July 21, 1992

Integrated
Fire&Failure
Technologies
Incorporated

~~Dr. Roy Gottesman~~
The Vinyl Institute
~~Wayne Interchange~~ Plaza II
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Dear Roy,

The publication of ASTM STP 1150, *"Fire Hazard and Risk Assessment"* has finally occurred.

That document includes a paper which I authored - **Performance of Plastic Plumbing and Electrical Products in Fire Resistive Assemblies**. It includes work which I think will be of interest to you. For that reason, I have enclosed a copy of the paper for your files.

I hope things are going well with your retirement. I look forward to hearing any questions or comments.

Sincerely yours,

Joe

Joseph B. Zicherman, Ph.D.
President

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Enclosure: (1)

7/29
Copies to
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For your info. + files.
Roy

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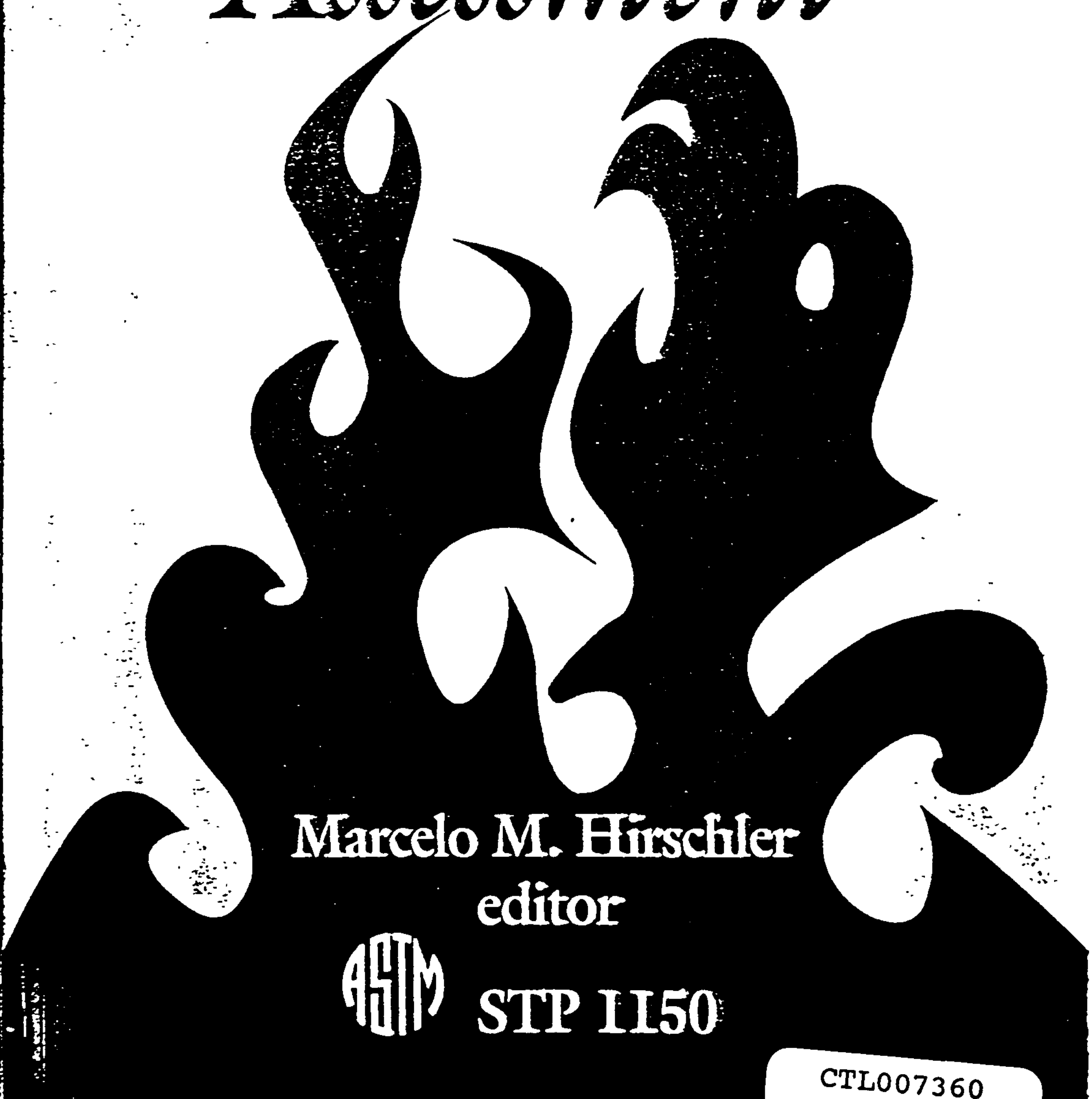
Fire Hazard and Fire Risk Assessment



Marcelo M. Hirschler
editor

ASTM STP 1150

Joseph B. Zicherman[1]

Performance of Plastic Plumbing and Electrical Products in Fire Resistive Assemblies

REFERENCE: Zicherman, J. B., **"Performance of Plastic Plumbing and Electrical Products in Fire Resistive Assemblies,"** *Fire Hazard and Fire Risk Assessment, ASTM STP 1150*, Marcelo M. Hirschler, Ed., American Society for Testing and Materials, Philadelphia, 1992, pp. 66–83.

ABSTRACT: The plastic pipe, tube, and conduit products used in the United States evolved from transplanted European technologies over the past 30 years. Though originally only used in non-fire rated construction, different versions of these products have qualified for use in a variety of fire rated assemblies and building types after appropriate fire endurance tests. End uses for these products include electrical power, signal distribution, and various plumbing and mechanical applications.

Plumbing systems showing acceptable performance in fire resistive assemblies include drain, waste, vent, and supply piping (domestic hot and cold water, sprinkler piping). Approved electrical applications include PVC-based rigid non-metallic conduit and a flexible polyvinylchloride (PVC) tubing product called electrical non-metallic tubing. Tested approaches available to safely install plastic pipe, tube, and conduit include passive and active fire stopping systems based on insulations, intumescent systems, and even mechanical "cut-off" devices for thermoplastic piping systems. Fire test results for these products and systems, and the designs that resulted from those testing programs, are widely available. Plastics used to manufacture these products include PVC, chlorinated PVC, acrylonitrile-butadiene-styrene (ABS), polybutylene (PB), and polypropylene (PP).

Fire risk assessments of potential performance of these products must take into account properties of the resin-polymer systems involved, the nature of the product itself (that is, drain, waste, and vent versus supply piping versus electrical conduit or tubing), where the product is installed (for example, within a cavity wall versus penetrating or encased in a slab), and the type of installation detailing used. Because of the number of possible combinations for end use, analytical approaches based on (1) standard test results, (2) field data on fire performance of the plastic pipe, tube, and conduit products, and (3) fire resistive assemblies into which they are installed all contribute to inferences drawn in conducting hazard assessments.

Specifically, this paper reviews information available to assist in preparing more specialized risk assessments for these products than the general studies cited above, under foreseeable, end use configurations in fire resistive assemblies. An attempt has been made to utilize approaches suggested for general fire hazard assessment procedures that have been under extended study within the ASTM Committee E-5 on Fire Standards over the past several years, but which have not reached the status of standards.

Most field performance data on plastic pipe come from residential occupancies where these products have been used for over 20 years, and where they constitute 95% of pipe installed. In addition, there have been numerous installations in non-combustible buildings (including high rises) here and outside the United States. This database represents a large population for evaluating the fire risk associated with using plastic piping products. The residential data are most interesting because (1) numerically, they represent the largest number of installations, (2) this occupancy type is the most fire prone, based on frequency of occurrence, and (3) these

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structures are constructed using the least sophisticated building technology. Similarly, electrical tubing and conduit products (having met standard fire endurance test conditions) have been used widely in the field without adverse effect since their incremental acceptance into the National Electrical Code (NEC) over the past decade.

For the above reasons, the three model building codes most widely used in the United States (which themselves represent an ad hoc risk assessment process) have accepted these products after requiring demonstration of both acceptable fire performance and availability of reasonable installation methodologies.

KEY WORDS: plastic pipe, fire endurance, through-penetration, hazard assessment, fire resistive assembly, intumescent.

