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James K. Stewart, Director
National Institute of Justice

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Development of a Test Method To Evaluate the Penetration Resistance of High-Security Glazing Subjected to Mechanical Impact and Heat

NIJ Report 300-85

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FOREWORD

The Law Enforcement Standards Laboratory (LESL) of the National Bureau of Standards (NBS) furnishes technical support to the National Institute of Justice (NIJ) program to strengthen law enforcement and criminal justice in the United States. LESL's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

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Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Law Enforcement Standards Laboratory, National Bureau of Standards, Gaithersburg, MD 20899.

Lester D. Shubin
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COMMONLY USED SYMBOLS AND ABBREVIATIONS

A	ampere	H	henry	nm	nanometer
ac	alternating current	h	hour	No.	number
AM	amplitude modulation	hf	high frequency	o.d.	outside diameter
cd	candela	Hz	hertz (c/s)	Ω	ohm
cm	centimeter	i.d.	inside diameter	p.	page
CP	chemically pure	in	inch	Pa	pascal
c/s	cycle per second	ir	infrared	pe	probable error
d	day	J	joule	pp.	pages
dB	decibel	L	lambert	ppm	part per million
dc	direct current	L	liter	qt	quart
°C	degree Celsius	lb	pound	rad	radian
°F	degree Fahrenheit	lbf	pound-force	rf	radio frequency
diam	diameter	lbf·in	pound-force inch	rh	relative humidity
emf	electromotive force	lm	lumen	s	second
eq	equation	ln	logarithm (natural)	SD	standard deviation
F	farad	log	logarithm (common)	sec.	section
fc	footcandle	*M*	molar	SWR	standing wave ratio
fig.	figure	m	meter	uhf	ultrahigh frequency
FM	frequency modulation	min	minute	uv	ultraviolet
ft	foot	mm	millimeter	V	volt
ft/s	foot per second	mph	mile per hour	vhf	very high frequency
g	acceleration	m/s	meter per second	W	watt
g	gram	N	newton	λ	wavelength
gr	grain	N·m	newton meter	wt	weight

area = unit^2 (e.g., ft^2, in^2, etc.); volume = unit^3 (e.g., ft^3, m^3, etc.)

PREFIXES

d	deci (10^{-1})	da	deka (10)
c	centi (10^{-2})	h	hecto (10^2)
m	milli (10^{-3})	k	kilo (10^3)
μ	micro (10^{-6})	M	mega (10^6)
n	nano (10^{-9})	G	giga (10^9)
p	pico (10^{-12})	T	tera (10^{12})

COMMON CONVERSIONS
(See ASTM E380)

ft/s × 0.3048000 = m/s
ft × 0.3048 = m
ft·lbf × 1.355818 = J
gr × 0.06479891 = g
in × 2.54 = cm
kWh × 3 600 000 = J

lb × 0.4535924 = kg
lbf × 4.448222 = N
lbf/ft × 14.59390 = N/m
lbf·in × 0.1129848 = N·m
lbf/in^2 × 6894.757 = Pa
mph × 1.609344 = km/h
qt × 0.9463529 = L

Temperature: $(T_{°F} - 32) \times 5/9 = T_{°C}$

Temperature: $(T_{°C} \times 9/5) + 32 = T_{°F}$

DEVELOPMENT OF A TEST METHOD TO EVALUATE THE PENETRATION RESISTANCE OF HIGH-SECURITY GLAZING SUBJECTED TO MECHANICAL IMPACT AND HEAT

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This report describes the development of a laboratory test method for transparent, high-security glazing. The test method was developed to evaluate the penetration resistance of glazing materials subjected to a simultaneous attack of mechanical impact with a sharp-nosed tool and heat application. The rationale for the determination of the test parameters and realistic parameter levels is given. Glazing panels, measuring 12×12 in, are simultaneously subjected to repeated impacts by a pendulum with a chisel-nosed impactor and a continuous diffusion (yellow) flame delivered by propane gas torches until the chisel nose penetrates the panel. Penetration of the panel by the chisel nose results in a hole that is about 1 inch in its longest dimension. The test apparatus can be easily constructed and reproducibly applies mechanical impact and heat to the test panels; the test is simple to perform. Sixty-three panels composed of laminated glass, glass-clad polycarbonate, or laminated polycarbonate were tested. Test results indicated a wide range in the number of impacts (1 to 116) required to penetrate the glazing. Increases in polycarbonate thickness resulted in increases in the number of impacts required for penetration. It was concluded that (a) the test method can be used to evaluate the penetration resistance of glazing materials when they are subjected to the specified test conditions, and (b) the test results can be used to rank the penetration resistance of the glazing materials, provided the variability of the test results is incorporated in the ranking.

Key words: flame; glass-clad polycarbonate; glazing; heat; high-security glazing; impact; laminated glass; penetration resistance; polycarbonate; test method.

1. INTRODUCTION, PURPOSE, SCOPE, AND APPROACH

1.1 Need for Standard Test Methods and Performance Criteria

"High-security" glazing is being used increasingly as a barrier material in correctional and other confinement-oriented facilities. It is used instead of steel bars to prevent inmates from escaping from the facilities, or accessing areas where they are not permitted, and from smuggling in weapons or other contraband. In this report, high-security glazing is defined as a transparent barrier, consisting of one or more laminates of glass, plastic, or air, that will display some level of resistance to penetration by a specified means.

There is currently a need for standard test methods and performance criteria to measure and specify the penetration resistance of high-security glazing. The lack of universally accepted performance tests and criteria has caused law enforcement officials, architects, and others who are responsible for the design and construction of new and renovated correctional facilities to rely on manufacturers' and marketing information to select and specify high security glazing or devise and conduct their own tests.

*Center for Building Technology, National Engineering Laboratory.

**Law Enforcement Standards Laboratory, National Engineering Laboratory.

1.2 Funding and Performing Agencies

Because of the need for performance tests and criteria to specify the required resistance to penetration, the National Institute of Justice (NIJ) authorized this research to develop needed performance tests and criteria as a part of the NIJ Technology Assessment Program. During 1982 to 1984, the work was performed at the National Bureau of Standards (NBS), Center for Building Technology, under the direction of the NBS Law Enforcement Standards Laboratory (LESL). This research builds upon prior NIJ sponsored LESL research that leads to the development of several performance standards for the physical security of door and window assemblies consistent with the needs of residential and small business buildings. These standards [1–3][1] are not suitable for the evaluation of glazing intended for use in high security applications such as correctional facilities, the focus of the present research.

1.3 Purpose and Scope

The purpose of this research was to develop a test method for the determination of the penetration resistance of transparent glazing materials used in high-security applications. The test developed is intended to simulate a specific attack scenario involving the directed application of heat combined with repeated impacts with a chisel-nosed weapon. This report provides a description of the development of the test method.

1.4 Approach

An initial study of potential methods that could be used by inmates to penetrate high-security glazing was conducted (chapter 2). Based on the study, an attack scenario was selected (chapter 2) which served as a basis for the development of the test method. A rationale was developed (chapter 3) for the selection of test parameters and the determination of test parameter levels (e.g., velocity, energy, and temperature) which simulated, insofar as possible, the attack scenario selected. These test parameters and their levels were used as a basis to design and construct a test apparatus to reproducibly deliver the required mechanical and heat application levels (chapter 4). A detailed test procedure was then developed (chapter 5).

The penetration resistance of 63 glazing panels, selected from three glazing types and consisting of several laminate sequences, was investigated (chapter 6) using the test apparatus and procedure developed. The test results were analyzed (chapter 7). Conclusions and recommendations for further research are given (chapter 8).

2. RATIONALE FOR SELECTION OF ATTACK SCENARIO

A major objective in the development of the test method was to make it pertinent to real-life situations. Therefore the first step, which is described in this chapter, was to determine which attack scenarios have been or might be used by inmates to penetrate high-security glazing barriers and to choose an attack scenario to serve as a basis for developing a test method.

During the initial part of the study, visits to prisons were made, discussions with law enforcement prison personnel were carried out, and accounts of breakouts were studied. Based on information obtained, it was concluded that there are many ways in which high-

[1] Numbers in brackets refer to references in chapter 9.

security glazing barriers can be penetrated, including the following important failure modes (by failure is meant the loss of the function of a part or component, permitting penetration):

- Failure of the glazing frame,
- Failure of the connections and/or interface material holding the glazing frame to the building structural element (wall, roof, door, etc.) containing the frame, with a separation of the glazing frame from the structural element,
- Failure of the glazing panel material, or the connections holding the glazing to the framing,
- Some combination of the above.

Penetration of the glazing panel material was selected as the first mode to be investigated and served as the basis for this study.

There are many actions which can be performed by one or more inmates and which can result in penetration of the glazing panel material. These actions include:

- Ramming, jacking, or prying a large portion of the glazing panel, or the entire panel, out of its frame,
- Fracturing the glass and/or plastic laminates of the panel by impact (including notching of the plastic components prior to impact),
- Punching, chipping, and/or cutting the panel,
- Creating a hole sufficiently large to insert a saw blade and then sawing the glass and/or plastic laminates of the panel,
- Heating the glazing causing melting (and/or burning) of the plastic laminates and thermal stresses, or cooling the glazing, causing increased brittleness and thermal stresses,
- Firing bullets or throwing hard objects at the glazing,
- Applying chemicals which attack and weaken the glass and/or the plastic laminates,
- Delaminating the glazing, where the laminating bond has been weakened by the environment or by other means, or
- Some combination of the above.

Discussions with prison personnel and others who are knowledgable about disturbances in prisons and other correctional institutions led to the following two conclusions:

1) Prison inmates can surreptitiously improvise and construct a variety of mechanical tools having different shapes, sizes, and weights and use these tools to attack a glazing barrier. They can also improvise many methods to apply heat to the glazing, and
2) The following attack scenario could be considered as a relatively common method used by inmates to penetrate security glazing: impacting with a sharp-nosed tool combined with the continuous application of heat at the impact region resulting in local penetration by chipping, punching, cutting, or melting.

Therefore an attack scenario of delivering impacts with a sharp-nosed tool combined with continuous heat application was chosen.

It is emphasized that the attack scenario chosen and the associated test method developed in this study is to be viewed as a first step in the process of developing a series of needed test methods which simulate important attack scenarios and their associated penetration modes as discussed in this chapter (see chapter 8 also).

3. RATIONALE FOR SELECTION OF TEST PARAMETERS AND THE DETERMINATION OF PARAMETER LEVELS

This chapter provides the rationale for the selection of test parameters and the determination of test parameter levels which simulate, insofar as possible, the chosen attack scenario. These test parameters and test parameter levels were used as the basis to develop the performance test apparatus and procedure.

3.1 Mechanical Impact

3.1.1 Simulated Tools and Size of Penetration

Using tools which they can improvise and construct, prison inmates can impart a wide range of forces and energies to glazing. Two hand-held hammers (fig. 1), weighing 2.5 and 4.9 lb respectively, were chosen to simulate typical tools inmates could readily construct and use to penetrate security glazing. Each hammer consisted of a handle with a housing at the impact end which secured a steel chisel with a 1-in wide[2] nose. A chisel-shaped nose was selected because it would cause a more pronounced stress increase at the area of impact as compared to a blunt-nosed impactor and therefore would be more effective in causing local penetration of the glazing.

To avoid complexity in the test method, it was decided to repeatedly impact the glazing at only one location with a 1-in wide chisel until the glazing was penetrated. This results in a hole that is about 1 inch in its longest dimension. The creation of larger holes, such as one that is large enough for a person to fit through, or one large enough to permit passage of contraband is also of concern. The development of a test method which would simulate the formation of larger-sized holes by either combined mechanical impact and heat application or by the other attack scenarios discussed in chapter 2, is an additional research need (see chapter 8 also).

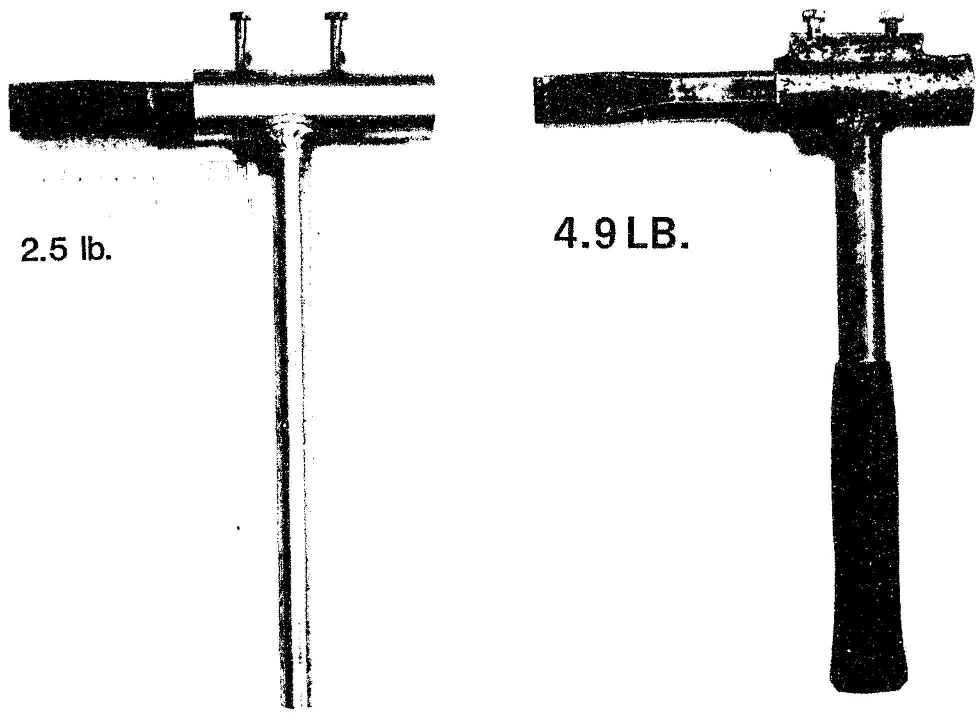


FIGURE 1. *Hand-held hammers, weighing 2.5 and 4.9 lb, used for human swings to determine an impact damage level. Hammer head secured a 1-in steel chisel weighing 1.3 lb. (The 2.5 and 4.9 lb hammer weights include the weight of the 1.3 lb chisel).*

[2] Conventional U.S. units are generally used throughout this report because they are often used by the glazing industry.

