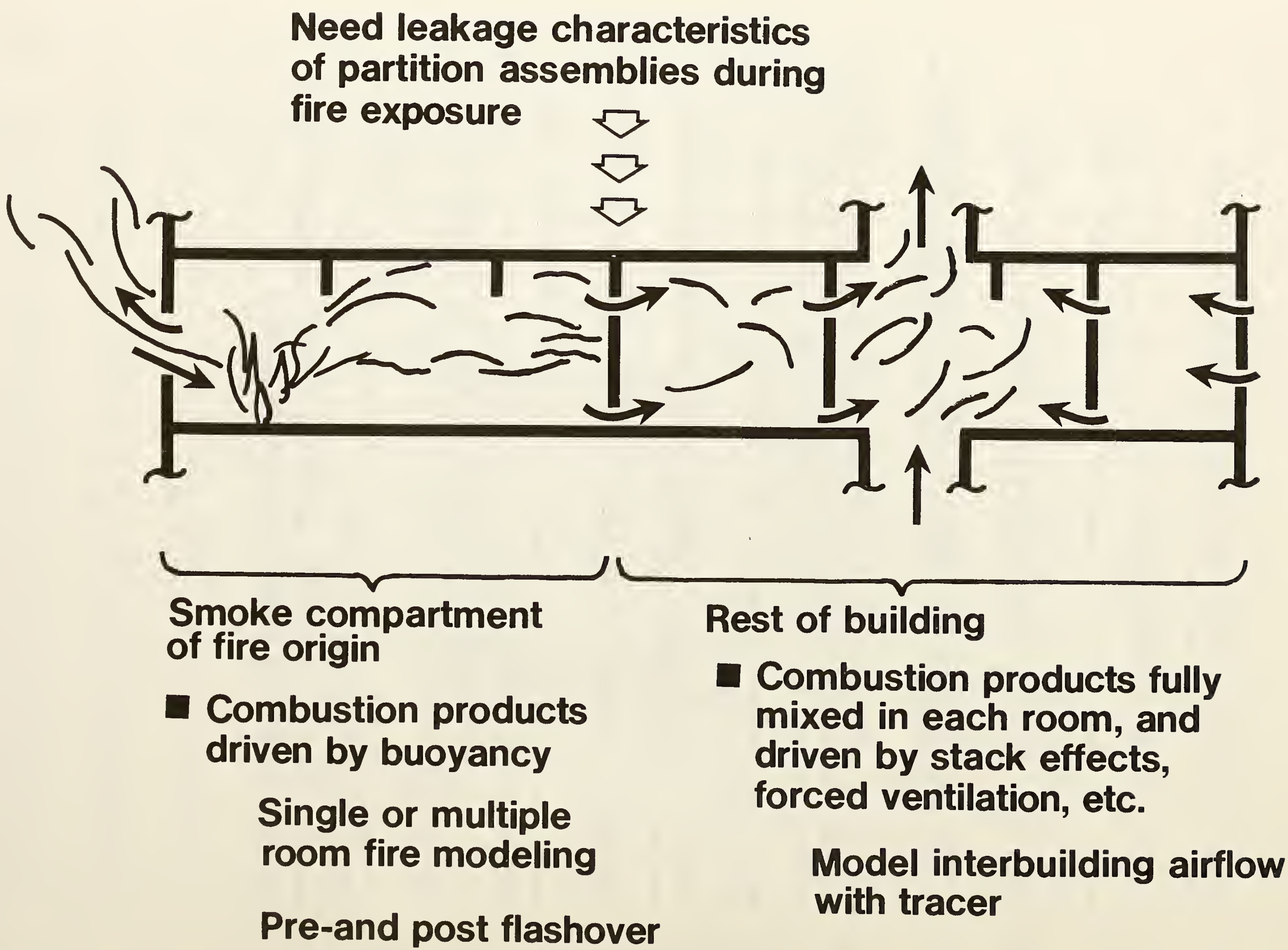



Figure 1. Mechanisms of intracompartment smoke migration (from reference 11)