The plastic pipe, tube, and conduit (hereafter called plastic pipe, unless otherwise noted) technology used in the United States and Canada has evolved to include many new uses following its introduction from Europe over the past 30 to 40 years. Originally permitted only in non-fire resistive construction, plastic pipe has been demonstrated as acceptable for fire resistive end uses after substantial testing and field evaluation.

Risk assessment studies addressing general use of plastic pipe and plastic electrical tubing have been published. Both were conducted as part of code adoption processes. One dealt with possible increases in fire hazards when allowable uses for unplasticized PVC electrical raceways were expanded in the National Electrical Code (NEC) [*1*]. The second included an assessment of fire related hazards associated with use of plastic plumbing pipe in fire resistive construction. That study can be found in the draft environmental impact report published recently by SRI International as part of the work associated with the state of California plumbing code adoption process [*2*].

Both of these studies considered the combustible nature of the plastic products and found their use appropriate in fire resistive construction if appropriate installation detailing occurred.

Hazard Assessment Bases

In considering fire hazard elements associated with use of plastic pipe, it is necessary to determine whether a proposed use will result in levels of safety which exceed, are consistent with, or are less than existing products performing the same function. In addition, methods to assess safety of new or non-classical uses of those products in fire resistive construction are also needed.

Potentially undesirable consequences needing examination may include rapid fire spread and unusual smoke threats. Failure or compromise of fire resistive assemblies prior to their design limits which lead to unanticipated levels of damage from fire also need to be evaluated

Considering this topic from the standpoint of the draft, "Standard Guide for the Development of Fire Hazard Assessment Standards for Products," produced by the ASTM E5 35.01 Task Group on Fire Risk and Fire Risk Assessment, the document instructs the analyst that "one needs to describe the product, how it is used, and its environment" [*3*]. Initially examining "its environment" is key to several questions related to both occupant safety and fire spread where uses of plastic pipe are concerned, and description of this environment will ultimately define what products are suitable for use. Intuitively, it can also be seen that the other two ("the product and how it is used") lend themselves to evaluation by tests that can lead to fairly specific but broadly applicable results. For these reasons "environment" will be considered first.

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End Use Environments for Plastic Pipe, Tube, and Conduit in Fire Resistive Construction

Plastic pipe, tube, and conduit are typically installed within the envelope which forms the boundaries of fire resistive spaces. Since these products are installed behind such wall and floor/ceiling surfaces, their longevity and resistance to involvement in a growing fire situation substantially exceeds human tenability in an affected space. Additionally, because this class of products are typically installed behind barriers, changes in preflashover characteristics of the space as compared to when metallic piping components are used will be minimal. Exceptions come in the form of minor amounts of plastic pipe found in plumbing traps, and so forth, whose quantity is minimal in comparison with total amounts of normally occurring, combustible room contents.

Further, for most plastic piping products and in the case of PVC electrical raceways, installation occurs within assemblies whose surface membranes (usually gypsum wallboard) possess a minimum 15 min finish rating. Thus, it will take at least 15 min for such materials to be exposed to temperatures of 325°F (165°C) or greater, a temperature range relied upon in judging the performance of protective membranes (as detailed in sections 46 and 47 of ASTM Method for Fire Tests of Building Construction and Materials), and one which is substantially lower than the ignition temperature for members of this generic class of materials. Because of this mode of installation, harm to occupants of such spaces from combustion products associated with these materials is minimized in an origin area. Additionally, because the nature of the fire resistive construction is intended to prevent migration of combustion products, smoke threats elsewhere will be limited.

As is well known, fire resistive construction depends on barriers at selected locations to prevent fire spread. In theory, if these barriers (walls, floor/ceilings, and so forth) function as intended, building occupants will have adequate time to avoid injury by exiting safely or evacuating to areas of refuge. Fire spread will also be limited. However, since actual structures contain openings such as doors, ducts for heating, ventilating, air conditioning, and channels for distributing all sorts of utilities and services, the concept that such barriers are monolithic in nature is generally only theoretical. In practice, most contain numerous openings which must be protected.

Thus, the environment being considered involves the envelope formed by fire resistive components with plastic pipe, tube, or conduit installed within them and/or passing through them.

No assumptions are made as to changes in fuel load which these products may provide. Rather, through testing, performance of assemblies which include combustible plastic elements are compared with tested designs which do not contain those materials (or details needed for their installation) and evaluations are made whether or not plastic inclusions reduce the fire endurance rating of the original design. Fire exposure conditions are prescribed in ASTM E 119, for full assemblies, and its derivative, ASTM E 814, Method for Fire Test of Through-Penetration Fire Stops, for testing of a penetration detailing itself.

Description of Product

The "product" in this case is various plastic pipe, tube, and conduit materials manufactured from a variety of generic polymer resins. These include unplasticized polyvinylchloride (PVC), chlorinated PVC (CPVC), acrylonitrile-butadiene-styrene (ABS), polypropylene (PP), polybutylene (PB). Each of these has its own physical properties which include melt point, melt viscosity, fuel content, ease of ignition, and so forth. Additionally, application of different manufacturing technologies has led to versions with solid or foam core in PVC and ABS drain, and waste and vent (DWV) pipe products.

Products are divided in the categories below with predominating generic resin for each use shown below.

1. Mechanical system end uses.
   (a) DWV Piping (unplasticized PVC, ABS, PP-specialized systems).
   (b) Domestic hot and cold water (DHCW) (CPVC, PB).
   (c) Condensate drains (unplasticized PVC).
   (d) Roof drains (unplasticized PVC, ABS).
   (e) Fire sprinkler systems (CPVC, PB).

2. Electrical tubing and conduit (also known as raceways) end-use (unplasticized PVC).
   (a) Electrical power distribution (110 to 220 volts).
   (b) Low voltage uses.
      (1) Signal systems.
      (2) Electronic data processing (EDP) distribution.

Currently, PVC is the only resin system available which provides the needed physical properties for the electrical end-use area.

How These Products are Used

To assess hazards associated with "how" plastic pipe products are used, the fire resistive assembly for which the hazard assessment is made must be specific. Typical fire resistive applications which may include plastic pipe can be broken down by the following variables, all of which assist in developing as exact a definition of the assembly type as possible.

1. Assembly Type
   A. Walls/Partitions
      1. Cavity type
      2. Monolithic type
   B. Floor/Ceiling and Roof/Ceiling Assemblies
      1. Cavity type
      2. Monolithic type
2. Construction Type
   A. Combustible systems
      1. wood stud walls and partitions
      2. wood joist floor/ceiling assemblies
      3. composite or mixed assemblies such as those including:
         (a) wood-based trusses
         (b) wood-based "I" beams
         (c) concrete decks on wood framing
   B. Non-combustible systems
      1. metal stud walls and partitions
      2. protected metal deck floor/ceiling and roof/ceiling assemblies including bar joist-types
      3. reinforced concrete assemblies with and without exterior metal framing, support or protective membranes.

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Piping and raceway configurations used with these assemblies fall in one or more of the categories following:

- Through-penetrating elements
- Partially penetrating elements
- Included elements
- Combinations of A, B, and C

Given the preceding background information, a 3-dimensional matrix to visualize variables in the evaluation is suggested. The three axes, (a) project fire environment, (b) product being considered, and (c) use format in project, form in the three axes as represented in Fig. 1.

Hazard Assessment Data for Plastic Pipe, Tube, and Conduit Based on ASTM E 119 and ASTM E 814 Testing

Results from well defined standard testing of assemblies are useful as input when conducting hazard assessments for plastic pipe, tube, and conduit installations. The scope for this paper defines the environment for these products as *fire resistive construction of one or more hours expected fire endurance*. Thus, when specific plastic pipe products are tested as part of an assembly designed for use in that environment, applicable test data results. The following sections describe and discuss such standard test results and provide references for them.