3.1.2 Impact Damage Level and Impact Delivery Method

Ideally, the damage to security glazing caused by repeated impacts from a mechanical apparatus should match the damage caused by repeated impacts delivered by persons swinging their improvised tools. Matching the damage is a very complex process since, for a thorough treatment, it would be necessary to match the damage for all mechanical and heat application histories. That is, the glazing stiffness would most likely progressively decrease with heat application and each mechanical impact. Moreover, the swing of a mechanical apparatus, such as a pendulum-type impactor, would be more reproducible than that of a person's swing. For example, the person would most likely not hit the same location with every impact and the force and angle of impact of the person's swing would probably vary from impact to impact. Such an ideal matching process was not within the project scope and was not pursued. Instead, it was decided to match, for the human and mechanical apparatus swings, the indentation depth resulting from a 1-in steel chisel impactor (fig. 2) being swung into a 2-in thick lead brick at room temperature. It was believed that by matching the indentation depth, the impact energy and damage caused by the mechanical apparatus would be roughly similar to that delivered by a person's swing. Lead was chosen as a target material because of (a) its reproducibility (99.999 percent purity) and (b) its softness, resulting in relatively deep, easily measured, indentations.

A pendulum was chosen to deliver the impacts because:

- it is simple to specify, build, and operate, and its reproducible velocity at the bottom of its arc can be easily checked.
- it delivers the required mechanical energy reproducibly as measured by the indentation of a steel chisel-nosed impactor into a 2-in thick lead brick.

To determine the required indentation depth, tests were performed by three physically fit men with the characteristics shown in table 1. The three men swung both the 2.5 and 4.9 lb hammers (fig. 1), which contained the same 1-in steel chisel (fig. 2). The indentation depth in a 2-in thick lead brick anchored in a steel frame (figs. 3 and 4) ranged from 9 to 13 mm for a single impact for the three men and for both hammers (table 1). It appeared that the weight of the hammer did not have a significant effect on the indentation depth produced.

TABLE 1. *Indentation depth values for men swinging hand-held hammers.*

	Man number		
	1	2	3
Age (yr)	30	28	21
Weight (lb)	221	199	182
Height (ft)	6.1	6.0	6.2
	with 2.5 lb hammer (fig. 1a)		
Range of indentation depth values (mm) in 2-in thick lead brick (based on two or more replicate swings[a])	9–12	11	10–13
	with 4.9 lb hammer (fig. 1b)		
	9–12	11–12	10–13

[a] Swings were directed either horizontally or vertically downward. The indentation depth was measured as the distance from the bottom of the indentation to the plane formed by the impact face of the lead brick and along a line perpendicular to the impact face of the brick.

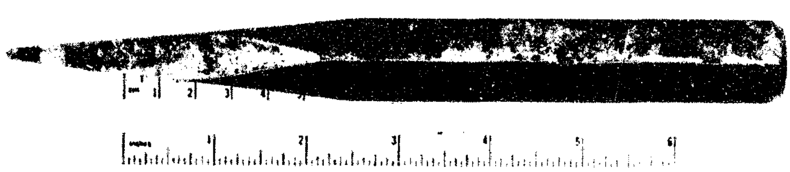


FIGURE 2. *Steel chisel used to impact lead bricks for human and pendulum swings. It weighed 1.3 lb, was 8-in long, and had a 1-in wide cutting edge. Values of the geometry and hardness of its chisel nose (fig. 10) were: S = 0.004 in, F = 80.00 °, G = 0.067 in, D = 0.114 in, A = 1.025 in, H = 0.319 in, Rockwell C scale hardness = 42.*

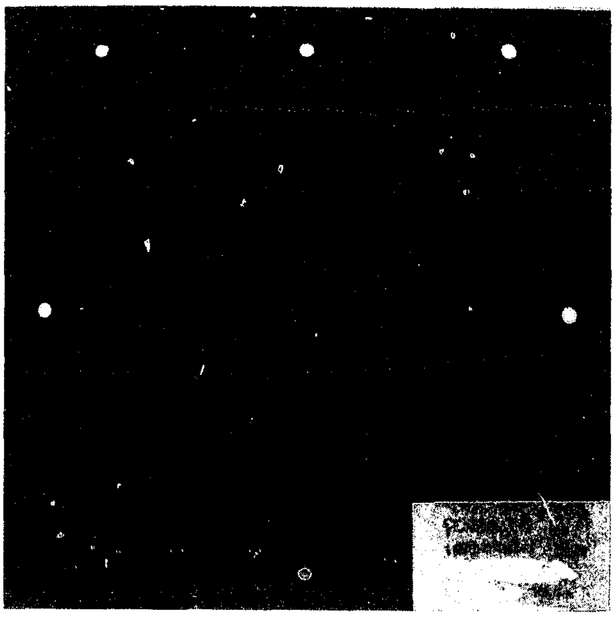


FIGURE 3. *Steel frame used to house lead brick for human and pendulum swings. A 10-mm deep indentation is shown in a mounted lead brick, measuring 6 × 6 × 2 in. (Brick was 2 in thick).*

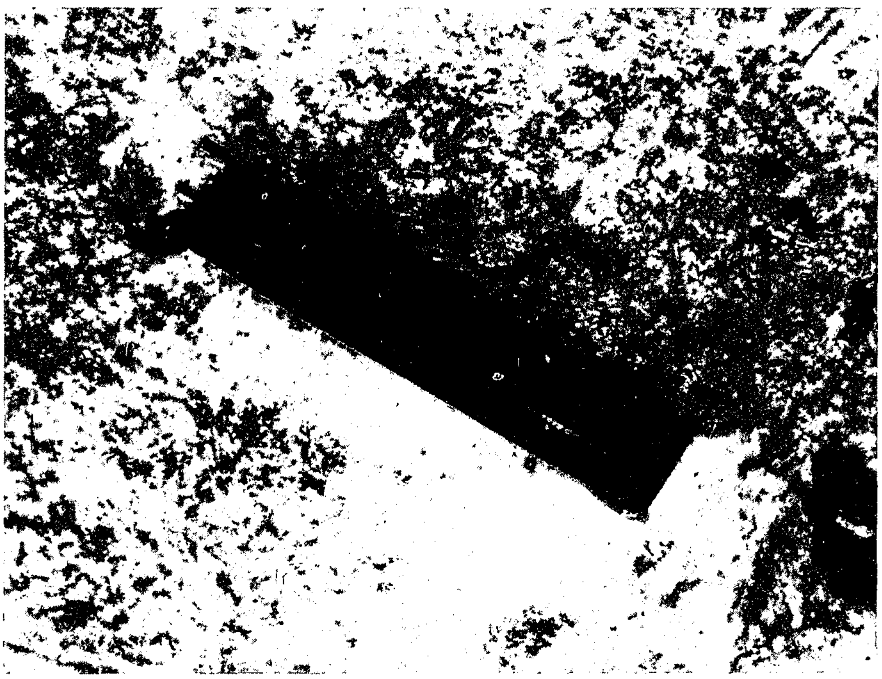


FIGURE 4. *Typical indentation of chisel nose into a lead brick.*

An indentation depth[3] of 9 to 10 mm was chosen as a reasonable indentation depth level to match with the pendulum when using the same chisel. The lower values (9 to 10 mm) of the indentation depth were considered reasonable because it was believed to be unlikely that an inmate could repeatedly deliver the full intensity of his swing to the same point on the glazing. The total weight of the 5-ft pendulum arm and the chisel housing assembly (fig. A3, app. A) were adjusted to result in a 9 to 10 mm indentation depth. The same chisel and similar mountings for the lead brick were used for both the human and pendulum swings. (The pendulum chisel impactor had a velocity of about 26 ft/s just prior to impact as discussed below.)

[3] Millimeters were used because the measurements were taken using this unit.

The maximum velocity just before impact was measured for four healthy men (nos. 1 and 3 in table 1 included) swinging their fastest, using hand-held hammers or rod-shaped objects ranging in weight from about 0.5 to 5.0 lb. Their swings were directed either horizontally or vertically downward. The velocity values ranged from about 30 to 80 ft/s. The velocity was measured as follows. An electronic chronometer started and stopped when the impact end of the hammer or rod-shaped object broke the first and then the second of two parallel laser beams that were 1.50 in apart. The 1.50-in distance between the beams was divided by the elapsed time on the chronometer to yield the swing velocity.

It was not possible to match the velocity of the pendulum impactor with that of the human swings because of the practical limitation imposed by choosing a pendulum as the mechanical apparatus. That is, the maximum distance between the impactor at the end of the cocked[4] pendulum arm and the impact zone on the glazing panel was limited to about 10 ft, resulting in a maximum possible velocity of about 26 ft/s. Although 26 ft/s is considerably less than the maximum measured velocity values of about 80 ft/s based on human swings, it is believed to be reasonable for the same reasons as given for matching at the lower end of the indentation values (i.e., it is unlikely that an inmate could repeatedly deliver the full intensity of his swing to the same point on the glazing).

3.2 Heat Application

3.2.1 Heat Application Method

Heat application levels can vary considerably, depending on the method of attack. For example, one or several cigarette lighters could represent a lower threat level, whereas a continuously fueled yellow-flame fire in the corner of a glazing frame could represent an increased threat level. Other examples include smearing and igniting a flammable solid on the glazing or igniting a flammable liquid in the trough at the bottom of a glazing frame. Because prison inmates often have access to combustible materials and the means to start a fire, a yellow flame (diffusion flame as opposed to a premixed flame) was chosen to apply the heat. A hotter blue flame, resulting from the premixing of gases, was not selected because it was believed unlikely that inmates could readily improvise a premixing apparatus and obtain the required fuel. For the test developed, gas torches, using commercial grade propane, were chosen to deliver the diffusion (yellow) flame because: (a) commercial grade propane gas is economical, (b) the gas flow rate can be set and monitored using in-line flowmeters, and (c) the torch flame can be made to impinge on a fixed area of a glazing panel while the specimen is being mechanically impacted. Further, the fabrication and placement of the torches and the air velocity near the torches can be specified for test reproducibility (see chapters 4 and 5).

Because inmates can readily impact the glazing while they apply heat, it was decided to apply the propane flame continuously to the glazing surface using two torches while simultaneously impacting the glazing with the chisel-nosed impactor.

3.2.2 Heat Application Level

Thermocouple measurements were used to estimate the flame temperatures. Sooting and melting patterns were used to observe and estimate the flame contact area.

Approximate flame temperatures for some commonly available materials and for a propane flame were measured using chromel-alumel thermocouples (table 2). The values are considered rough estimates because the results appeared to depend on the location and time duration that the thermocouple was held in the flame. In addition, the results need to be interpreted in a relative manner, since the flame temperature measurement depends significantly on the thermocouple characteristics [4,5]. Although the temperature estimate of the diffusion flame from a torch using commercial grade propane exceeded the temperature estimates for burning wood scraps, rags, toilet paper, and butane, it was well below that for a burning emergency road flare, and was selected as a reasonable compromise for this study.

[4] "Cocked" position refers to the pendulum arm held against the pendulum backstop (fig. A1, app. A).

Preliminary tests were performed and the resulting sooting patterns on the glazing were used to locate the two propane torches (figs. 5 and 6) and determine the gas flow rate so that the central region of the test panel where the impactor struck the glazing was heated adequately. Details of the torches and their mounting are given in chapter 4.

TABLE 2. *Approximate flame temperature of some flammable materials potentially available to inmates of correctional institutions.*

Material	*Estimate*[a] *of flame temperature* (°C)
Wood scraps	600 ($\approx$10 s)[a]
	650–800 ($\approx$30 s)
Rags	450–500 ($\approx$10 s)
Toilet paper	500 ($\approx$10 s)
Butane in a cigarette lighter	700–725 ($\approx$20 s)
Propane torch (diffusion flame, not premixed)	875–950 ($\approx$30 s)
Emergency road flare	Greater than 1200 ($\approx$10 s)

[a] These values are considered rough estimates because the results appeared to depend on the location and time duration (shown in parentheses) that the thermocouple was held in the flame. In addition, the results need to be interpreted in a relative sense because flame temperature measurement depends significantly on the thermocouple characteristics (chromel-alumel wire, with a diameter of about 0.021 in for a single bare wire, was used).