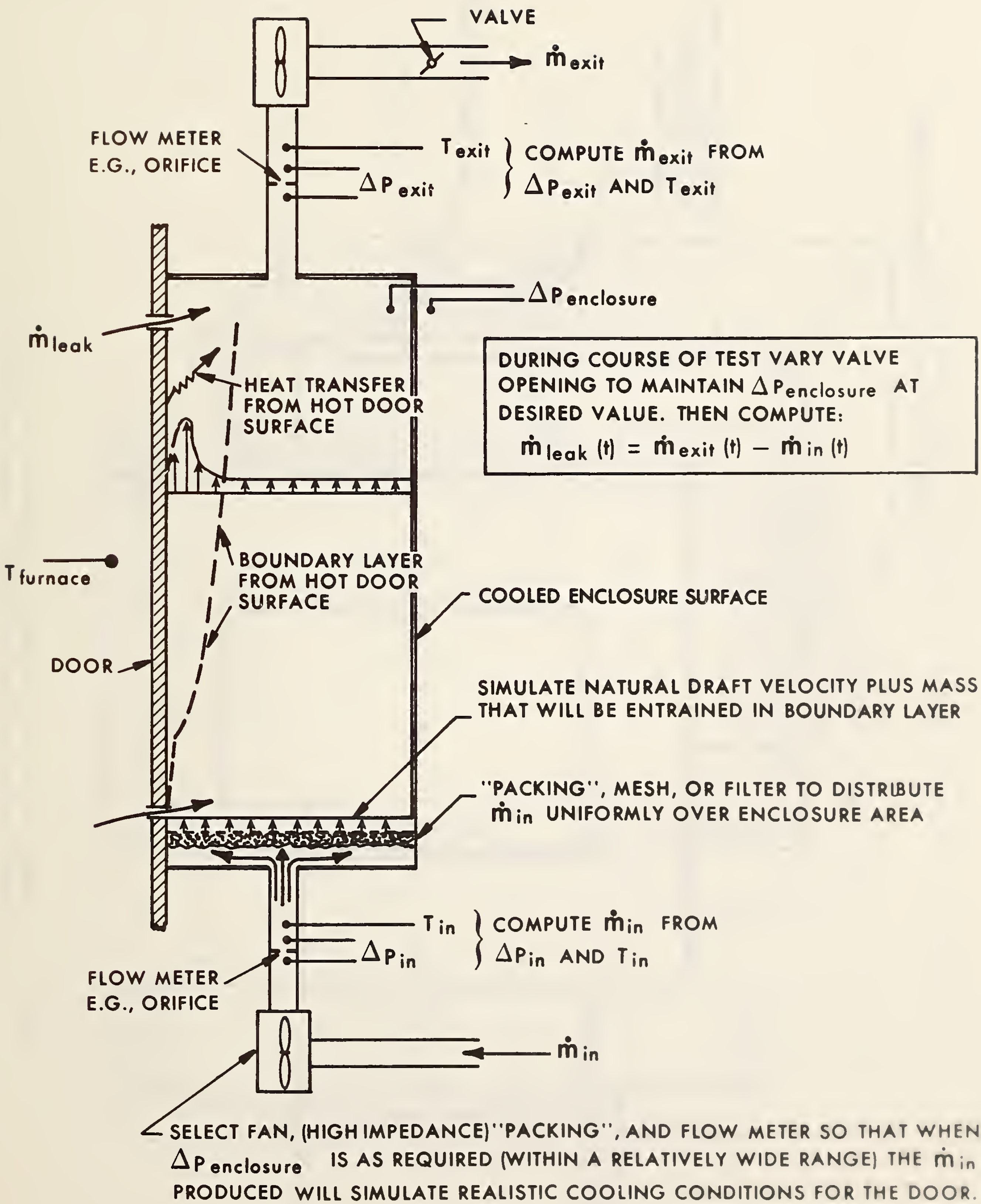



Figure 2. A test concept for measuring leakage of door assemblies. During course of test, valve opening is varied to maintain $\Delta P_{enclosure}$ at the desired value (from reference 24)