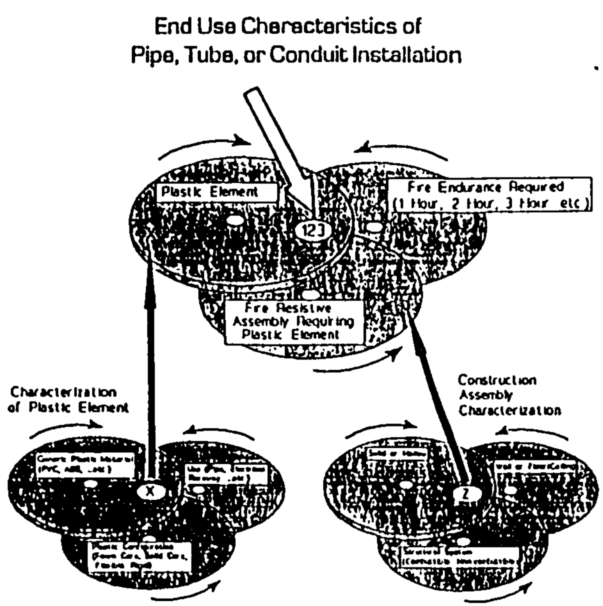

FIG. 1—*Schematic representation of possible combinations of factors which must be evaluated when installing plastic pipe, tube, and conduit in a fire resistive assembly.*

In overviewing ASTM E 119 and ASTM E 814 results for plastic pipe, derating of fire resistive assemblies and impact of penetrating element diameter vs. thickness of assembly are important.

Concerning derating of assemblies (reduction in fire endurance of the assembly containing the plastic pipe product as compared to one without that product), the concept of finish rating can be applied to compare performance of assemblies.[2] In the case of the 1- and 2-h gypsum wallboard clad wall assemblies, direct comparisons can be made between finish rating (time) with and without plastic pipe, tube, and conduit installed. Such a series of comparisons are shown in Table 1 and reflect no substantial variation between specimens with pipe and/or conduit installed, and those without those products present. These results are particularly important, since early failures of fire resistive assemblies are the most critical and potentially catastrophic ones.

A second element of fire endurance behavior for assemblies containing plastic pipe is the relationship between penetration diameter and assembly thickness. This was explored years ago in ad hoc testing in Europe, where different diameters of plastic pipe were installed in concrete slabs of differing thicknesses [9]. Recently, the author conducted similar tests which were 2 h in duration. Four direct through penetrations were evaluated in 114.3- and 165.1-mm (4½- and 6½-in.) thick concrete slabs. PVC-DWV sizes tested included 38.1, 50.8, 76.2, and 101.6 mm (1½, 2, 3, and 4 in.). The pipe was installed in 6.35-mm (¼-in.) oversized holes with ceramic fiber packing as firestopping. In both thicknesses of slab, the 38.1-mm (1½-in.) pipe performed satisfactorily for the full 2-h test duration and the 50.8- and 76.2-mm (2- and 3-in.) pipe installations performed satisfactorily in the 165.1-mm (6½-in.) thick slab. The 101.6-mm (4-in.) pipe failed in both thickness of slab with the generic firestopping used, as did the 50.8- and 76.2-mm (2- and 3-in.) pipe in the thinner slab. Overall, failure times in the thin slab for the 2-h test were inversely proportional to pipe diameter and all failure times for all pipe diameters were proportionally longer in the thicker slab [*10*]. This relationship between slab thickness and pipe diameter is an expression of what could be called an "aspect ratio" as relates to plastic pipe use and allows one to generalize, not surprisingly, that larger openings are less desirable than smaller ones, and thinner assemblies are less desirable than thicker ones, where fire endurance is concerned.

The impact of elevated atmospheric pressure on the performance of plastic pipe, tube, and conduit in fire affected rooms is of recognized importance. Of these, vented applications (as found in plumbing uses) are the most critical. Conversely, minimal air flows can be expected within electrical raceways which contain substantial fill and are essentially closed at terminating locations in junction, switch, or outlet boxes. Additionally, electrical raceways are used typically in substantially smaller diameters.

The actual pressure gradients which exist during postflashover fires begin with negative values in the range of −0.508 to −0.254 mm (−4.98 to −2.49 Pa.) of water at floor level and increase to zero at about one-third the height of an affected room. They continue to increase such that, near the ceiling, positive pressure in the range of +.508 to +1.02 mm (+4.98 to +9.97 Pa.) of water may exist [*10*].

The effect of these pressure gradients on possible fire travel through assemblies which include penetrations has been debated extensively in code forums, where pressures utilized in test furnaces have been at issue. In response, code agencies have stipulated that some degree of positive pressure be applied to assemblies tested under the ASTM E 814 standard

[2] A confusing situation exists in the field, in that finish rating measurements for dissimilar assemblies are taken with thermocouples which may be located at vastly different locations, that is, individually under the gypsum membranes for wall tests above vs. at wood joists at the top of a plenum space when rated hung ceilings are tested. Both measurements, however, represent a "finish rating."

TABLE 1—*Fire endurance and finish ratings of 1- and 2-h walls including PVC pipe, tube, and conduit.*

Included Element	Finish Rating, min	Fire Endurance, h	Reference
none	20.0	1	[*4*]
none	19.5	1	[*4*]
none	19.0	1	[*4*]
PVC-DWV	19.5	1	[*5*]
EMT section	67.0	2	[*6*]
PVC ENT section	67.0	2	[*6*]
EMT section	60.0	2	[*7*]
PVC ENT section	60.0	2	[*7*]
none	66.0	2	[*8*]

This is a conservative assessment, however, since the most common plumbing wall penetration of a fire resistive assembly (a pipe trap at a sink) is under negative pressure during a postflashover fire. Nevertheless, positive pressure is justified in testing since piping also may pass through fire resistive assemblies high in a room (as at floor penetrations or above a hung ceiling). Sprinkler piping, for example, is often run overhead, as is DHCW.[3]

Finally, most of the test results which follow are for plastic pipe products installed using common, generic firestopping materials to ensure fire resistive integrity which is usually the simplest and most cost effective installation solution. However, because plastic pipe, tube, and conduit do melt and burn, in some applications such as larger diameters of pipe or with oversized penetrations, installation details based on proprietary firestopping materials (such as intumescent rubbers, proprietary fiber insulations) and mechanical firestopping devices are necessary to provide superior and/or cost effective protection. Test results involving such detailing (which are usually listed and sometimes labeled by third party organizations) are included where needed to illustrate particular points. For the most extensive listings of such products, the reader is referred to the Underwriters Laboratory, Inc., *Fire Resistance Directory* [*8*].

Standard Fire Testing of Plastic Pipe

Most plastic plumbing pipe is run vertically in walls and shaftways in fire resistive constructions where pipe installations are bounded by gypsum wallboard. For this reason, most of the early fire test work was directed at evaluating the integrity of such generic plumbing walls with plastic pipe installed in various ways.

Because of a lack of baseline data for classically used steel and copper pipe, the initial fire test study conducted included these materials as well as PVC and ABS plastic DWV pipe [*13*]. To date, no other standard test results for metal plumbing products have been published, which makes the question of performance criteria for them in conducting hazard assessments somewhat ill defined. In the other early tests of plastic DWV, generic plumbing walls with commonly available fire stopping materials (such as grout and thermal insulations) were evaluated [*14–21*]. These are similar approaches to that followed in the initial series

[3]Interestingly, in Canada the building code calls for positive pressure testing to be conducted at a level which is 10 times that called for in the United States [*12*]. The justification for this is, in part, based upon "stack effect" arguments. One can question the requirement for such high pressure differentials at test, based on the presence of engineered smoke control pressurization systems in high rise buildings constructed today. Conversely, in low rise, fire resistive buildings, the stack effect is not a factor.

at the National Institute for Standards and Technology's Center for Fire Research (formerly National Bureau of Standards).

Test results produced and the plumbing and fire stopping configurations that resulted from these tests reflect the evolution in understanding of needed installation technology that occurred from the initial series through the most recent tests of one and two h metal framed wall systems. The latter are found in typical non-combustible buildings [*5,22*]. Many of the assemblies tested in these series were designed to simulate a plumbing wall undergoing a fire exposure, on a floor between two similar fire resistive assemblies above and below the test floor. This testing was used to assess possible vertical fire spread where vented DWV systems are installed as well as horizontal fire spread across such assemblies. The latter is the most obvious behavior expected in a fire resistive assembly with combustible through penetrating elements. Vertical spread has not been observed in properly constructed test assemblies due to both (a) the propensity of the DWV materials to melt and close off openings at protected locations within cavity walls and (b) the functioning of fire stopping or normal clearance penetrations at simulated floor lines.