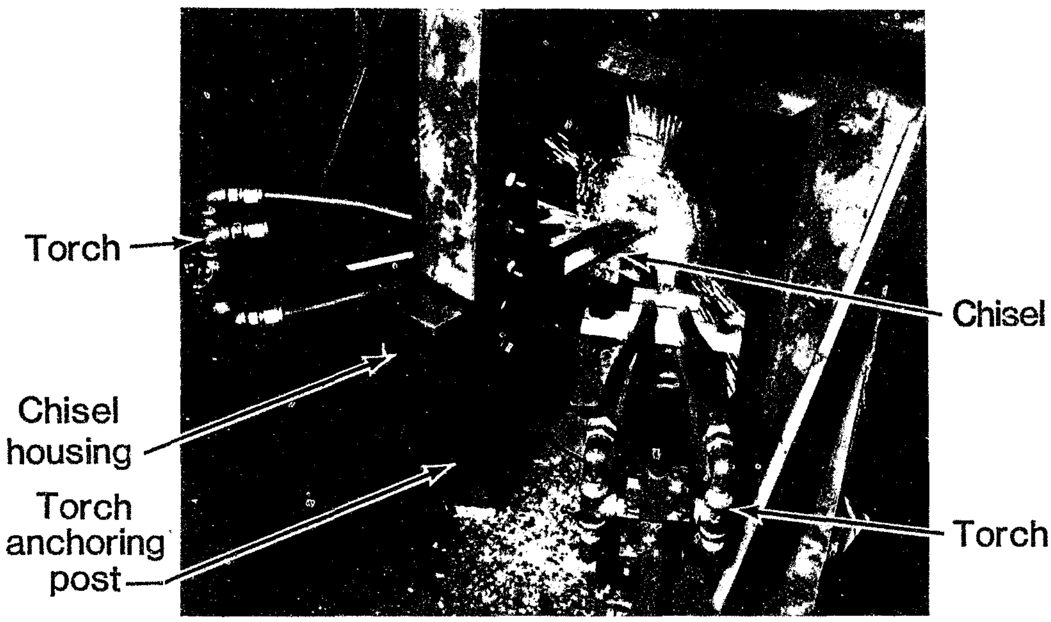
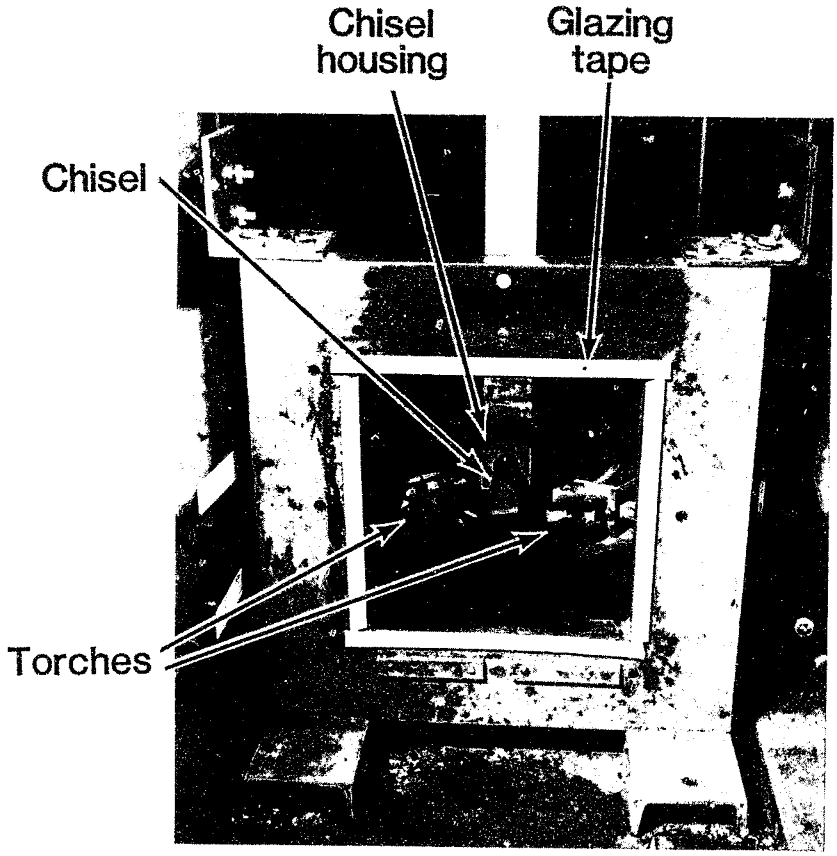
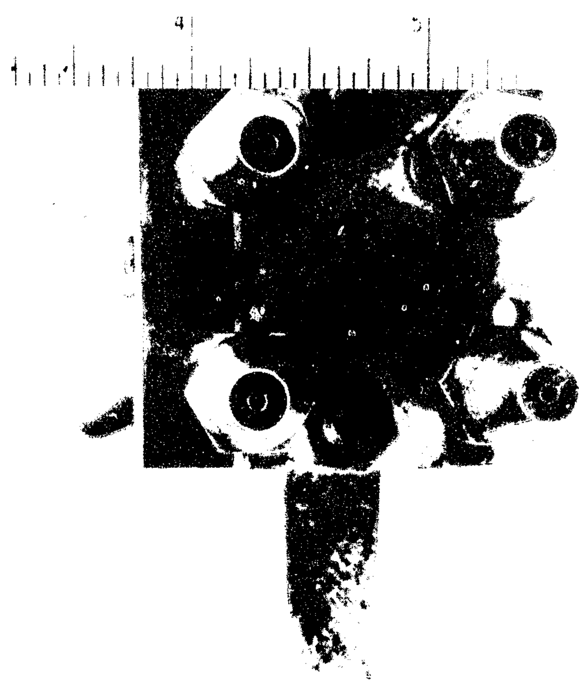


FIGURE 5. *Impact side of glazing frame. Chisel housing, chisel, two torches, and a torch anchoring post are shown.*



(a)

FIGURE 6a. *Nonimpact side of glazing frame. The glazing clamp, which secures the glazing panel, is not shown. Two torches, the chisel housing, chisel, and glazing tape, with its protective cover not yet removed, are also shown.*



(b)

FIGURE 6b. *View of one torch, looking almost directly into its four orifices.*

3.3 Glazing Test Panel Size

The objective of this study was to determine the penetration resistance of glazing subjected to a local attack, rather than a global penetration of the glazing, such as the glazing bowing out of its frame. The 12×12-in glazing test panel size that was selected exposed a 10×10-in test surface with the panel clamped completely around its periphery (see fig. A4, app. A, which also shows the location of the 1/2-in wide glazing tape that was used on both surfaces of the panel). The exposed glazing surface area was sufficiently large to apply heat to the central region of the glazing surface where the impactor struck, yet small enough to result in local penetration at the center of the panel, as demonstrated by the test results that are discussed in chapter 7. It should be noted, however, that glazing panels that are less rigid than those tested in this study may not fail in a local penetration mode.

3.4 Glazing Tape

A butyl-polyisobutylene preformed, preshimmed, glazing tape[5], 1/2 in wide by 1/8 in thick with a built-in, continuous, synthetic rubber spacer rod was used. (The tape was sticky on both of its sides.) The 1/16 in diameter rod was located in the middle of the 1/2-in tape width. The tape was used on both sides of the glazing panel when it was mounted in the glazing frame (fig. A4, app. A). Chapter 5 provides the details of the tape installation. According to the manufacturer, the tape met the Architectural Aluminum Manufacturers Association specification 804.1. This tape was chosen because it (a) is commonly used in the installation of certain types of high security glazing, (b) reduces the probability of damage occurring, such as crack formation, near the panel edges, and (c) is easy to install and is readily available.

4. TEST APPARATUS

This chapter provides the details of the test apparatus (figs. 7a,b,c) used in the test method. The apparatus included a vertical structure to support the pendulum, a pendulum arm with a chisel housing assembly at the impact end of the arm, a glazing frame to house the test panel, and two propane gas torches to apply a diffusion (yellow) flame to the test panel (fig. 7c). Practical considerations dictated that the entire test apparatus be less than 12 ft tall (with the pendulum cocked), because the test apparatus had to be contained in a large exhaust hood, of sufficient size to accommodate the apparatus and its accessories (including a strip chart recorder, timer, propane tank, and ladder) and test personnel (figs. 7a,b). Detailed drawings of the test apparatus are given in appendix A (figs. A1 to A6).

4.1 Pendulum Frame, Arm, and Impactor

Figures 7a and 7b show the pendulum apparatus used. Drawings of the pendulum apparatus, the pendulum support system, and the chisel housing assembly are given in figures A1, A2, and A3 (app. A). The 5-ft pendulum arm was raised to a nearly vertical position and cocked (cocked position refers to the pendulum arm held against the pendulum backstop, fig. A1 (app. A), with the arm forming a 6° angle with the vertical) before being allowed to fall freely. This resulted in a 10-ft drop as measured from the chisel-nosed impactor at the end of the pendulum arm in its cocked position to the lowest point of the pendulum impactor arc.

[5] Tremco (Cleveland, OH) preshimmed No. 440 glazing tape was used and found to perform satisfactorily. Certain manufacturer names, commercial equipment, instruments, or materials are identified in this report in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards or the National Institute of Justice, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Aluminum square tubing, having a 2.0 in outside dimension by a 1/8 in wall thickness, was used for the pendulum arm to provide both the required stiffness and light weight. The impactor was an 8-in steel chisel with a 1-in wide cutting edge secured in a chisel housing at the impact end of the pendulum arm (fig. A3, app. A).

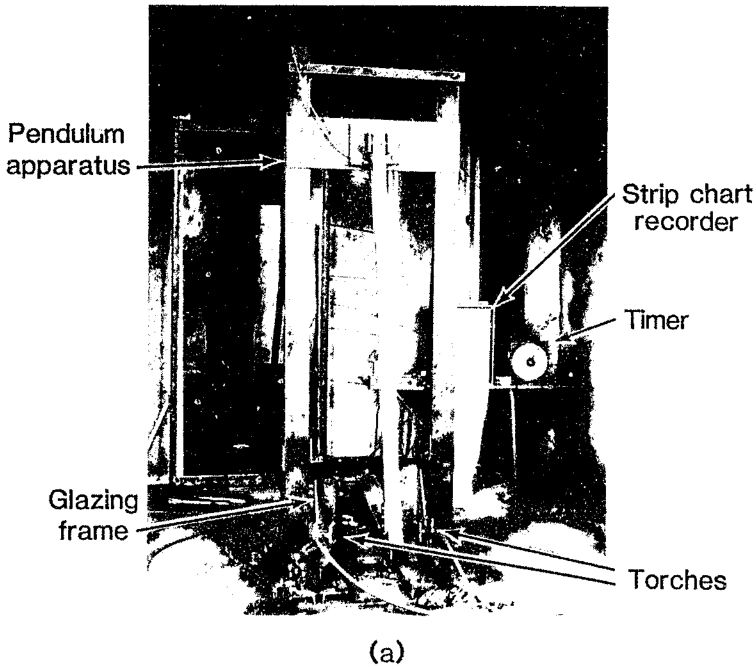


FIGURE 7a. *Test apparatus in large hood, including pendulum apparatus, glazing frame, torches, strip chart recorder, and timer.*

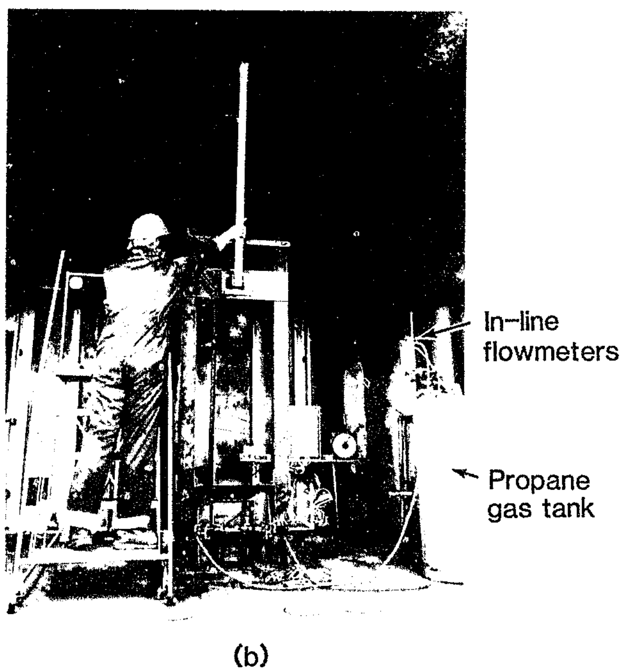


FIGURE 7b. *Pendulum arm being raised by Operator 1, who is positioned on a nonskid ladder with side rails. Propane gas tank and two in-line flowmeters (one for each torch) are also shown.*

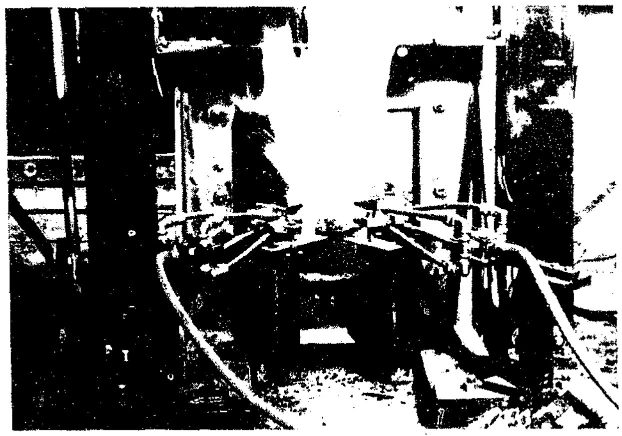


FIGURE 7c. *Torches ignited and applying heat to impact side of test panel.*

To reduce frictional losses, the pendulum arm rotated on low friction bearings[6] (fig. A2, app. A). A steel block (fig. A2, app. A) inserted inside of, and attached to, the pendulum arm at the pivotal end of the arm, prevented excessive lateral sway of the arm during its fall and impact. The pendulum apparatus was bolted to a steel base plate which was anchored to the floor to prevent the apparatus from moving relative to the floor during impacts.

Relative to the bottom of the pendulum arc, the calculated combined potential energy of the pendulum arm and the chisel housing assembly (fig. A3, app. A), including the chisel, when the arm is cocked is 110 ft-lb (app. B). At the bottom of the arc just before impact, all of the 110 ft-lb of potential energy is converted into kinetic energy and the calculated velocity of the chisel is 26.5 ft/s (app. B). The velocity of the chisel nose was measured near the lowest point of the pendulum arc, with the pendulum arm at an angle of about 7° with the vertical (fig. 8b). When the velocity was measured, the chisel nose was about 7 in from the impact surfacae of the glazing panel and the 1-in wide chisel nose dimension was vertical. In most cases, the measured velocity values ranged from about 26.0 to 26.5 ft/s. The velocity measuring apparatus (fig. 8a) was the same as that used to measure the velocity of the human swings.