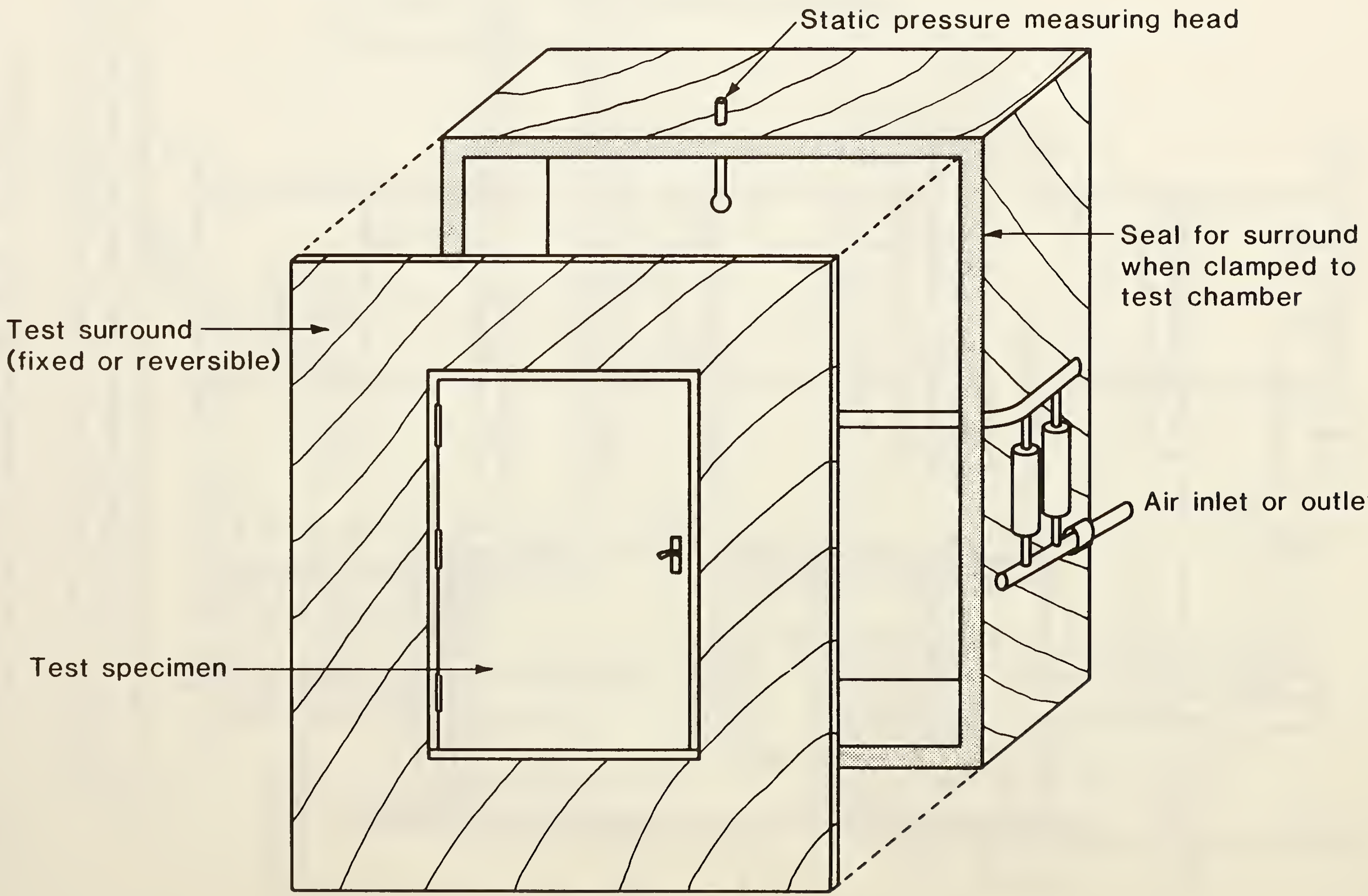



Figure 3. Example of an air leakage test chamber that might be used to carry out ISO DIS 5925/1 (from reference 28)