Consistent with the above, failure modes observed in testing DWV systems have included early horizontal burn through in test assemblies where installations included oversized annular spaces at through penetration locations and/or plumbing fittings bearing on gypsum wallboard membranes [*13,23*].

With regard to amount of plastic pipe tested on fire performance, the most conservative trials have included 4.877 m (16 ft) of 50.8 mm (2 in.) and 76.2 mm (3 in.) PVC DWV installed together in a 139.7 mm (5½ in.) deep, 2.048 × 3.658 m (10 × 12 ft) metal frame plumbing wall. The installation included two through penetrations. The same plumbing configuration was successfully tested in one and two hour wall designs. The test assembly included six vertical wall cavities and simulated upper and lower floors, two of which included the DWV pipe. A schematic of the test assembly can be seen in Fig. 2 [*24*]. For ABS-DWV pipe, a single plumbing cavity, in a 3.048 × 3.658 m (10 × 12 ft) 1 h 50.8 × 152.4 mm (2 × 6 in.) wood framed test wall with the same plumbing configuration shown above represents the most pessimistic condition tested to date [*19*].

In order to assess the impact of foam core technology in which coextrusion techniques are used to produce plastic DWV pipe with solid exterior layers and a low density foam core, a test on the penetration detail only for the assembly described above was conducted according to the ASTM E 814 test standard. Test results showed no difference in performance for the foam core product as compared to the solid core test result [*25*]. Table 2 summarizes the test series discussed above for DWV pipe in gypsum wallboard clad 1- and 2-h metal and wood framed assemblies.

Specialized, proprietary systems for DWV through penetration of gypsum shaft walls or masonry walls by plastic pipe have been developed and tested. These include guillotine-like systems or intumescent closures for 2- or 3-h assemblies for plastic pipe diameters up to 152.4 mm (6 in.). [*27–31*].

From a standpoint of fire performance of plastic pipe used for sprinklers or DHCW applications as compared to DWV (which is largely empty and of greater diameter), the latter poses a greater threat to fire spread. However, PB sprinkler and DHCW pipe up to 50.8 mm (2 in.) in diameter have been tested in both metal and wood framed assemblies under the criteria of the ASTM E 814 standard [*32,33*].

Although these applications contain water, this was not possible for testing. Thus, test results are conservative since the presence of water will increase fire endurance.

Because far less plumbing pipe is found in fire resistive floor/ceiling assemblies, fewer fire endurance tests have been run with such systems. Test results available are summarized in Table 3.

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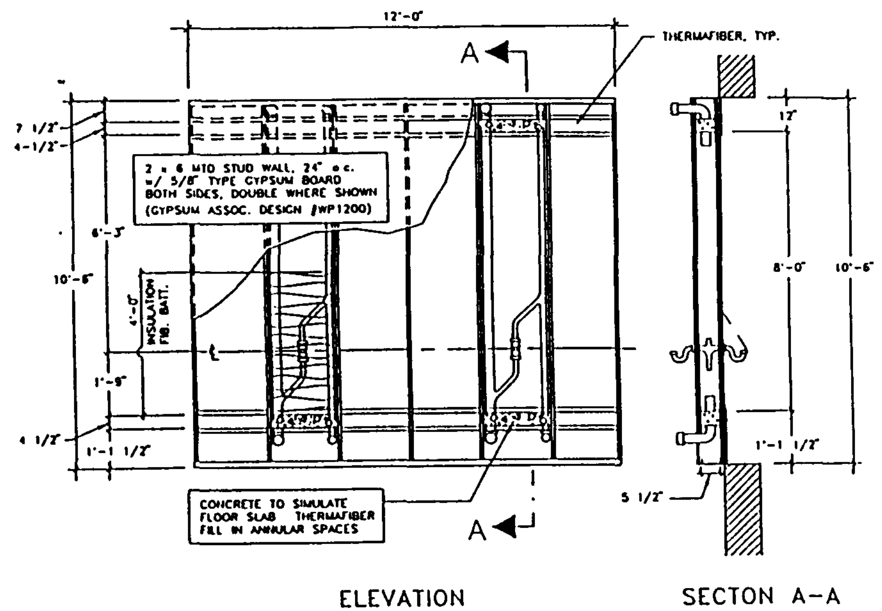

FIG. 2—*Generic gypsum board clad, metal stud wall assembly for fire testing. Specimen includes vertical drain and vent lines (with simulated plumbing penetrations) as well as lateral plumbing penetrations.*

TABLE 2—*Gypsum clad 1- and 2-h wall assemblies containing plastic DWV.*

Hourly Rating	Penetrating Material[a]	Structural System[b]	Testing Agency[c]	Reference
1	ABS (solid core)	wood frame	A, B, C	[*13, 17, 19*]
1	ABS (foam core)	wood frame	D	[*25*]
1	PVC	wood frame	A, B, C	[*13, 17, 19*]
1	PVC	metal frame	E	[*5*]
2	ABS (solid core)	wood frame	B	[*17*]
2	PVC	wood frame	B	[*14*]
2	PVC	metal frame	E	[*22*]

[a]Penetrating materials are all 1½ of 2-in. (3.81 of 5.08-cm) DWV pipe. Vent and drain size range from 2 to 4 in., depending on assembly and generic pipe type. For specific sizes and types, consult Ref *26*.
[b]For minimum thickness of test assembly and description of structural elements, consult Ref *26*.
[c]Key to agencies:
A—National Institute of Standards and Technology Center for Fire Research (formerly National Bureau of Standards).
B—Ohio State University
C—University of California, Berkeley
D—Warnock Hersey International, Inc., Vancouver, B.C., Canada.
E—Warnock Hersey International, Inc., Pittsburg, CA.

TABLE 3—*Examples of fire endurance test results for floor/ceiling assemblies.*

Hourly Rating	Penetrating Material[a]	Structural System[b]	Testing Agency[c]	Reference
2	PVC	concrete slab	A	[*34*]
2	PVC	wood frame	A	[*35a,b,c*]
1 h, 56 min.[c]	ABS, PVC	concrete slab on metal deck with hung ceiling detail	B	[*36*]
1 h, 30 min.	ABS	wood frame	A	[*35a*]

[a]Maximum pipe sizes—3 or 4 in. (7.6 or 10 cm) depending on specific design tested.
[b]Key to agencies:
A—Underwriter's Laboratories
B—Ohio State University
[c]In the test of this 2-h assembly, an apparently random failure occurred in the protective hung ceiling lower membrane, leading to slightly premature failure.

Standard Fire Testing of Unplasticized PVC Products for Electrical End Uses

ASTM E 119 testing of fire resistive assemblies with unplasticized PVC electrical raceway (and boxes) installed has been conducted. Initially, this test work was directed at demonstrating the equivalency of the PVC products with competing metal products. Subsequently testing took the form of more usual performance testing based on the ASTM E 119 standard alone. Once again, scant test results existed for the metal products with no tests available for fire resistive wall assemblies including rigid metallic conduit, for example. Tests of wall assemblies containing various PVC materials are summarized in Table 4.

Based upon analysis of the preceding test results, the Conference of American Building Officials (CABO) established that PVC raceway can be used in combustible and noncombustible 2-h assemblies based on 50.8 × 101.6 mm (2 × 4 in.) nominal framing [*37*].

Three different floor/ceiling designs containing PVC electrical components have been tested successfully. One, a 3-h design with concrete deck and metal structural system, included a plenum in which three different combinations of PVC raceway and boxes were tested. A fourth, control section, included metallic raceway and boxes. The lower membrane was a fire rated, inorganic tile [*38*]. This testing verifies that PVC boxes (see also Ref [*39*] for an evaluation of PVC box impact in combustible floor/ceiling assemblies) and raceway can be successfully used in floor/ceiling assemblies without compromising fire performance. In particular, it addresses the hazard posed when PVC materials melt onto a lower membrane which has a critical protective function as where, in the test cited above, the lower membrane provided protection for steel members supporting a concrete deck.