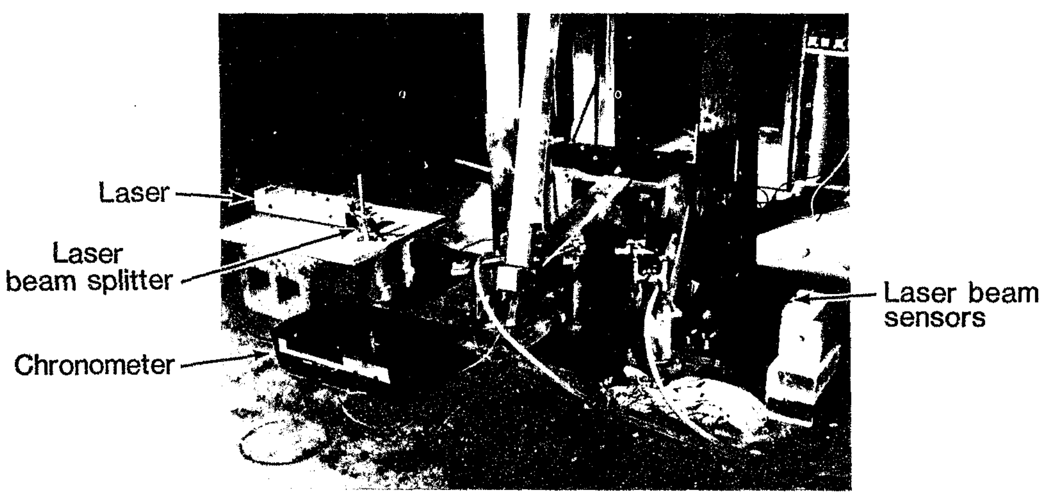


FIGURE 8a. *Velocity measuring apparatus, including laser, laser beam splitter, laser beam sensors, and chronometer.*

[6] Bearings used were single row, radial, inch dimensioned, extra light series, retainer type, with two shields. Dimensions were: bore=0.5000 in, O.D.=1.250 in, and width=0.3125 in. Examples of two manufacturers are: Fafnir (no. S5KDD) and New Departure (no. 77R8).

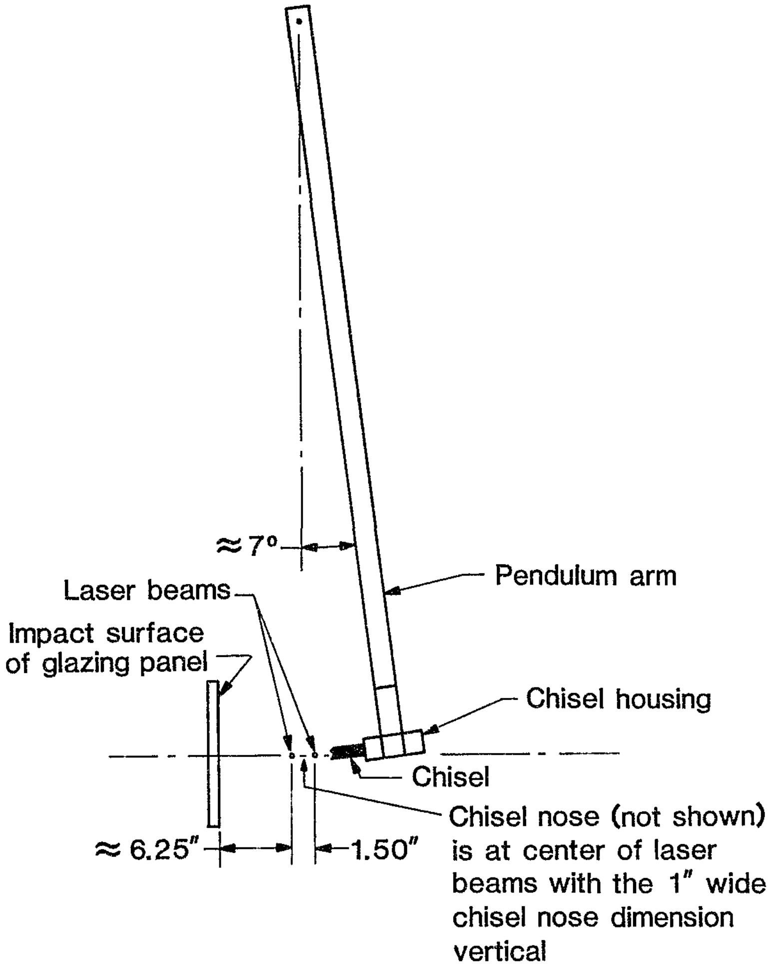


FIGURE 8b. *Position of pendulum, chisel nose, and laser beams when chisel velocity was measured.*

4.2 Time History of Impacts

A permanent record of each impact, the time interval between successive impacts, the total number of impacts, and the total time between the first and last impacts was obtained using a strip chart recorder as follows. A microswitch, mounted on the pendulum shaft support (fig. A2, app. A) and connected by an electrical circuit to the strip chart recorder, was activated by a thin metal flap attached to the pendulum arm each time the pendulum-held chisel impacted the test panel. The electrical circuit caused a deflection in the strip chart pen whenever the microswitch was activated by the metal flap.

4.3 Glazing Frame

The steel glazing frame (figs. 6a and 9), was designed to secure a 12×12-in glazing panel during testing and provided a 10×10-in exposed surface. Details of the glazing frame and its connections, and the positions of the test panel, the glazing tape, and the glazing clamp are shown in figures A4 and A5, appendix A.

During the testing program, the question was raised concerning movement of the glazing frame during impact. In an attempt to answer this question, a video tape recording of the movement of the glazing frame mounted in the pendulum apparatus during impact was taken. Based on the video tape recording, it appeared that the maximum movement of "face A" of the glazing frame (fig. A4, app. A) was insignificant, being about 1 mm or less. Based on these observations, it is believed that the glazing frame adequately constrained the movement of the glazing test panel during impact.

FIGURE 9. *Steel glazing frame, nonimpact side. Test panel no. 69, which had been tested, was secured to the glazing frame by the steel glazing clamp with bolts as shown.*

4.4 Torches, Torch Mounting and Position, and Propane Flow Rate

The two torches used are shown in figures 5, 6, and 7c. Drawings of the torches, including their positions relative to the glazing panel, are shown in figure A6, app. A. The torches were firmly secured to the base plate (fig. A6, app. A) to prevent their movement due to vibration and thermal effects that occurred during testing. Each torch consisted of four orifices that formed the corners of a square having a side length of 1.0 in. Each orifice consisted of a nozzle[7], with an orifice tip diameter of 0.070 in (fig. A6, app. A). One flowmeter was used in series with each torch to measure and set the flow rate of the commercial grade propane gas. Other than the nozzle with its 0.070 in orifice, the smallest constriction in the approximately 9 ft long tubing and connections which connected the flowmeter outlet with the torch was about 3/16 in. A propane gas flow rate[8] of 9.5 ± 0.5 ft^3/h at 70 °F and 14.7 psi absolute pressure through each torch was used to provide a reproducible flame geometry that extended roughly in a horizontal direction until it impinged on the test panel and then swept upwards on the panel. This flame geometry appeared to heat the central area of the impact surface of the glazing test panels in a reproducible manner as indicated by the sooting patterns, melted polycarbonate, or melted interlayer observed on the test panels after testing (chapter 7). Preliminary tests indicated that excessive drafts (air currents) near the torches and the test panel could significantly affect the flame shape. Air speed values from about 15 to 30 ft/min were measured in the large vented hood

[7] OX3—Blowpipe tip nozzles obtained from Veriflo Corp., Richmond, CA were used and found to perform satisfactorily.

[8] The pressure at the downstream side (at the flowmeter outlet) was about 0.8 in water (0.03 psi) above atmospheric pressure when the propane gas was flowing at the reference conditions (9.5 ft^3/h at 70 °F and 14.7 psi absolute pressure) and the torch was burning.

The flowmeters were calibrated with commercial grade propane gas flowing through them using a volumetric bell prover, with the flow measurement traceable to NBS. Calculation of the propane volume flow rate based on the air volume flow rate was not possible for the flowmeters used.

One scale setting on the flowmeters,which corresponded to the propane flow at the reference conditions, was used when testing all panels. The actual flow rate used during testing varied somewhat from the flow at the reference conditions due to day to day variations in the temperature and barometric pressure which occurred when testing the panels.

test facility (fig. 7a) using a hot-wire anemometer (anemometer measurement locations and procedures are given in chapter 5). The anemometer had an accuracy of ±2 ft/min and its calibration was traceable to NBS. These air speeds did not appreciably affect the flame geometry, yet were adequate to exhaust the combustion products.

5. TEST PROCEDURE

This chapter presents the test procedure developed to reproducibly deliver the required mechanical impact and heat application levels to a glazing panel.

The tests were performed in a large, vented hood maintained at about room temperature. The following checks were performed before, and periodically during the test program.

a. The pendulum apparatus (fig. A1, app. A) was checked to see that all bolts were tight.
b. The pendulum arm was checked to see that it made a 6° angle with the vertical in its cocked position, with the arm pressed against the pendulum backstop (fig. A1, app. A).
c. The velocity of the chisel nose was measured to be about 26 ft/s when the pendulum arm made an angle of about 7° with the vertical, near the lowest point of its arc (sec. 4.1, fig. 8a,b). When the velocity was measured, the chisel nose was about 7 in from the impact surface of the glazing panel and the 1-in wide chisel nose dimension was vertical. The pendulum arm was released from its cocked position when measuring the velocity.
d. Indentation depth from the impact of the chisel (fig. 2) into a 2-in thick lead brick (figs. 3 and 4) was checked to be 9 to 10 mm deep when releasing the pendulum arm from its cocked position. The impact surface of the lead brick was mounted in the same position as that of the impact surface of a glazing panel.

In addition, prior to beginning each test, the following steps were performed:

1. The pendulum arm was checked to be sure that it rotated freely on its bearings and that the lateral movement of the pendulum arm was not excessive (less than about 1/8 in).
2. The glazing panel was inspected for flaws, such as delaminations and cracks. Panels with flaws which would likely affect the test results were not used. The panel was labeled on its nonimpact surface near one corner of its bottom edge. The panel length, width, and thickness were measured. The thickness was measured at each of the four corners, using a dial caliper. An effort was made to randomize the testing order of the panels.
3. The glazing panel and the glazing tape were installed in the position shown in figure A4, appendix A, as follows. The tape was adhered to "face A" of the glazing frame (fig. A4, app. A) and to the glazing clamp (fig. A4, app. A). The protective paper was removed from the nonadhered side of the tape on the glazing frame and the glazing clamp. The panel was then seated on the two panel seats at the bottom of the glazing frame (fig. A4, app. A) such that the impact surface of the panel was toward "face A" and the center of the panel was located at the center of the 10×10-in opening in the glazing frame. The panel was then pressed against "face A" and held there by the tape. The opening of the glazing clamp was aligned with the opening of the glazing frame; the glazing clamp was then pressed against the nonimpact surface of the panel and bolted to the glazing frame. Eight bolts were used to secure the glazing clamp—four bolts were torqued to about 28 in-lb with a torque wrench and the other four bolts were finger tightened without tools (see fig. A4, app. A for bolt locations).
4. A chisel made of AISI 9254 alloy steel and which had been manufactured to generally be in conformance with Federal Specification GGG-C-313C, August 16, 1976, for a type IV, class 1, regular length, 8-in long cold chisel, with a width of

cutting edge, A (fig. 10), of 1 in was selected. Notable exceptions to conformance occurred in many cases for (a) hardness and (b) thickness of the cutting edge, D (fig. 10). (Chisel nose geometry and hardness measurements were taken—see sec. 6.2.) In almost all cases, a chisel was selected which had not been previously used in a test.

5. The chisel was inserted in the chisel housing so that the nonimpact end of the chisel was in contact with the end of the 1-in drill hole in the chisel housing (side view, fig. A3, app. A). The chisel was then secured by two screws in the chisel housing and was checked to see that the end of the chisel nose was close (either touching or within about 1/4 in) to the impact surface of the glazing panel when the pendulum arm was hanging freely. The 1-in wide chisel nose dimension was horizontal when testing the glazing panels.
6. The air speeds were measured with a hot-wire anemometer near the torch tips when the following three conditions were satisfied: (a) the hood exhaust fan was operating as it would during testing and the air flow had stabilized, (b) the glazing panel was mounted and, (c) no propane was flowing through the torches. The tip of the anemometer was positioned at the locations shown in figure 11. At each measuring location, the anemometer tip was rotated to determine the maximum air speed at that location, which was then recorded. The air speeds generally ranged from 15 to 30 ft/min.

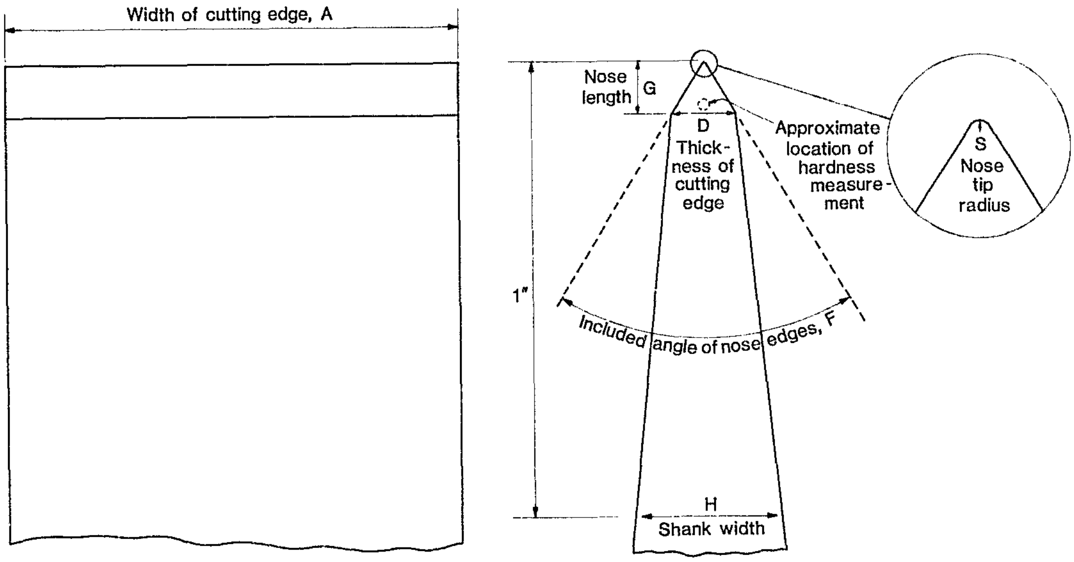


FIGURE 10. *Chisel geometrical nose variables measured. The approximate location of the hardness measurement is also shown.*