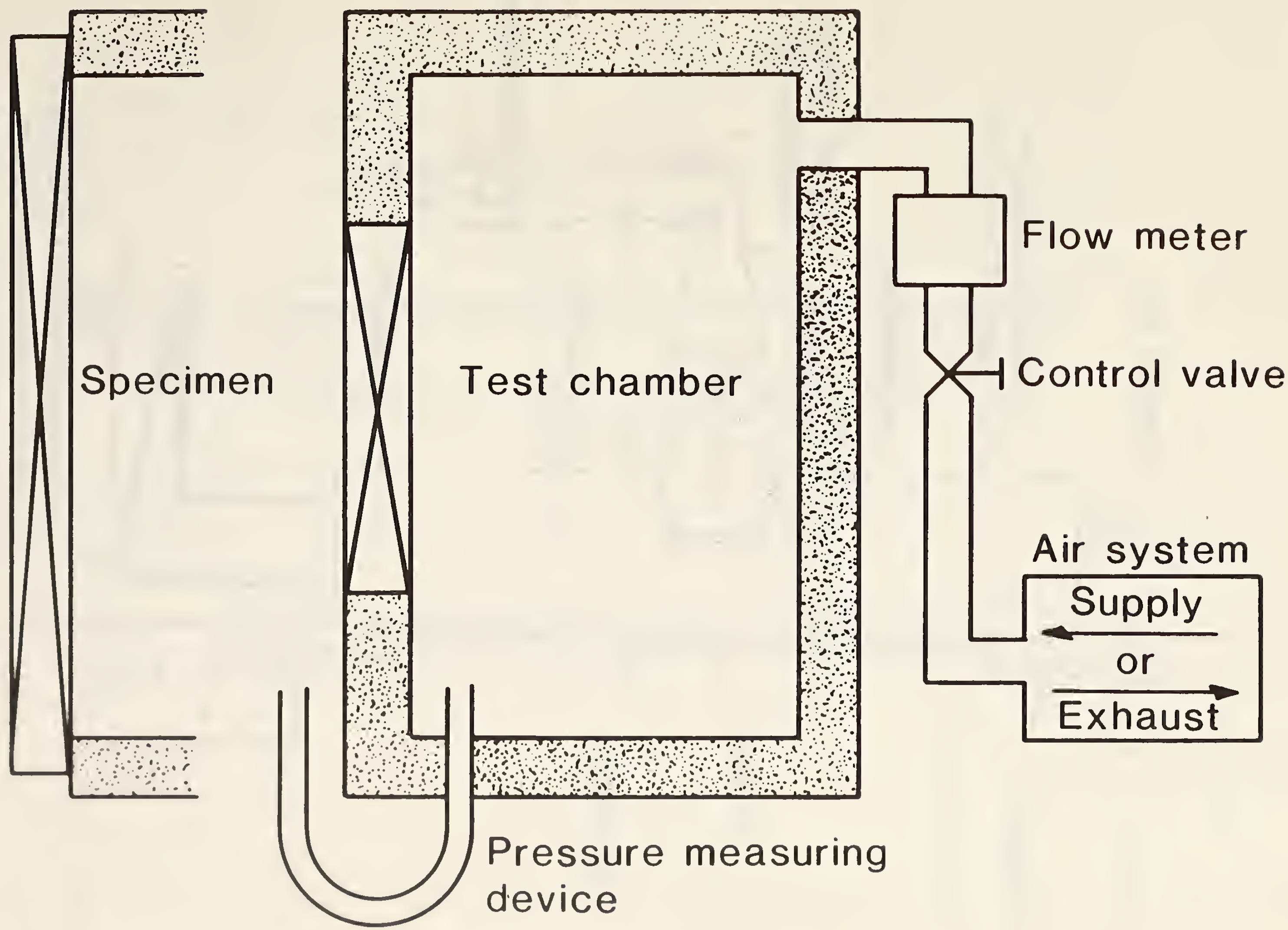



Figure 4. General arrangement of the air leakage apparatus to be used to carry out ASTM E 283-73 (from reference 27)