TABLE 4—*PVC electrical raceway tested in gypsum clad, fire resistive wall assemblies*[a]

Hourly Rating	PVC Material	Structural System	Reference
2	½-in. (12.7-mm) rigid nonmetallic conduit	2 × 4-in. (50 8 × 101 6 -mm) nominal wood studs or 3⅝-in. (92 08-mm) 22 gauge steel studs	[*6*]
2	¾-in. (19.05-mm) electrical nonmetallic tubing	3⅝-in (92 08-mm) 25 gauge steel studs	[*7*]

[a]Both tests run at Underwriter's Laboratories, Inc.

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The other two systems tested were based on poured in place slabs of 2-h design. One was of normal weight concrete 114.3-mm (4½-in.) thick and contained three runs of 25.4-mm (1 in.) PVC electrical non-metallic tubing (ENT) raceway [40]. The other system, based on lightweight concrete, was formed on a proprietary corrugated metal pan system [41]. Both of these tests were conducted on 1.829 × 2.438-m (6 × 8-ft) specimens according to the ASTM E 119 time temperature curve. Testing was primarily to determine temperature rise above the ENT on the unexposed surface of the slab or where the non-metallic tubing exited the unexposed face. Figures 3a and b illustrates test specimens.

Test results for the two unprotected concrete slabs address possible fire risks in using PVC raceway in a cast in place format. Where possible derating of such assemblies is at issue, two failure modes are potentially important.

- possible increases in backface temperature rise due to the presence of PVC (electrical raceways) and
- possible fire spread along PVC raceway, leading from exposed to the unexposed side or from internal ignition of raceway within the slab to the unexposed side.

In relation to the first item, data from thermocouples placed directly above ENT runs in these tests showed lower readings than in areas where concrete only was present. This is a reflection of the lower thermal conductivity of the PVC raceway as compared to the thermal conductivity of the concrete itself. Figures 4a and b illustrates this for the normal weight

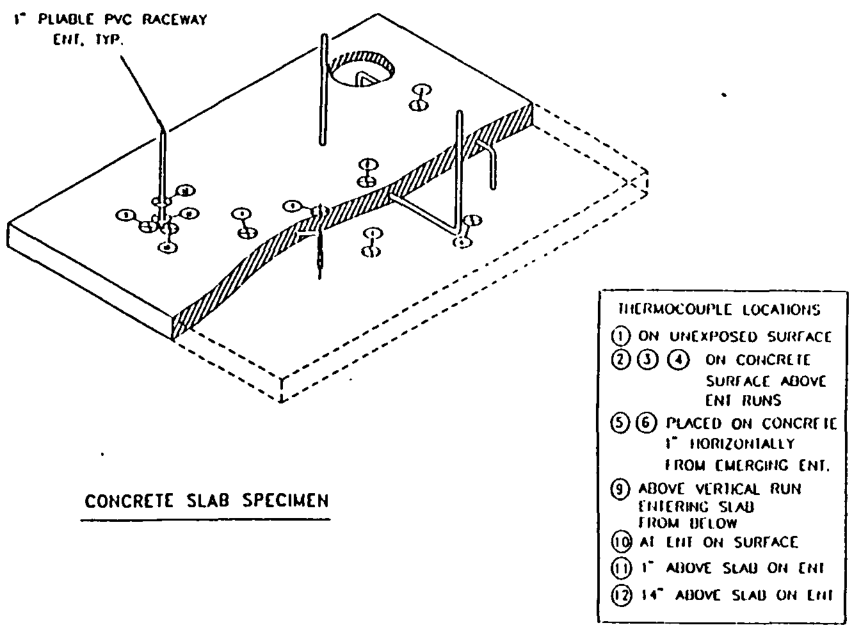

FIG. 3(a)—*Concrete slab test specimens 1.829 × 2.438-m (6 × 8-ft); Self supporting 114.3-mm (4½-in.) thick slab. Thermocouples Nos. 1 to 9 are ASTM E 119 standard; Nos. 10 to 12 are ASTM E 814.*

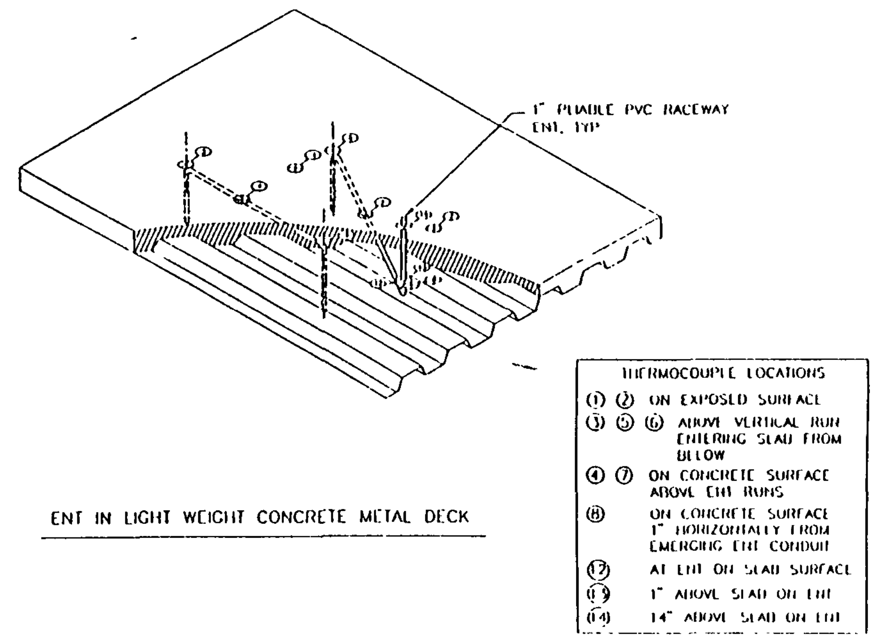

FIG. 3(b)—*Concrete slab test specimens 1.829 × 2.438-m (6 × 8-ft); Lightweight concrete slab cast on proprietary metal pan, 88.9-mm (3½-in.) minimum slab thickness. Thermocouples Nos. 1 to 8 are ASTM E 119; balance are ASTM E 814 thermocouples.*

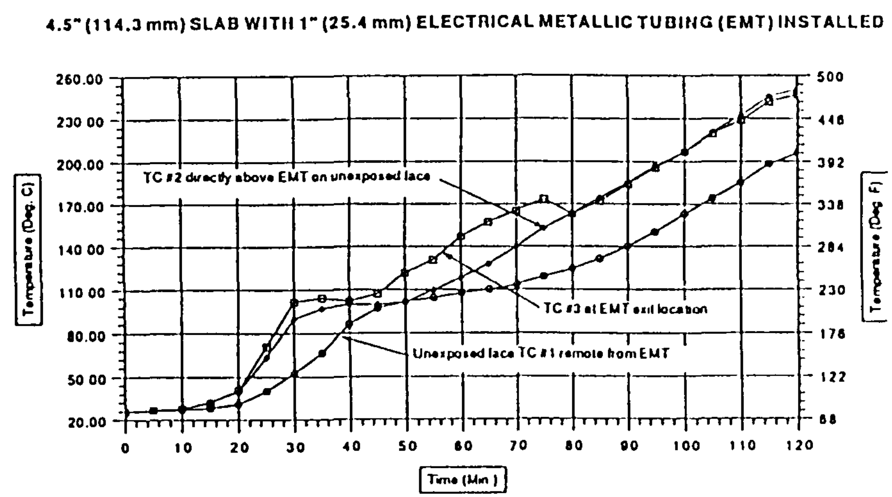

FIG. 4(a)—*Comparative time temperature curves for thermocouples associated with metallic electrical raceways tested in concrete slabs.*

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4.5" (114.3 mm) SLAB WITH 1" (25.4 mm) ELECTRIC NONMETALLIC TUBING (ENT) INSTALLED