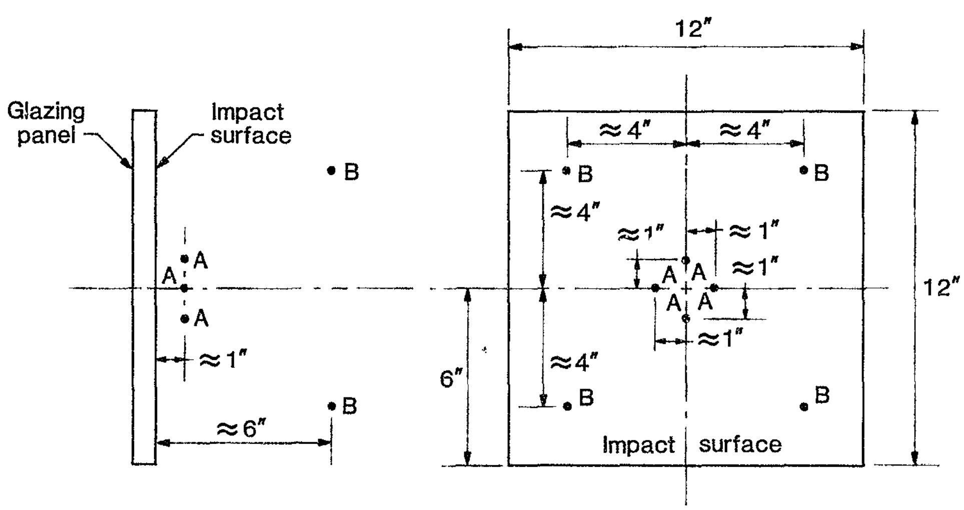


FIGURE 11. *Locations where hot-wire anemometer readings were taken. Hot-wire anemometer tip was rotated at each of the eight locations and the maximum reading obtained at each location was recorded.*

7. The two flowmeters (one for each torch) were adjusted (see footnote 8 in sec. 4.4) for a propane gas flow rate of 9.5 ft^3/h at 70 °F and 14.7 psi absolute pressure. The two torches were checked to be sure that the propane flame was being emitted uniformly from all eight orifices (four orifices for each of two torches). Each torch was checked to see that it was properly positioned (fig. A6, app. A) and that it was securely mounted.
8. The microswitch (sec. 4.2) and strip chart recorder were checked to be sure they were operating properly so that each impact and the time interval between impacts would be recorded. A chart speed of 2 mm/s was used. A stopwatch and a resettable timer, that produced a loud buzz to inform the person releasing the pendulum for the next impact, were checked.
9. The glazing panel was almost always tested within about 30 min of its installation in the glazing frame. The necessary safety precautions, which were taken during testing, were discussed with the testing personnel. Testing was a two-person operation.

The panel was tested as follows:

I. Operator 1 cocked the pendulum so that the pendulum arm made an angle of 6° with the vertical. Then Operator 2 started the strip chart recorder and started[9] the proper propane gas flow and then immediately ignited the torches using a prelit ignition stick (a long metal rod with lit flammable material at one end). As soon as the torches were lit and Operator 2 was out of the way, Operator 1 started the stopwatch and released the pendulum arm from its cocked position, allowing it to fall and impact the test panel.

II. At the sound of the first impact, Operator 2 set the timer to 5 s and Operator 1 caught the pendulum arm as it rebounded after impact and then lifted and cocked the pendulum arm.

III. At the sound of the buzz from the timer (when the set time had run down to 0 s), Operator 1 released the cocked pendulum. The time interval between successive impacts often was within the range of about 5.50 to 6.50 s for many of the panels tested. (Note: In order to adhere to the 5.50 to 6.50 s interval, the "5 s" setting may need to be adjusted depending on the operators.)

IV. At the sound of the next impact, Operator 2 set the timer to 5 s while Operator 1 caught, lifted, and cocked the pendulum arm.

V. Steps III and IV were repeated until the chisel-nosed impactor penetrated through to the nonimpact side of the test panel, as indicated by the impact end of the chisel clearly protruding through the nonimpact panel surface. (Bulging on the nonimpact surface without the end of the chisel protruding through that surface was not considered penetration.) When penetration occurred, Operator 1 stopped the stopwatch and Operator 2 shut off the propane gas flow.

6. CHARACTERISTICS OF GLAZING PANELS AND CHISELS USED FOR TESTS

Using the test developed, 63 glazing panels were tested to investigate (a) the ability of the test method to differentiate between the penetration resistance of glazing panels of different compositions and thicknesses and, (b) the repeatability of the test results for "identical" panels. This chapter provides the composition of the glazing panels tested and a description of the chisels used.

[9] The propane gas flow was started by opening one valve, which resulted in the proper gas flow as registered by the two preset in-line flowmeters.

6.1 Glazing Test Panels

Three types of security glazing, which covered a wide range of the glazing available for security applications, were investigated: laminated glass, glass-clad polycarbonate, and laminated polycarbonate. Tables 3, 4, and 5 show the number and variety of panels tested and their composition, including the thickness and sequence of the laminates. Figure 12 schematically shows the typical laminate sequences for the panels tested. An effort was made to test a range of security levels by varying the total specimen thickness and using several laminate sequences for each of the three glazing types. In developing a limited test program, panels from only one to three manufacturers for each glazing type were tested.

TABLE 3. *Composition of laminated glass test panels, including sequence and thickness of laminates.*

Manufacturer number	*Order of laminates[a] and thickness[b] (in)*									*No. of panels tested*
	G	*PVB*	*G*	*PVB*	*G*					
1	0.125[c]	0.060	0.125[c]	0.060	0.125[c]					2
2	0.107[c]	0.060	0.107[c]	0.060	0.107[c]					2
	G	*PVB*	*G*	*PVB*	*G*	*PVB*	*G*			
1	0.125[c]	0.060	0.125[c]	0.060	0.125[c]	0.060	0.125[c]			1
2	0.107[c]	0.060	0.107[c]	0.060	0.107[c]	0.060	0.107[c]			1
1	0.125[c]	0.090	0.125[c]	0.090	0.125[c]	0.090	0.125[c]			3
2	0.107[c]	0.090[d]	0.107[c]	0.090	0.107[c]	0.090	0.107[c]			3[d]
	G	*PVB*	*G*	*PVB*	*G*	*PVB*	*G*	*PVB*	*G*	
1	0.125[c]	0.090	0.125[c]	0.090	0.125[c]	0.090	0.125[c]	0.090	0.125[c]	2
2	0.107[c]	0.090	0.107[c]	0.090	0.107[c]	0.090	0.107[c]	0.090	0.107[c]	2

[a] G = glass; PVB = polyvinyl butyral interlayer.
[b] Nominal thicknesses as provided by the manufacturer are shown. Laminate thicknesses were difficult to measure, particularly with the PVB thicknesses. In some cases, the measured PVB thicknesses differed from their nominal thicknesses.
[c] Denotes chemically-strengthened glass.
[d] Two of the three panels had nominal PVB thicknesses of 0.060 in. Because the measured PVB thicknesses for these two panels were comparable to panels having PVB thicknesses of 0.090 in, the two panels were treated as having nominal PVB thicknesses of 0.090 in.

TABLE 4. *Composition of glass-clad polycarbonate test panels, including sequence and thickness of laminates.*

Manufacturer number	Order of laminates[a] and thickness[b] (in)									No. of panels tested
	G	*IL*	*PC*	*IL*	*G*					
1	0.125[c]	0.050	0.125	0.050	0.125[c]					2
2	0.107[c]	0.055[d]	0.125	0.055	0.107[c]					2
3	0.125[e]	0.050	0.125	0.050	0.125[e]					2
1	0.125[c]	0.050	0.250	0.050	0.125[c]					2
2	0.107[c]	0.055	0.250	0.055	0.107[c]					2
3	0.125[e]	0.050	0.250	0.050	0.125[e]					2
1	0.125[c]	0.050	0.375	0.050	0.125[c]					3
2	0.107[c]	0.055	0.375	0.055	0.107[c]					3
3	0.125[e]	0.050	0.375	0.050	0.125[e]					2
3	0.187[e]	0.050	0.375	0.050	0.187[e]					1
	G	*IL*	*PC*	*IL*	*PC*	*IL*	*PC*	*IL*	*G*	
1	0.125[c]	0.050	0.125	0.050	0.125	0.050	0.125	0.050	0.125[c]	2
2	0.107[c]	0.055	0.125	0.055	0.125	0.055	0.125	0.055	0.107[c]	3
3	0.125[e]	0.050	0.125	0.050	0.125	0.050	0.125	0.050	0.125[e]	2
3	0.187[e]	0.050	0.125	0.050	0.125	0.050	0.125	0.050	0.187[e]	1

[a] G = glass; PC = polycarbonate; IL = proprietary interlayer.
[b] Nominal thicknesses as provided by the manufacturer for the glass, interlayer, and polycarbonate laminates are shown.
[c] Denotes chemically-strengthened glass.
[d] One panel had interlayer thicknesses of about 0.025 in.
[e] Denotes heat-strengthened glass.

TABLE 5. *Composition of laminated polycarbonate test panels, including sequence and thickness of laminates (manufacturer number 4).*

Order of laminates[a] and their thickness[b] (in)									Number of panels tested
PC									
0.500									4
PC	*IL*	*PC*							
0.1875	0.034	0.1875							2
PC	*IL*	*PC*	*IL*	*PC*					
0.125	0.034	0.250	0.034	0.125					2
0.125	0.034	0.500	0.034	0.125					5
PC	*IL*	*PC*	*IL*	*PC*	*IL*	*PC*			
0.125	0.034	0.500	0.017	0.500	0.034	0.125			3
PC	*IL*	*PC*	*IL*	*PC*	*AIR*	*G*[c]	*PVB*[c]	*G*[c]	
0.125	0.034	0.250	0.034	0.125	0.250	0.110	0.040	0.110	2

[a] G = glass; PC = polycarbonate; IL = proprietary interlayer; PVB = polyvinyl butyral interlayer; AIR = air gap.
[b] Nominal thicknesses as provided by the manufacturer for the polycarbonate and interlayer laminates are shown.
[c] Manufacturer not identified; thicknesses shown are based on measurements and are considered rough estimates.

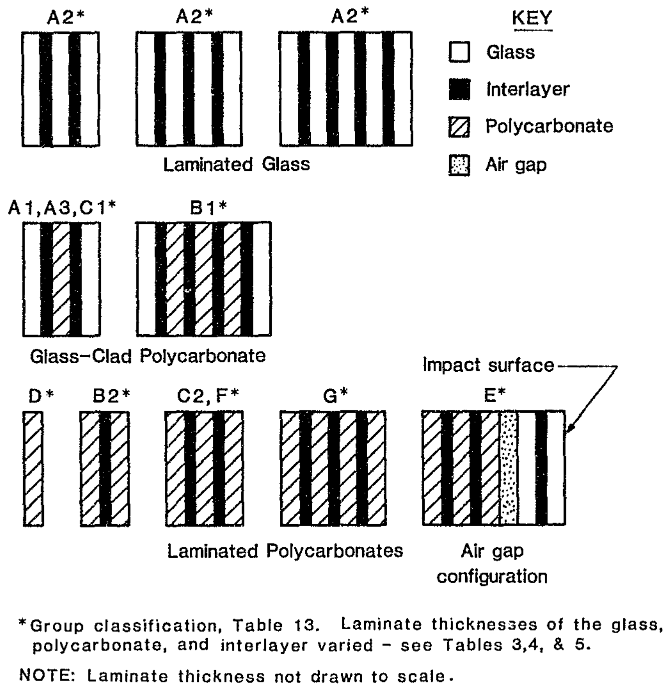


FIGURE 12. *Typical laminate sequences for the laminated glass, glass-clad polycarbonate, and laminated polycarbonate test panels.*

6.2 Chisels

The chisels used in testing were provided by one manufacturer. They had a cutting edge width of 1 in, a length of 7.875 to 8.188 in, and a weight of 1.3 lb, and were made of AISI 9254 alloy steel. They generally met Federal Specification GGG-C-313C (August 16, 1976) for type IV, class 1, regular length, 8-in long, cold chisels with a width of cutting edge, A (fig. 10), of 1 in. With each chisel used in testing, Rockwell C scale hardness measurements were taken at the chisel nose; geometrical nose features which were believed to possibly affect the test results were also measured (chapter 7 discusses the effects of the chisel characteristics on the test results). Figure 10 shows which variables were measured, while table 6 provides the range in the variables for the chisels used in testing the glazing. Chisels which deviated from the specification for the nose angle of 57 to 72° were not used except in four cases where the nose angle was between 72 and 73°. With one exception, chisels having a nose-tip radius exceeding 0.003 in were not used and, except for one case, chisels with hardness values less than 40 were not used. The hardness values for many of the chisels used were below the minimum of 53 in the specification. With one exception, all chisels used had hardness values less than the maximum hardness value of 59 in the specification. With many of the chisels used, the thickness of the cutting edge exceeded the maximum specification value of 0.141 in. The effects of these differences (in hardness and the thickness of the cutting edge) on the test results were not considered to be significant (chapter 7). With two exceptions, a new chisel was used for each test.

TABLE 6. *Range of geometrical and hardness variables of chisels used in testing panels.*

Variable (see fig. 10)	*Minimum*	*Maximum*
Nose tip radius, S (in)	0.001	0.005
Included angle of nose edges, F (°)	60.75	72.87
Nose length, G (in)	0.100	0.129
Thickness of cutting edge, D (in)	0.123	0.163
Width of cutting edge, A (in)	1.000	1.050
Shank width, H (in)	0.314	0.351
Hardness (Rockwell C scale)	31.5[a]	60

[a] Average of 23 and 40.

7. TEST RESULTS, ANALYSIS, AND DISCUSSION

This chapter presents the results, analysis, and a discussion of the 63 glazing panels tested using the test method developed.

7.1 Pendulum Calibration

Periodically during the testing program, the velocity near impact (fig. 8b) and the indentation depth into a 2-in thick lead brick of the chisel-nosed impactor were measured using the chisel shown in figure 2. In most cases, the velocity values were close to 26 ft/s and usually agreed well with the calculated value of 26.5 ft/s, while the indentation depths were always 9 to 10 mm.

7.2 Penetration Parameters and Criteria

The test results are presented in terms of the two parameters chosen to describe penetration of the glazing test panels:

(a) the number of impacts to penetration and

(b) the flame exposure time, defined as the time duration from when the flame is first applied (just prior to the first impact) to the final impact which results in penetration of the test panel.