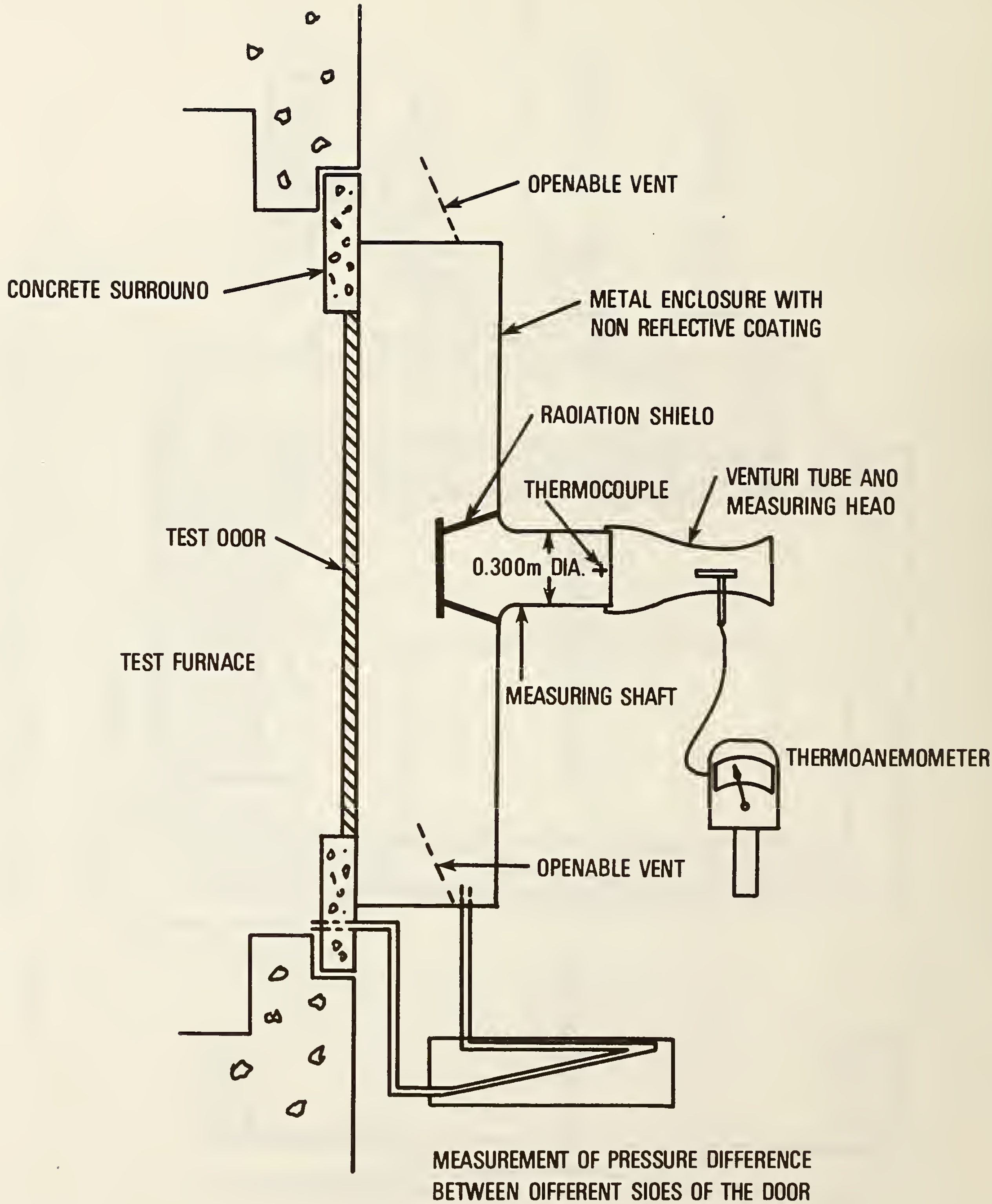



Figure 5. The test equipment arrangement for measuring leakage by the proposed ISO DP 5925, Part 3 test method (redrawn from reference 33)