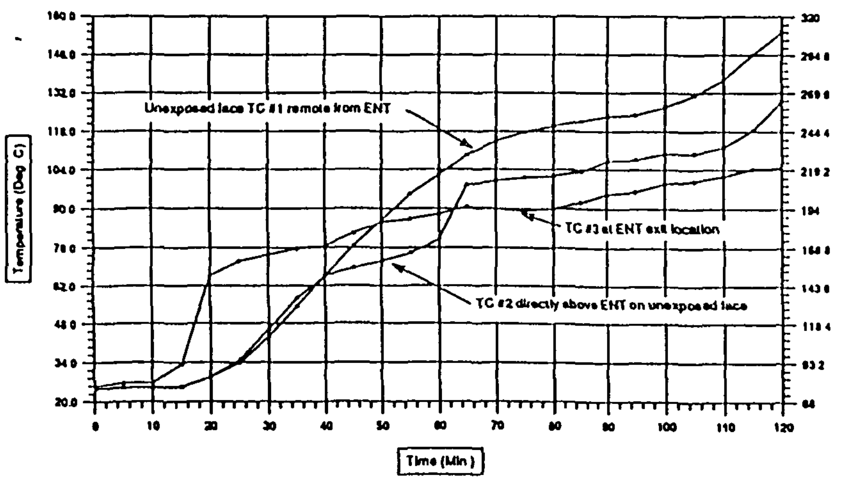

FIG. 4(b)—*Comparative time temperature curves for thermocouples associated with metallic (Fig. 4a) and non-metallic (Fig. 4b) electrical raceways tested in concrete slabs.*

slab. Similar results were also obtained with the lightweight test slab which included the 25.4-mm (1-in.) ENT raceway.

Regarding possible fire spread along the PVC raceway, testing showed that no such fire spread occurred. Rather, the material within the slab charred gradually and temperatures at locations where ENT exited the test assemblies were below failure criteria for ASTM E 814 (Fig. 4b).

Conversely, an identical specimen, tested with cast in place, thin wall electrical metallic tubing (EMT) showed higher backface temperatures above the metallic raceway during testing than in the field of the concrete (Fig. 4a). In addition, at exit locations on the unexposed side, temperatures also exceeded allowable levels for ASTM E 814. Test assembly design was identical to that of the normal weight slab shown in the preceding Fig. 3. Back face time temperature curves showed higher temperatures above the EMT as well as at outlet locations on the unexposed surface of the slab [42]. These readings are a consequence of the high thermal conductivity of the steel tubing as compared to both the concrete and the PVC raceway.

Nonstandard Sources of Hazard and Risk Assessment Data

In addition to results from standard testing, hazard and risk assessment procedures often must draw on other data to reach reasonable conclusions. Often a standard test may not address a foreseeable consequence of the use of a product or the intended use may differ from the standard assembly result. Thus, engineering judgment, a non-standard test, and/or field data will be required to provide needed answers. An inescapable fact is that *so many potential end-use configurations exist for pipe, tube, and conduit products* (as with other widely used construction products) that *one is precluded from testing of all combinations of these* making some form of hazard assessment a necessity.

In the case of PVC electrical raceway products, for example, portions of the hazard assessment findings in Ref *1* were based on non-standard test results used in concert with modeling results to assess probable impact of combustion products created from fire exposures of these products. The findings demonstrated that no unusual hazards existed, based upon direct exposure of *PVC electrical raceway to flame*, as *did later findings based on* rodent exposures to PVC smoke from the same products [*43*].

Likewise, potential ignition hazards posed by all electrical raceway systems should be considered and evaluated although these are not readily subjected to standard test conditions. *However, reports are available on this topic which show that PVC raceways provide intrinsic* safety factors not found in metallic raceway systems due to their inability to fault to ground [*44,45*].

It is obvious that redundant fire protection features required in many contemporary buildings impact fire risk levels there. This was demonstrated for PVC electrical products in a test conducted when sprinkler protection was added to an older, fire resistive building in a demonstration of upgrading capabilities of modern construction materials and techniques [*46*]. In this case, the active protection provided by sprinklers based on plastic pipe prevented damage to PVC-ENT installed within fire resistive wall assemblies to such an extent that electrical continuity was maintained after even the fire test exposure had been conducted. In actual situations like this test scenario, actual fire loads rarely challenge properly installed barriers (such as single or multiple layers of wallboard) and the presence of sprinklers further reduces hazard levels. The presence of these construction features should be taken into account in preparing a fire hazard assessment of such structures.

The emergence of CPVC and PB as listed materials for fire sprinkler pipe has been reviewed [*47*] and reports on the testing to qualify them for listing are also available [*48*]. Those test results also have implications for pipe uses in DHCW supply based on the same generic plastics which are qualified for use as sprinklers. For example, in test protocols for plastic pipe sprinkler systems, the piping, charged with water, is exposed to a wood crib heptane fire. When the test is begun and following initiation of sprinkler discharge, water flow is continued through the plastic pipe which is itself exposed to the ongoing wood crib/heptane fire. This provides adequate evidence of piping integrity and resistance to flame impingement under conditions where water is present and should relieve those concerned that CPVC and PB for DHCW uses will derate fire resistive assemblies in which they are installed.

Concerning non-standard postflashover testing of through penetration of slabs and partitions by plastic DWV, two early Canadian studies showed mixed results for tests in which attempts were made to follow the ASTM E 119 time temperature curve, for small specimens. These tests also presented different approaches to through penetration fire stopping, including application of metal sleeving at through penetration locations to protect pipe for periods beyond one h [*49,50*].

Australian researchers conducted tests on both unprotected PVC pipe penetrating concrete slabs and protected situations where PVC pipes were installed with intumescent fire stopping systems. Their results reinforced the finding that fire stopping protection for direct, through penetrations of PVC pipe through slabs was required to maintain fire resistance ratings. These researchers also conducted tests with metal pipes which showed high unexposed face temperatures but no transmission of fire [*51–53*].

Finally, no bona fide field data documenting the existence of identified fire hazards due to plastic pipe, tube, or conduit as currently used is available. This includes an Australian study of the subject [*54*] and searches and inquiries in the United States to various incident reporting systems and databases by the author have failed to develop field data demonstrating a fire hazard. Likewise, a search of field data on installations in fire resistive buildings made

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under alternate materials and methods sections in the building codes since the 1970s did not show a recognizable fire incidence related to plastic pipe use. Similar inquiries related to field performance of electrical raceways based on PVC raceway, whose use increased first with the 1987 NEC acceptance and incrementally further with the 1990 NEC, have been negative.

Discussion

The preceding section presented data which will assist in projecting expected fire performance of plastic pipe, tube, and conduit in specific situations. Generalizations which can be drawn from these data include the following below.

Although the different generic materials used for plastic pipe, tube, and conduit have been tested to varying degrees in both combustible and non-combustible construction assemblies of widely differing types, such testing has not been conducted on every type of included or penetrating element in every possible fire resistive assembly. The testing which has been conducted in both standard fire endurance formats (as well as for uses in fire resistive buildings which include sprinklers based on plastic pipe) supports the following general ranking where test results for a specific combination of pipe assembly are unavailable.

CPVC > PVC > fire retardant PP > PP, PB, *and* ABS

The basis for this ranking can be found by comparing tabulated test results in reports such as Ref *13* and fire endurance periods presented in listing documents such as Ref *8* where differing generic resins, used to fabricate plastic pipe, tube, and conduit have been tested in identical installations. From a standpoint of measured fire resistance times in side by side testing, both of those references present data that support this ranking for products used in plumbing and electrical applications. Likewise, properties such as resistance of polymer resins to ignition (as expressed by numerical results in ASTM D 2863 testing) are of importance. Finally, presence or absence of fire retardants (as in the polypropylene materials cited) and differing melt and charring tendencies of the classes of resins used for pipe, tube, and conduit will impact fire endurance.