The penetration criterion was that the chisel-nosed impactor penetrated through to the nonimpact surface of the test panel as indicated by the impact end of the chisel clearly protruding through the nonimpact panel surface. (Bulging on the nonimpact surface without the chisel end protruding through that surface did not constitute penetration.)

The flame exposure time was determined in two ways: (1) measured with a stopwatch and, (2) estimated by using the strip chart output of the time interval between the first impact and the last impact which caused penetration. As given in the test procedure, the pendulum was released to deliver the first impact as soon as the torches were ignited. Thus, the impactor chisel nose fell and came in contact with the test panel for the first time several seconds from the time the torches were ignited. This resulted in the flame exposure time as estimated from the strip chart output being smaller than the flame exposure time measured by the stopwatch, by the several seconds required for the pendulum to be released and fall during its first impact.

Flame exposure times from the stopwatch were used because they were more accurate than the times based on the strip chart output. There were cases, however, where the stopwatch times were not taken properly. In these cases (see footnotes in tables 7, 8, and 9), the flame exposure time was based on the strip chart output, with a value of 3 s used as an estimate of the time duration from when the torches were ignited to when the chisel-nosed impactor contacted the panel at the first impact. Figure 13 illustrates a sample strip chart output showing the time history of the impacts and the estimated flame exposure time.

7.3 Test Results

Tables 7 (laminated glass), 8 (glass-clad polycarbonate), and 9 (laminated polycarbonate) present the following information for each panel tested:

- average total specimen thickness, measured with a dial caliper. The average of four thickness measurements, one taken at each of the four corners of the panel, is shown.
- number of impacts to penetration
- flame exposure time
- geometrical chisel-nose variables shown in figure 10. The measurements were taken with an optical comparator using a 10 power magnification lens.
- chisel hardness, Rockwell C scale, at nose. In almost all cases, one hardness reading was taken on each chisel near the nose tip (fig. 10).

TABLE 7. *Number of impacts to penetration, flame exposure time, and chisel-nose geometry and hardness values for laminated glass test panels.*

Test panel number	Manufacturer number	Number of glass laminates	Polyvinyl butyral thickness[a] (in)	Total[b] panel thickness (in)	Number of impacts to penetration	Flame[c] exposure time (s)	Chisel-nose geometry[d] and hardness (fig. 10): Nose-tip radius, S (in)	Included angle of nose edges, F (°)	Nose length, G (in)	Thickness of cutting edge, D (in)	Width of cutting edge, A (in)	Shank width, H (in)	Hardness (Rockwell C scale)
29	1	3	0.060	0.495	3	15	0.001	63.25	0.123	0.147	1.040	0.331	46
54	1	3	0.060	0.493	2	12	0.001	63.50	0.117	0.140	1.045	0.327	60
14	2	3	0.060	0.446	4	29[e]	0.002	72.00	0.112	0.161	1.025	0.351	51
39	2	3	0.060	0.442	1	≈3	0.001	61.17	0.113	0.138	1.032	0.315	52
61	1	4	0.060	0.658	4	26	0.001	63.00	0.120	0.147	1.040	0.324	51
35	2	4	0.060	0.628	3	15	0.001	61.83	0.129	0.156	1.040	0.334	53
15	1	4	0.090	0.754	4	25[e]	0.002	70.75	0.101	0.144	1.025	0.334	50
18	1	4	0.090	0.758	4	21	0.002	71.50	0.110	0.156	1.032	0.338	51
55	1	4	0.090	0.754	4	23	0.001	62.00	0.113	0.139	1.040	0.321	51
7	2	4	0.090	0.703	3	19	0.001	62.50	0.111	0.132	1.032	0.319	43
23	2	4	0.090	0.720	3	17[e]	0.001	61.83	0.107	0.130	1.035	0.319	45
66	2	4	0.090	0.710	3	15	0.001	61.67	0.115	0.137	1.030	0.321	50
41	1	5	0.090	0.861	4	25	0.001	61.00	0.108	0.127	1.025	0.320	42
16	1	5	0.090	0.852	4	24	0.001	62.00	0.110	0.133	1.045	0.314	50
11	2	5	0.090	0.900	5[f]	32	0.002	72.25	0.105	0.149	1.030	0.337	45
52	2	5	0.090	0.906	4	22	0.002	71.00	0.106	0.152	1.022	0.335	43

[a] Nominal thicknesses provided by the manufacturer are shown for individual interlayer thicknesses. Table 3 contains further details.
[b] Average of four thickness measurements, one at each of the four corners.
[c] Measured by stopwatch unless noted otherwise.
[d] Optical comparator with a 10 power magnification lens used.
[e] Estimate determined from strip chart output as duration from first to last impact plus 3 s (sec. 7.2).
[f] Asymmetrical sooting pattern.

TABLE 8. *Number of impacts to penetration, flame exposure time, and chisel-nose geometry and hardness values for glass-clad polycarbonate test panels.*

							Chisel-nose geometry[d] and hardness (fig. 10)						
Test panel number	Manufacturer number	Number of polycarbonate laminates	Total[a] polycarbonate thickness (in)	Total[b] panel thickness (in)	Number of impacts to penetration	Flame[c] exposure time (s)	Nose-tip radius, S (in)	Included angle of nose edges, F (°)	Nose length, G (in)	Thickness of cutting edge, D (in)	Width of cutting edge, A (in)	Shank width, H (in)	Hardness (Rockwell C scale)
28	1	1	0.125	0.455	2	12	0.001	62.75	0.108	0.135	1.025	0.320	45
45	1	1	0.125	0.457	2	11	0.001	61.25	0.101	0.123	1.042	0.320	45
31	2	1	0.125	0.394	2	10	0.001	61.50	0.120	0.141	1.050	0.338	49
49	2	1	0.125	0.388	2	11	0.001	61.50	0.119	0.138	1.037	0.320	50
25	3	1	0.125	0.486	2	11	0.001	62.25	0.112	0.133	1.050	0.324	55
46	3	1	0.125	0.476	2	10	0.001	72.87	0.105	0.158	1.020	0.345	44
22	1	1	0.250	0.570	6	34	0.001	61.42	0.123	0.143	1.040	0.324	40
36	1	1	0.250	0.575	6	34	0.001	62.25	0.113	0.135	1.015	0.323	46
19	2	1	0.250	0.514	5	27	0.001	72.75	0.105	0.154	1.032	0.336	46
51	2	1	0.250	0.506	4	22	0.001	62.17	0.112	0.139	1.030	0.324	45
32	3	1	0.250	0.581	4	22	0.001	62.25	0.121	0.144	1.035	0.323	45
37	3	1	0.250	0.582	4	22	0.001	64.00	0.119	0.143	1.035	0.326	50
21	1	1	0.375	0.705	19	120	0.001	62.25	0.122	0.149	1.040	0.337	51
48	1	1	0.375	0.696	15	91	0.001	62.00	0.115	0.139	1.032	0.318	55
57	1	1	0.375	0.683	14	82	0.001	62.30	0.107	0.131	1.037	0.320	52
10	2	1	0.375	0.618	14	100	0.001	62.33	0.115	0.135	1.030	0.320	54
43	2	1	0.375	0.619	15	88	0.001	63.75	0.113	0.134	1.040	0.325	50
68	2	1	0.375	0.620	15	87[e]	0.001	61.67	0.119	0.145	1.038	0.320	49
5	3	1	0.375	0.833	18	131[e]	0.001	72.00	0.114	0.161	1.025	0.348	31.5[f]
34	3	1	0.375	0.715	17	99	0.001	71.25	0.100	0.140	1.025	0.329	44
38	3	1	0.375	0.714	16	95	0.001	61.00	0.111	0.138	1.032	0.323	49
30	1	3	0.375	0.813	13	77[e]	0.001	63.50	0.111	0.137	1.030	0.317	53
47	1	3	0.375	0.807	12	72	0.001	62.00	0.110	0.128	1.020	0.316	45
3	2	3	0.375	0.700	11[g]	82[e]	0.002	72.50	0.110	0.161	1.025	0.342	49
50	2	3	0.375	0.698	8	47	0.001	71.75	0.100	0.146	1.032	0.334	48
58	2	3	0.375	0.696	8	46	0.001	62.50	0.107	0.129	1.032	0.314	55
8	3	3	0.375	0.930	11	80	0.003	71.67	0.100	0.148	1.020	0.330	43
44	3	3	0.375	0.808	10	62[e]	0.001	61.17	0.117	0.142	1.042	0.321	50
70	3	3	0.375	0.817	10	58	0.001	62.25	0.117	0.141	1.037	0.317	55

[a] Thickness of polycarbonate laminates taken collectively; entries based on nominal thicknesses provided by manufacturers; table 4 contains further details.
[b] Average of four thickness measurements, one at each of the four corners.
[c] Measured by stopwatch unless noted otherwise.
[d] Optical comparator with a 10 power magnification lens used.
[e] Estimate determined from strip chart output as duration from first to last impact plus 3 s (see sec. 7.2).
[f] Average of 23 and 40.
[g] Asymmetrical sooting pattern.

TABLE 9. *Number of impacts to penetration, flame exposure time, and chisel-nose geometry and hardness values for laminated polycarbonate test panels for manufacturer number 4.*

						Chisel-nose geometry[d] and hardness (fig. 10)						
Test panel number	Number of polycarbonate laminates	Total[a] polycarbonate thickness (in)	Total[b] panel thickness (in)	Number of impacts to penetration	Flame[c] exposure time (s)	Nose-tip radius, S (in)	Included angle of nose edges, F (°)	Nose length, G (in)	Thickness of cutting edge, D (in)	Width of cutting edge, A (in)	Shank width, H (in)	Hardness (Rockwell C scale)
17	2	0.375	0.380	10	63	0.001	61.25	0.110	0.130	1.015	0.318	55
40	2	0.375	0.382	10	57	0.002	71.17	0.102	0.146	1.020	0.332	45
20	3	0.500	0.531	19	117	0.001	61.75	0.110	0.133	1.032	0.318	51
26	3	0.500	0.539	21	124	0.001	63.00	0.112	0.137	1.020	0.327	49
2	1	0.500	0.518	26	203[e]	0.005	71.00	0.111	0.163	1.025	0.348	50
60	1	0.500	0.480	23	137	0.001	61.75	0.104	0.124	1.022	0.317	45
64	1	0.500	0.479	22	129	0.001	62.50	0.105	0.131	1.031	0.320	53
67	1	0.500	0.473	23	136	0.001	62.50	0.120	0.143	1.035	0.342	55
33	3	0.500	1.063[f]	33	207[e]	0.003	72.00	0.105	0.153	1.000	0.341	50
42	3	0.500	1.055[f]	36	221	0.001	70.10	0.106	0.148	1.025	0.339	40
12	3	0.750	0.805	76[g]	580	0.001	61.50	0.111	0.135	1.032	0.322	54
59	3	0.750	0.815	75	471	0.001	62.17	0.116	0.142	1.032	0.327	55
63	3	0.750	0.813	75	457	0.001	60.75	0.113	0.140	1.045	0.327	55
65	3	0.750	0.809	75	449	0.001	62.00	0.123	0.150	1.020	0.333	50
69	3	0.750	0.811	69	417	0.001	62.00	0.124	0.143	1.035	0.332	55
53	4	1.250	1.316	114	697	0.001	61.25	0.109	0.134	1.030	0.321	50
56	4	1.250	1.345	110	666	0.001	62.50	0.113	0.137	1.035	0.315	52
62	4	1.250	1.315	116	706	0.001	61.00	0.114	0.131	1.032	0.318	48

[a] Thickness of polycarbonate laminates taken collectively; entries based on nominal thicknesses provided by manufacturer. Table 5 contains further details.
[b] Average of four thickness measurements, one at each of the four corners.
[c] Measured by a stopwatch unless noted otherwise.
[d] Optical comparator with a 10 power magnification lens used.
[e] Estimate determined from strip chart output as duration from first to last impact plus 3 s (see sec. 7.2).
[f] Configuration with air-gap (fig. 12).
[g] Chisel impact location about 1.1 in off center.

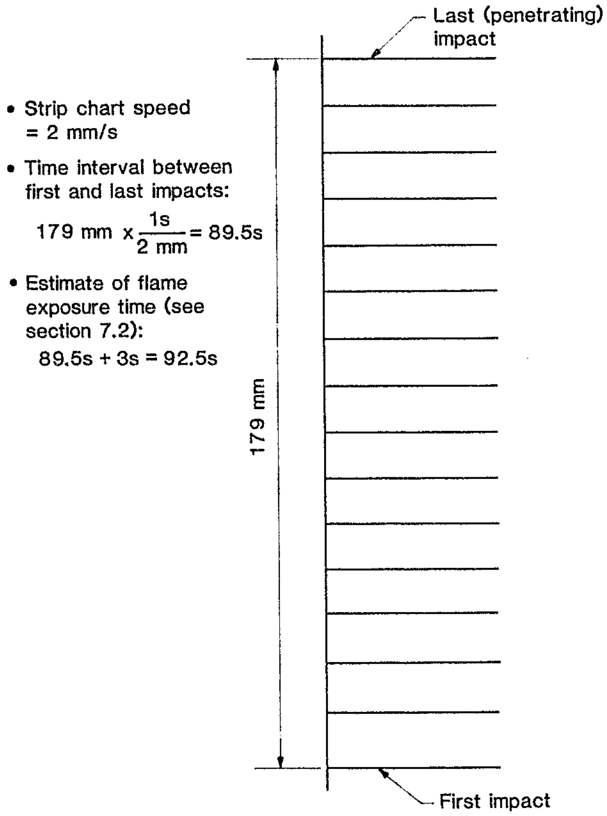


FIGURE 13. *Sample strip chart recorder output showing the time history of the 16 impacts required for penetration. The time interval between the first and last impacts and an estimate of the flame exposure time are also shown.*

7.4 Analysis of Test Results

The time intervals between successive impacts often were within the range of about 5.50 to 6.50 s for many of the panels tested. Because the time intervals between successive impacts were generally close in value, the number of impacts to penetration and the flame exposure time for each test were closely correlated (correlation coefficient=99.6 percent). Hence, either the number of impacts to penetration or the flame exposure time could be used to analyze the test results. In this chapter, the number of impacts to penetration was used.[10]

Tables 10 (laminated glass), 11 (glass-clad polycarbonate), and 12 (laminated polycarbonate) provide the minimum, maximum, average, standard deviation, and coefficient of variation values of the number of impacts to penetration for test panels from each manufacturer and selected groupings of manufacturers.