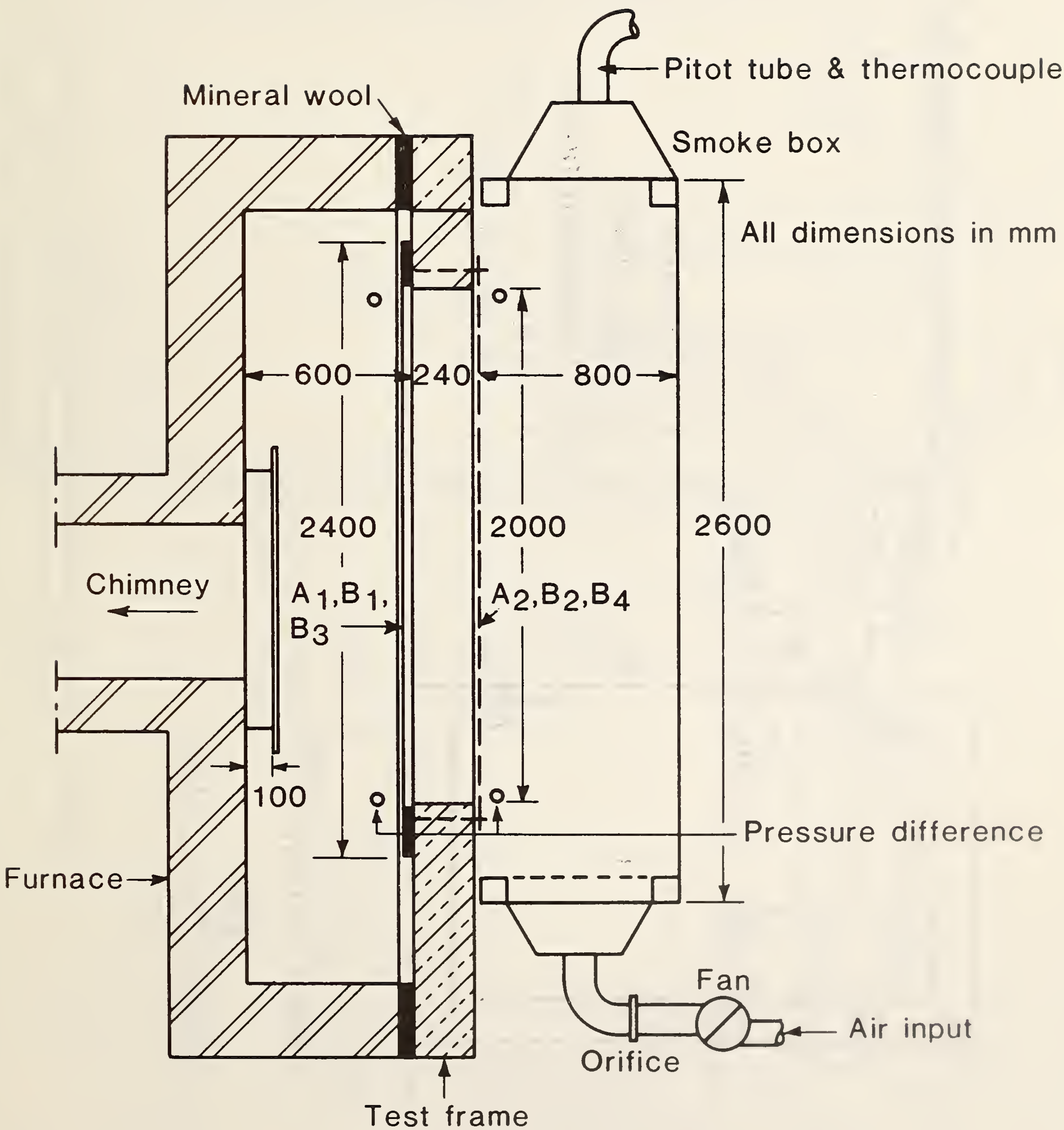