Model Code Acceptance

Each of the three model building codes, the Uniform Building Code (UBC), Standard Building Code (SBC), and the National Building Code (NBC),[4] upon which most locally adopted building codes are based, provide for the use of plastic pipe, tube, and conduit in fire resistive construction in their latest versions. Other specialized or regional codes (such as the NEC and the National and Standard Plumbing Codes) allow for unlimited use of plastic pipe, tube, and conduit, as specified. Likewise the ANSI S-40 committee recently developed a plumbing code allowing for use of plastic pipe in fire resistive construction and the Conference of American Building Officials, Board for the Coordination of Model Codes (CABO-BCMC) issued guidelines for use of plastic pipe, tube, and conduit in shaft, duct, and at through penetration locations several years ago. However, differences exist from community to community regarding adoption and amendment of these codes. Certain major cities which promulgate their own codes, and the model plumbing code used in much of the western and midwestern United States, restrict use of these products in a variety of ways. It is the author's opinion that these restrictions are based on economic, rather than technical, grounds, inasmuch as there is a substantial, positive record for these product's fire performance characteristics.

[4]UBC, promulgated by the International Conference of Building Officials (ICBO), Whittier, CA; SBC, promulgated by the Southern Building Code Congress International (SBCCI), Birmingham, AL; NBC, promulgated by the Building Officials and Code Administrators International (BOCA), Country Club Hills, IL.

Conclusion

Adequate literature and test results exist to conduct hazard assessments related to many uses of plastic pipe, tube, and conduit. In doing so, application of products must be considered in light of their specific function, the type of assembly in which they will be installed, and the overall design of the structure concerned. Whenever possible, standard test results and knowledge from field performance should be applied to make these assessments.

References

[1] Benjamin, I. A., "Toxic Hazard Analysis: Electrical Non-Metallic Tubing," *Journal of Fire Sciences*, Vol. 5, Jan.-Feb. 1987, pp. 25–49.
[2] "Plastic Plumbing Pipe," including "Technical Appendices," Draft Environmental Impact Report, SRI International, (Menlo Park, CA), Department of Housing and Community Development, State of California, Sacramento, Draft I, 1983, and Draft II, Aug. 1989.
[3] "Standard Guide for the Development of Fire Hazard Assessment Standards for Products," ASTM Task Group E5.35 on Fire Hazard and Fire Risk Assessment, Committee E-5 on Fire Standards, Project X-95-7, (draft), 20 April 1990.
[4] "Results of 3 ASTM E 119 1-Hour Tests of Gypsum Wallboard/Steel Stud Assemblies," (from L. Laymon), UL NC505, Project 76 NK1268, Underwriters Laboratories, Inc., Northbrook, IL, 20 April 1976.
[5] "Report on the Fire Endurance and Hose Stream Tests of PVC Plastic Pipe Penetrations Through a 7¼" Thick, 1-Hour Rated Gypsumboard and Steel Stud Wall," and "Fire Performance of PVC Pipe in Non-combustible Construction," File WHI-495-PSV-0580 and WHI-495-PSV-0635, Warnock Hersey International, Inc., Pittsburg, CA, Jan. 1989.
[6] "PVC and Rigid Metallic Conduit and Metallic Outlet Boxes in a Nonbearing Partition Assembly," UL NC546-1,-2, Project 73 NK7657, Underwriters Laboratories, Inc., Northbrook, IL, 21 Dec. 1973.
[7] "Electrical Nonmetallic Tubing (ENMT), Electrical Metallic Tubing (EMT), and Metallic Outlet Boxes in a Nonbearing Partition Assembly," UL R8326-4, Project 80 NK11747, Underwriters Laboratories, Inc., Northbrook, IL, 17 Sep. 1980.
[8] *Fire Resistance Directory 1990*, Underwriters Laboratories, Inc., Northbrook, IL, 1990
[9] Danielsson, C., Linder, P., Lundin, O., and Prenell, P. A., "Fire Tests with Plastic Tubes Carried Out at the Research Station in Studsvik, Spring 1963," Report 18:1966, National Swedish Institute for Building Research, Studsvik, Jan. 1963.
[10] Zicherman, J. B., Unpublished test data, IFT Technical Services, Inc., Berkeley, CA, 1988
[11] Fang, J. B., "Static Pressures Produced by Room Fires," *NBSIR 80-1984*, Center for Fire Research, National Institute of Standards and Technology (formerly National Bureau of Standards), Gaithersburg, MD, 1984.
[12] Choi, K. K., "Fire Stops for Plastic Pipe," *Fire Technology*, Vol. 23, No. 4, Nov. 1987, pp. 267–279.
[13] Parker, W. J., Paabo, M., Scott, J. T., Gross, D., and Benjamin, I. A., "Fire Endurance of Gypsum Board Walls and Chases Containing Plastic and Metallic Drain, Waste and Vent Plumbing Systems," *National Bureau of Standards* Building Science Series 72, U.S. Department of Commerce, Sept. 1975.
[14] Bletzacker, R. W. and Birle, J. G., "Standard ASTM Fire Endurance Test and a Fire and Hose Stream Test on Duplicate Non-load Bearing Plumbing Wall Assemblies," Report 5615, Ohio State University, Building Research Laboratory, College of Engineering, Jan. 1974
[15] Bletzacker, R. W. and Birle, J. G., "Standard ASTM Fire Endurance Test and Fire and Hose Stream Test on Duplicate Load Bearing Polyvinylchloride Plumbing Wall Assemblies," Report 5561, Ohio State University, Building Research Laboratory, College of Engineering, May 1974

[16] Bletzacker, R. W. and Birle, J. G., "Standard ASTM Fire Endurance Test and Fire and Hose Stream Test on Duplicate Non-load Bearing Polyvinylchloride (PVC) Plumbing Wall Assemblies," Report 5474, Ohio State University, Building Research Laboratory, College of Engineering, April 1973.
[17] Bletzacker, R. W. "Standard ASTM Fire Endurance Test and Fire and Hose Stream Test on Duplicate Load-Bearing Acrylonitrile-Butadiene-Styrene Plumbing Wall Assemblies," Report 5560, Ohio State University, Building Research Laboratory, College of Engineering, 1974.
[18] Bletzacker, R. W. "Standard ASTM Fire Endurance Test and Fire and Hose Stream Test on Duplicate Non-Load Bearing Acrylonitrile-Butadiene-Styrene (ABS) Plumbing Wall Assemblies," Report 5560, Ohio State University, Building Research Laboratory, College of Engineering, 1973.
[19] Draemel, R. B. and Williamson, R. B., "Fire Tests of Six Inch Wood Stud One-hour Fire-rated Walls with Plastic DWV Plumbing Systems," Service to Industry Report 76-7, University of California, Berkeley, Department of Civil Engineering, Structural Research Lab, Nov. 1976.
[20] Draemel, R. B. and Williamson, R. B., "Fire Test of a Six Inch Wood Stud One-Hour Fire-Rated Wall with a Fire Retardant Polypropylene DWV Plumbing System," Service to Industry Report 7702, University of California, Department of Civil Engineering, Structural Research Lab. Berkeley, 1977.
[21] Williamson, R. B., "Fire Test of a Six Inch Wood Stud One-hour Fire-rated Wall with a Polyvinylchloride DWV Plumbing System, Structures, Materials and Fire Research," University of California, Berkeley, Department of Civil Engineering, Structural Research Lab, Feb. 1985.
[22] "Report on the Fire Endurance and Hose Stream Tests of PVC Plastic Pipe Penetrations Through an 8½" Thick, 2-Hour Rated Gypsumboard and Steel Stud Wall," and "Fire Performance of PVC Pipe in Non-combustible Construction," Files WHI-495-PSV-0580 and WHI-495-PSV-0635, Warnock Hersey International, Inc., Pittsburg, CA, Jan. 1989.
[23] Plumbers' and Steamfitters Union Local 467/Goldberg Research and Development Associates Corp., "The Effects of ABS Plastic Plumbing Runs on a Wood Stud and Gypsum Wallboard Partition Exposed to a Standard Fire Endurance Test," File WHI-495-0456, Warnock Hersey International, Inc., Pittsburg, CA, 8 Oct. 1982.
[24] Zicherman, J. B., "Fire Safety of PVC-Based Plastic Piping," *Fire Journal*, Vol. 84, No. 6, Nov./Dec. 1990, pp. 36–42.
[25] "Standard Fire Endurance Test Program To Evaluate and Compare the Fire Resistance of Two Types of ABS Plastic Pipe When They Penetrate a Fire-Resistive Wall," IFT Technical Services, Inc., Report 5213, Coquitlam, B.C., Canada, Warnock Hersey Professional Services, Ltd., Pittsburg, CA, 16 Jan. 1987.
[26] Plastic Pipe and Fittings Association (PPFA), *Plastic Pipe in Fire Resistive Construction*, The Design and Installation Manual for Plastic Pipe in Fire Resistive Construction, PPFA, Glen Ellyn, IL, 1985.
[27] "Fire Test Investigation of Through-Penetration Firestop Systems in Gypsum Wallboard/Steel Stud Wall Assemblies," UL R9700, Project 85 NK17181, 3M Company, Underwriters Laboratories, Inc., Northbrook, IL, 18 Sept. 1985.
[28] "Report on Through-Penetration Fire Stop Devices," UL R10100-1,2, Project 83 NK19794, Orion Industries, Inc., Kansas City, KS, Underwriters Laboratories, Inc., Northbrook, IL, 28 Nov. 1984.
[29] "Report on Wall Opening Protective-Devices-in Concrete or Masonry Walls Assemblies," UL R9269-1,2 and R9700, Projects 81 NK4314 and 81 NK7951, 18 Dec. 1981; Letters, "Report Types PSS 7902 and PSS 7904 Through-Penetration Firestop Devices in Concrete Floor Assemblies," UL R9269, Project 82 NK2200, 6 May 1983, and Letter Report R9269, 31 March 1983, Underwriters Laboratories, Inc., Northbrook, IL.
[30] Meyer, G. and Brittain, W., "Two Hour Fire Resistance and Hose Stream Tests of R & G Sloane Fire Valve," WHI File 495.0621 and 495.0622, Warnock Hersey International (WHI), Pittsburg, CA. 1984.
[31] "Report on Through-Penetration Fire Stop Devices," UL R101000-1,2, Project 83 NK19794, Orion Industries, Inc., Kansas City, KS, Underwriters Laboratories, Inc., Northbrook, IL, 28 Nov. 1984.
[32] "ASTM E 814-83 Standard Method of Fire Tests of Through-Penetration Fire Stops: Polybutylene Pipe Penetrations of a 1-Hour Rated Fire-Resistive Wall Assembly," Project 01-8305-028, SRI, Menlo Park, CA, May 1985.
[33] "Fire Test Evaluation on Polybutylene (PB) Plastic Piping in a Steel and Wood Studded Gypsum Board Partitions," Design WP 735 for Shell Chemical Company, Houston, TX, File J.I. OK9Q6.AC (4510), Factory Mutual Research, Norwood, MA, 13 Nov. 1984.
[34] "Report on Through-Penetration Fire Stop Devices in Concrete Floor Assemblies," UL R10338-1,2,3, Project 83 NR4820 for Proset Systems, Atlanta, GA, Underwriters Laboratories, Inc., Northbrook, IL, 25 Nov. 1983.