The repeatability of the number of impacts to penetration of "identical" panels having the same glazing type (e.g., laminated glass), manufacturer (e.g., no. 2), and composition (e.g., five glass laminates with 0.090-in interlayer thickness) was difficult to determine from the test results. The small number of replicates (usually two or three) performed for "identical" panels prevented an accurate determination of the repeatability. In this study, the coefficient of variation[11] values were used to provide an indication of the repeatability. Many of the sets of "identical" panels (tables 10, 11, and 12) had coefficient of variation values of 10 percent or less, which was believed to be an indication that the test method has reasonably good repeatability.

[10] When comparing the same test panels, the variability as measured by the coefficient of variation was often smaller for the number of impacts to penetration as compared to the flame exposure time.

[11] It should be noted that the coefficient of variation values may have been affected by the wide range (1 to 116 impacts) in the number of impacts to penetration for all the panels tested. The possible dependence of the coefficient of variation on the number of impacts to penetration should be considered when using the coefficient of variation values.

TABLE 10. *Minimum, maximum, average, standard deviation, and coefficient of variation values of the number of impacts to penetration for laminated glass test panels.*

Manufacturer number	Number of glass laminates	Polyvinyl butyral thickness[a] (in)	Number of panels tested	Number of impacts to penetration				
				Min.	Max.	Avg.	Std. dev.	Cov[b] %
1	3	0.060	2	2	3	2.50	0.707	28.3
2	3	0.060	2	1	4	2.50	2.12	84.9
1,2	3	0.060	4	1	4	2.50	1.29	51.6
1	4	0.060	1	4	4	c	c	c
2	4	0.060	1	3	3	c	c	c
1,2	4	0.060	2	3	4	3.50	0.707	20.2
1	4	0.090	3	4	4	4.00	0.000	0.0
2	4	0.090	3	3	3	3.00	0.000	0.0
1,2	4	0.090	6	3	4	3.50	0.548	15.6
1,2	4	0.060,0.090	8	3	4	3.50	0.534	15.3
1	5	0.090	2	4	4	4.00	0.000	0.0
2	5	0.090	2	4	5	4.50	0.707	15.7
1,2	5	0.090	4	4	5	4.25	0.500	11.8
1,2	4,5	0.060,0.090	12	3	5	3.75	0.622	16.6
1,2	3,4,5	0.060,0.090	16	1	5	3.44	0.964	28.0

[a] Nominal thicknesses provided by the manufacturer are shown for individual interlayer thicknesses. Table 3 contains further details.
[b] Cov % = Coefficient of variation, in percent, defined as: (standard deviation/average) × 100.
[c] Calculation not possible—one panel tested.

TABLE 11. *Minimum, maximum, average, standard deviation, and coefficient of variation values of the number of impacts to penetration for glass-clad polycarbonate test panels.*

Manufacturer number	Number of polycarbonate laminates	Total[a] polycarbonate thickness (in)	Number of panels tested	Number of impacts to penetration				
				Min.	Max.	Avg.	Std. dev.	Cov[b] %
1	1	0.125	2	2	2	2.00	0.00	0.00
2	1	0.125	2	2	2	2.00	0.00	0.00
3	1	0.125	2	2	2	2.00	0.00	0.00
1,2,3	1	0.125	6	2	2	2.00	0.00	0.00
1	1	0.250	2	6	6	6.00	0.00	0.00
2	1	0.250	2	4	5	4.50	0.707	15.7
3	1	0.250	2	4	4	4.00	0.00	0.00
1,2,3	1	0.250	6	4	6	4.83	0.983	20.3
1	1	0.375	3	14	19	16.0	2.65	16.5
2	1	0.375	3	14	15	14.7	0.577	3.94
3	1	0.375	3	16	18	17.0	1.00	5.88
1,2,3	1	0.375	9	14	19	15.9	1.76	11.1
1	3	0.375	2	12	13	12.5	0.707	5.66
2	3	0.375	3	8	11	9.00	1.73	19.2
3	3	0.375	3	10	11	10.3	0.577	5.59
1,2,3	3	0.375	8	8	13	10.4	1.77	17.0

[a] Thickness of polycarbonate laminates taken collectively; entries based on nominal thicknesses provided by the manufacturers. Table 4 contains further details.
[b] Cov % = Coefficient of variation, in percent, defined as: (standard deviation/average) × 100.

TABLE 12. *Minimum, maximum, average, standard deviation, and coefficient of variation values of the number of impacts to penetration for laminated polycarbonate test panels for manufacturer number 4.*

Number of polycarbonate laminates	*Total[a] polycarbonate thickness (in)*	*Number of panels tested*	*Number of impacts to penetration*				
			Min.	*Max.*	*Avg.*	*Std. dev.*	*Cov.[b] %*
2	0.375	2	10	10	10.0	0.00	0.00
3	0.500	2	19	21	20.0	1.41	7.07
1	0.500	4	22	26	23.5	1.73	7.37
3	0.500[c]	2	33	36	34.5	2.12	6.15
3	0.750	5	69	76	74.0	2.83	3.82
4	1.250	3	110	116	113.3	3.06	2.69

[a] Thickness of polycarbonate laminates taken collectively; entries based on nominal thicknesses provided by the manufacturer. Table 5 contains further details.

[b] Cov % = Coefficient of variation, in percent, defined as: (standard deviation/average) × 100.

[c] Configuration with air gap (fig. 12).

The laminated glass in the air-gap configuration (fig. 12) provided some shielding of the polycarbonate from the flame. This shielding effect was most likely the cause of the increase in the number of impacts to penetration in the air-gap panels (nos. 33 and 42, table 9) as compared to comparable panels (nos. 20 and 26, table 9), which did not have the air-gap and laminated glass.

As shown in table 11, the number of impacts to penetration was greater for the glazing with a monolithic thickness of 0.375 in polycarbonate as compared to the glazing with three 0.125 in layers of polycarbonate.

Figure 14 is a plot of the number of impacts to penetration versus the total polycarbonate thickness (thickness of polycarbonate laminates taken collectively) of both glass-clad polycarbonate and laminated polycarbonate panels. Laminated glass panels are also plotted at a zero polycarbonate thickness value. (The grouping arrangement used in fig. 14 is shown in table 13 and is discussed below.) Figure 14 shows there is an increase in the number of impacts to penetration as the polycarbonate thickness increases. For example, with one exception, all laminated glass panels and panels having a total polycarbonate thickness of 0.25 in or less were penetrated in two to six impacts. In contrast, panels with total polycarbonate thicknesses of 0.75 and 1.25 in were penetrated on the average in 74 and 113 impacts, respectively.

To illustrate that the glazing panels could be ranked according to their penetration resistance under the specified test conditions, the panels were grouped as shown in table 13. It is recognized that many grouping arrangements are possible—table 13 is an example of one grouping arrangement. The minimum, maximum, average, standard deviation, and coefficient of variation values for groups A through G are given in table 13. The minimum and the maximum number of impacts to penetration for the groups are shown graphically in figure 14. As evident from table 13, 60 percent of the panels tested were penetrated in 13 or fewer impacts.

When comparing successive groups (A with B, B with C... and F with G), the difference between the average number of impacts to penetration for each pair of successive groups was six to seven impacts for groups A, B, C, D; 11 impacts for groups D and E; and 39 impacts for groups E, F and G. The Student's t statistic was used to give an indication if the successive group averages differed significantly from one another (app. C). Due to the small number of panels in some groups (e.g., two or three) and, in some cases the apparent differences in variability when comparing successive groups, quantitative statistical significance levels were not determined. Values of t of about three or more, however, were interpreted as being statistically significant in this study. As shown in table C1, appendix C, the t values were five[12] or more, indicating that there was most likely a statistically significant difference in the average number of impacts to penetration when comparing each pair of successive groups.

[12] If the flame exposure time is used instead of the number of impacts to penetration when comparing successive group averages, the t values based on the flame exposure time are less than the corresponding t values based on the number of impacts to penetration. With one exception (t = 2.4, group D compared to group E), the t values based on the flame expousre time exceeded 3.0.

The chisel-nose geometrical and hardness variables which were measured (fig. 10, tables 7 to 9) did not appear to substantially affect the number of impacts to penetration—this may be due to the limited range of these variables (table 6). To determine the importance of the effects of chisel-nose geometry and hardness on the number of impacts to penetration, a systematic study designed to quantify these effects would be required, using a larger range in the nose geometry and hardness variables than used in this study.

In most cases, the sooting, melting (polycarbonate or interlayer), and glass cracking patterns on each panel were roughly symmetrical with respect to a vertical line passing through the impact location on the panel (e.g., fig. 15). Tables 7 and 8 show two individual cases (see footnotes) where the sooting pattern was asymmetrical; in one of these cases the lack of symmetry may have caused an increase in the number of impacts to penetration (panel no. 3 as compared to panel nos. 50 and 58, table 8).

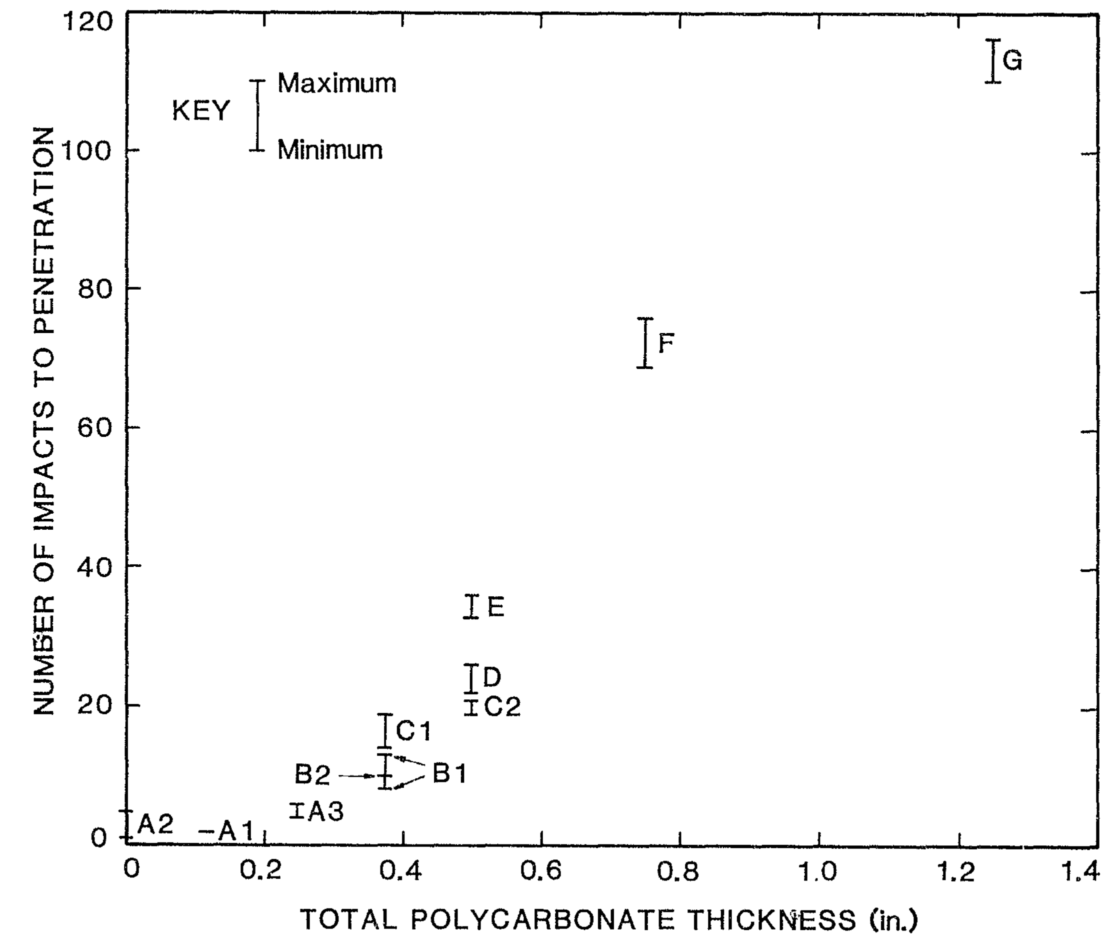


FIGURE 14. *Number of impacts to penetration versus total polycarbonate thickness (thickness of polycarbonate laminates taken collectively)—see table 13 for definition of groups A1,A2, ...F,G, and the number of panels in each group.*

TABLE 13. *An example of one grouping arrangement for the test results showing the minimum, maximum, average, standard deviation, and coefficient of variation values of the number of impacts to penetration for each group.*

Group	Number of panels tested	Panel description	Total[a] poly-carbonate thickness (in)	Number of polycarbonate laminates	Number of impacts to penetration				
					Min.	Max.	Avg.	Std. dev.	Cov[b] %
A1	6	Glass-clad polycarbonate	0.125	1	2	2	2.00	0.00	0.00
A2	16	All laminated glass panels	c	c	1	5	3.44	0.964	28.0
A3	6	Glass-clad polycarbonate	0.250	1	4	6	4.83	0.983	20.3
A	28				1	6	3.43	1.26	36.7
B1	8	Glass-clad polycarbonate	0.375	3	8	13	10.4	1.77	17.0
B2	2	Laminated polycarbonate	0.375	2	10	10	10.0	0.00	0.00
B	10				8	13	10.3	1.57	15.2
C1	9	Glass-clad polycarbonate	0.375	1	14	19	15.9	1.76	11.1
C2	2	Laminated polycarbonate	0.500	3	19	21	20.0	1.41	7.07
C	11				14	21	16.6	2.33	14.0
D	4	Monolithic polycarbonate	0.500	1	22	26	23.5	1.73	7.37
E	2	Laminated[d] glass and laminated polycarbonate (air gap configuration)	0.500	3	33	36	34.5	2.12	6.15
F	5	Laminated polycarbonate	0.750	3	69	76	74.0	2.83	3.82
G	3	Laminated polycarbonate	1.250	4	110	116	113.3	3.06	2.69

[a] Thickness of polycarbonate laminates taken collectively; entries based on nominal thicknesses provided by the manufacturers. Tables 4 and 5 contain further detail.