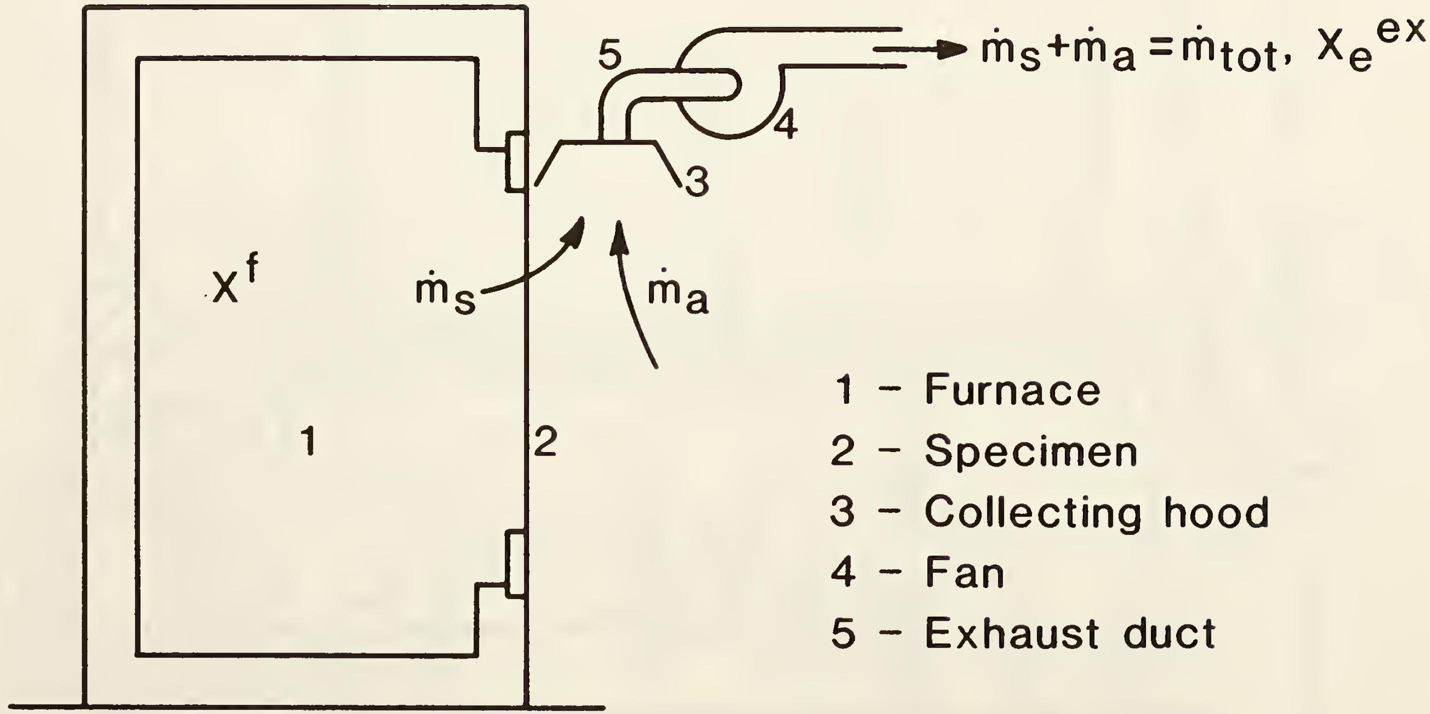