[35] *Fire Resistance Directory 1990*, System 160, 167, and 303, Underwriters Laboratories, Inc., Northbrook, IL 1990, pp. 1264, 1265, and 1382
[36] Bletzacker, R. W. and Birle, J G., "Standard ASTM Fire Endurance Test on a Floor and Ceiling Assembly," Report 5539, Ohio State University, Plastic Pipe Institute, Building Research Laboratory, Columbus, OH, May 1974.
[37] Council of American Building Officials (CABO), "Fire Resistive Noncombustible Partition Assembly Containing Electrical Non-Metallic Tubing and Rigid Non-Metallic Conduit," Report NER-290, Carlon, National Evaluation Service Committee, Country Club Hills, IL, May 1987.
[38] "Fact-Finding Report on Metallic and Nonmetallic Tubing, Conduits and Boxes in the Concealed Space of Floor-Ceiling and Roof-Ceiling Assemblies with Suspended Ceiling," UL NC 546-5, Project 78 NK27319, NEMA/UL Underwriters Laboratories, Inc., Northbrook, IL, Attention B Swytnyk, March 1989.
[39] "Nonmetallic Electrical Outlet Boxes for Use in Floor-Ceiling Assemblies Consisting of Wood Joists, Wood Flooring and Gypsum Wallboard," UL R8326, Project 81 NK 24119, Carlon, Underwriters Laboratories, Inc., Northbrook, IL, 22 Dec. 1981.
[40] "Report of the Pilot Scale Fire Endurance Test of an Unrestrained 6' by 8' by 4½" Thick, Reinforced Concrete Slab without an Applied Load, and with 1" Diameter, PVC, Flexible, ENT Conduit Runs," File WHI 495-PSH-1065, IFT Technical Services, Inc., Warnock Hersey International, Inc., Pittsburg, CA, 7 May 1990.
[41] "Report of the Pilot Scale Fire Endurance Test of 1" Diameter, PVC, Flexible, ENT Conduit Runs in an Unrestrained 6' by 8' by 5¼" Thick, Reinforced Concrete/Corrugated Steel Deck Floor/Ceiling Assembly without an Applied Load," File WHI-495-PSH-0169, IFT Technical Services, Inc., Warnock Hersey International, Inc., Pittsburg, CA, 16 July 1990.
[42] "Report of the Pilot Scale Fire Endurance Test of an Unrestrained 6' by 8' by 4½" Thick, Reinforced Concrete Slab without an Applied Load, and with 1" Diameter, Steel, EMT Conduit Runs," File WHI-495-PSH-0170, IFT Technical Services, Inc., Warnock Hersey International, Inc., Pittsburg, CA, 17 July 1990.
[43] Packham, S. C. and Crawford, M. P., "An Evaluation of Smoke Toxicity and Toxic Hazard of Electrical Non-Metallic Tubing Combustion Products," *Journal of Fire Sciences*, Vol. 2, Jan.-Feb. 1984, pp. 37–59.
[44] Kahn, M. M., "Electrical Failure of Wires Inside 1-inch Conduit Under Simulated Fire Conditions," Technical Report FMRC J.I., OH4R4.RC, Carlon, Factory Mutual Research Corporation, Norwood, MA, Oct. 1984.
[45] Fuller, J. F., Hanna, W. J., and Kallenbach, G. A., "Arcing Faults in Metallic Conduit at 120 and 240 v," *IEEE Transactions on Industry Applications*, Vol. IA-21, No. 4, May/June 1985.
[46] Benjamin/Clarke Associates, Inc., "Operation San Francisco: Smoke/Sprinkler Test, Technical Report," distributed by International Association of Fire Chiefs (IAFC), Marriot Corporation, San Francisco Fire Dept., and FEMA/USFA, Washington, DC, April 1984.
[47] Wilging, R. C., "Plastic Fire Sprinkler Piping 1967-1987," *The Building Official and Code Administrator*, July/Aug. 1988.
[48] "Report on CPVC Pipe and Fittings for Sprinkler Systems," UL Ex3754, Project 85 NK837, Underwriters Laboratories, Inc., Northbrook, IL, 17 July 1985.
[49] Atwood, P., "Penetration of Fire Partitions by Plastic Pipe," *Fire Technology*, Vol. 16, No. 1, July 1980, pp. 37–62.
[50] McGuire, J. H., "Penetrations of Fire Partitions by Plastic DWV Pipe," *Fire Technology*, Vol 9, No. 1, Feb. 1973, p. 5.
[51] Burn, L. S. and Martin, K. G., "Intumescent Fire Stoppers For UPVC Pipes Penetrating Concrete Slabs," Commonwealth Scientific and Industrial Research Organization, Division of Building Research, Highett, Victoria, Australia, 1980.
[52] Brown, S. K. and Martin, K. G., "Model Fire Resistance Tests of UPVC Pipes Penetrating Concrete Slabs," Commonwealth Scientific and Industrial Research Organization, Division of Building Research, Highett, Victoria, Australia, 1979.
[53] Burn, L. S. and Martin, K. G., "Early Fire Hazard Assessment of UPVC Pipe Formulations," Commonwealth Scientific and Industrial Research Organization, Division of Building Research, Highett, Victoria, Australia, 1981.
[54] Brown, S. K., "Review of Actual and Simulated Fires Involving Plastics and Pipes and Fitting," Commonwealth Scientific and Industrial Research Organization, Division of Building Research, Highett, Victoria, Australia, 1979.

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