Figure 6. Test equipment arrangement for a proposed high temperature leakage test (from reference 42)




$$\dot{m}_s \cdot X^f = \dot{m}_{tot} \cdot X^{ex}$$

$$\dot{m}_s = \frac{X^{ex}}{X^f} \cdot \dot{m}_{tot}$$

Figure 7. The test equipment arrangement for measuring leakage by the $CO_2$, tracer gas method (from reference 44)

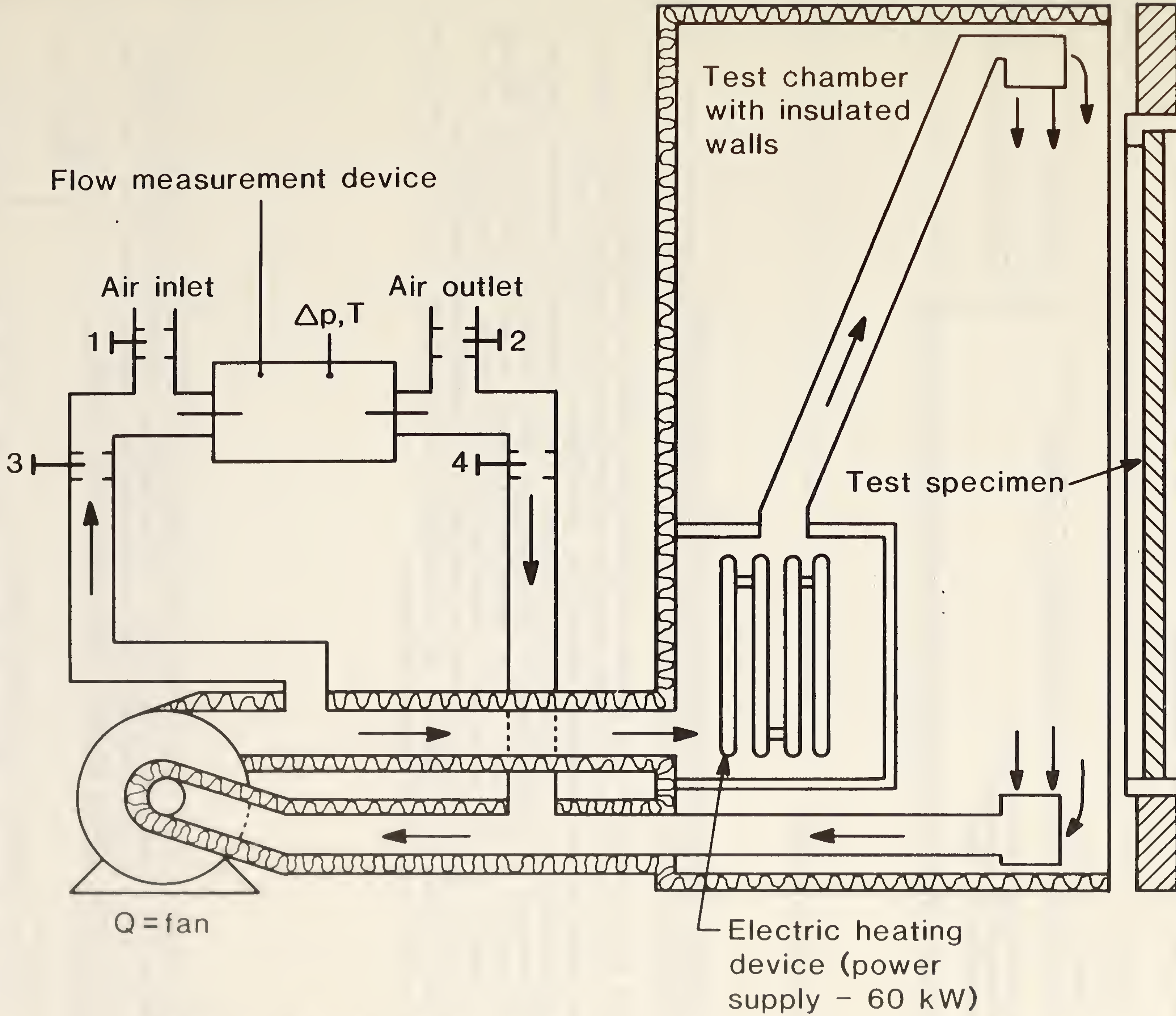



Figure 8. Example of an air leakage test chamber designed to test door assemblies at ambient and at medium air temperature (from reference 37)

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**5. AUTHOR(S)**

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This paper identifies and places into perspective relevant information that would assist in focusing future research and development on test methods to measure the smoke leakage characteristics of door assemblies. The concept of smoke compartmentation is introduced and developed. The importance of cross-door pressure differential in establishing the performance of door assemblies in fire generated environments is discussed. Door assembly performance is then related to life safety, in general, and to the design of compartments of safe refuge, in particular. All of the discussion suggests a listing of required door assembly test methods, and, finally, leads to a review of the availability and development status of existing and potential future test method candidates.

**12. KEY WORDS** *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

compartmentation, compartment fires, door assemblies, high-rise buildings, leakage, life safety, pressure differential, pressurization, property protection, safe refuge, smoke control, smoke movement, stack effect, test methods.

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