[b] Cov % = Coefficient of variation, in percent, defined as: (standard deviation/average) × 100.

[c] No polycarbonate—see table 3 for composition.

[d] Laminated glass provided some shielding of the polycarbonate from the flame (see discussion in sec. 7.4).

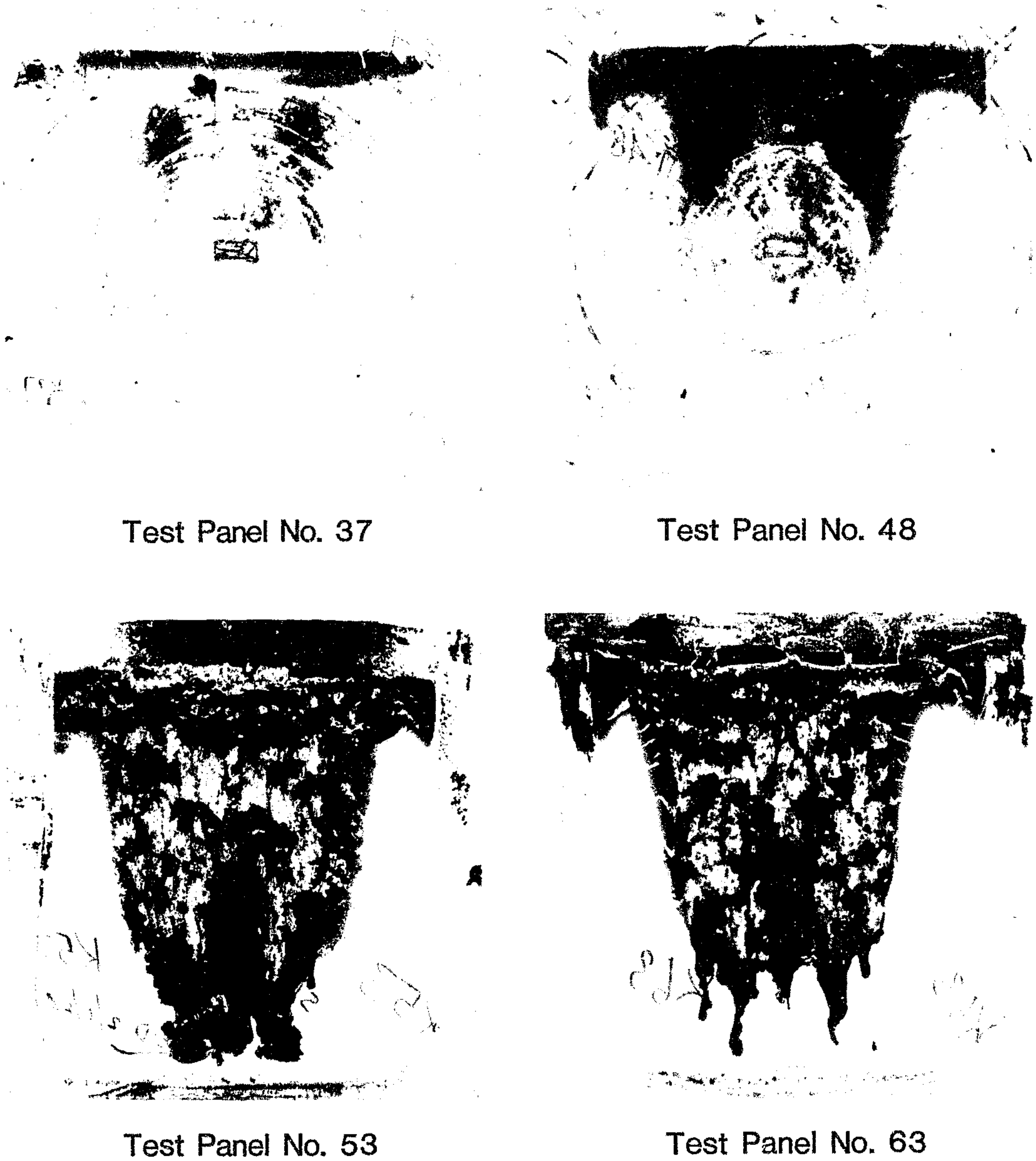


FIGURE 15. *Examples of (a) symmetrical sooting and glass cracking and (b) symmetrical sooting and melting. Impact surfaces shown.*

7.5 Use and Limitations of Test Method

The grouping example of the previous section (7.4) indicates that the test method can be used to rank the panels according to their penetration resistance as determined under the test conditions, provided the variability of the test results is incorporated in the ranking.

Penetration, as defined in the test method developed in this report, results in a hole that is about 1 inch in its longest dimension. The time and energy required to create larger holes, such as one large enough for a person or various objects to fit through, cannot be predicted on the basis of the test method and test results of this report, because of the many ways mechanical impact and heat can be applied. Additional research needs to be conducted to relate the test method to the time and energy needed to create larger-sized holes (see sec. 8.2). The test method is applicable only for simulating the specified combined attack of mechanical impact and heat application resulting in a small, local, penetration in the glazing. Other attack scenarios and their corresponding penetration modes for glazing materials, connections, framing, and assemblages are not covered by the test method (see sec. 8.2).

Additional research needs to be conducted before performance criteria can be established for the test method (see sec. 8.2).

Further research is also needed to determine the relative effects of heat application and mechanical impact on the number of impacts required for penetration. For example, preliminary tests were conducted on five panels according to the test method, but without heat (flame) applied. With three panels having a total polycarbonate thickness of 0.375 in (two glass-clad polycarbonates and one polycarbonate laminate), there appeared to be a substantial increase in the number of impacts to penetration for the panels tested without flame as compared to comparable panels tested with flame. For two laminated glass panels (one with four glass laminates, the other with five glass laminates), however, there appeared to be little or no difference in the number of impacts to penetration for the panels tested without flame as compared to comparable panels tested with flame. Perhaps the time duration (about 25 s) of the flame application in the case of the laminated glass panels used in the comparison was too short to affect their penetration resistance.

8. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this report, the following conclusions and recommendations are made:

8.1 Conclusions

1. A test method has been developed for transparent, high-security glazing. The test method is intended to simulate a realistic attack scenario involving the simultaneous application of mechanical impact with a chisel-nosed tool and heat using a propane diffusion (yellow) flame.
2. The test apparatus, which can be easily constructed, reproducibly applies mechanical impact and heat to the test panels. The test is simple to perform.
3. Tests on glazing panels, which covered a wide range of the glazing available for security applications, indicated a wide range in the number of impacts (1 to 116) required to penetrate the glazing. Increases in polycarbonate thickness resulted in increases in the number of impacts required for penetration.
4. The test method can be used to evaluate the penetration resistance of glazing materials when they are subjected to the specific test conditions. The test results can be used to rank the penetration resistance of the glazing materials, provided the variability of the test results is incorporated in the ranking.
5. Penetration, as defined in the test method, results in a hole that is about 1 inch in its longest dimension. The time and energy required to create larger holes, such as those large enough for a person or a smuggled object to fit through, cannot be predicted on the basis of the test method and test results of this report, because of the many ways mechanical impact and heat can be applied.
6. The test method developed is applicable only for simulating the specified combined attack of mechanical impact and heat application directed locally on a glazing test panel having the specified surface area. The test method developed does not apply to other attack scenarios and their corresponding modes of penetration.

8.2 Recommendations

1. With regard to the test method developed, the following additional research should be considered:

   (a) Determination of the relative effects of the application of mechanical impact and heat on the number of impacts required for penetration.

   (b) Modification of the test method to create larger-sized holes under combined mechanical impact and heat application.

2. Performance criteria for the test method developed should be established after (a) the test method is thoroughly evaluated with respect to its repeatability within, and reproducibility among laboratories, using a statistically designed experiment and round-robin testing, and (b) the relationship is determined between the number of impacts required for penetration using the test method developed and the time and number of impacts required by a team of able-bodied men using chisel-tipped hammers and a method of heat application to create holes large enough to be of importance (e.g., man-sized or weapon-sized holes).
3. A user guide, incorporating all of the important factors for the selection and application of security glazing in correctional institutions, should be developed. It is suggested that this be accomplished through a committee, which would include representatives from the engineering, architectural, correctional, and glazing manufacturing communities. The guide should include a security classification system for glazing.
4. Performance tests and criteria for glazing materials should be developed for the other important attack scenarios and their corresponding modes of penetration.
5. Performance tests and criteria should be developed for all components of glazing connections and framing for the important attack scenarios and their corresponding modes of penetration.
6. Performance tests and criteria should be developed for the complete glazing assemblage or system tested as a unit for the important attack scenarios and their corresponding modes of penetration.

9. REFERENCES

[1] Physical security of door assemblies and components. NILECJ-STD-0306.00. National Institute of Justice, U.S. Department of Justice, Washington, DC 20531; 1976 May.

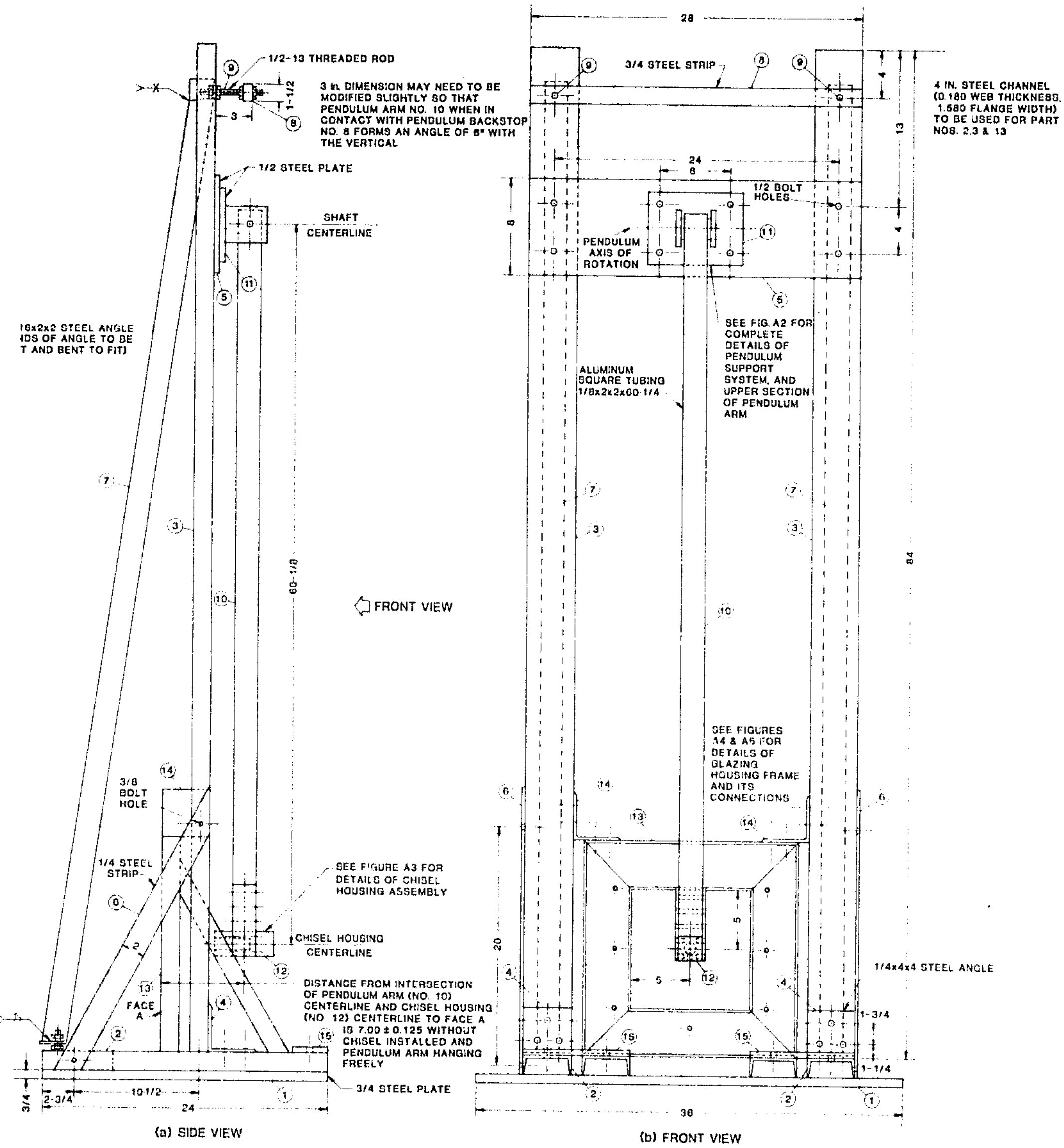
[2] Physical security of window units. NIJ Standard-0316.00. National Institute of Justice, U.S. Department of Justice, Washington, DC 20531; 1980 August.

[3] Physical security of sliding glass door units. NIJ Standard-0318.00. National Institute of Justice, U.S. Department of Justice, Washington, DC 20531; 1980 August.

[4] *Manual on the use of thermocouples in temperature measurement.* STP 470A. American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103; 1974.

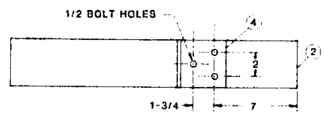
[5] Lee, B. T. Thermocouple size and temperature measurement in room fires. Memorandum dated May 20, 1977. Center for Fire Research, National Bureau of Standards, Gaithersburg, MD 20899.

Appendix A—Test Apparatus Drawings



PARTS LIST

PART NO.	PART NAME	NO. PIECES	PART NO.	PART NAME	NO. PIECES
1	Base plate (anchored to structural floor)	1	8	Pendulum backstop	1
2	Base channel	2	9	Threaded rod 1/2-13	2
3	Upright channel	2	10	Pendulum arm	1
4	Channel connector	2	11	Pendulum shaft support	1
5	Pendulum support system mounting plate	1	12	Chisel housing	1
6	Brace	2	13	Glazing frame	1
7	Brace	2	14	Connector angle	2
			15	Connector plate	2

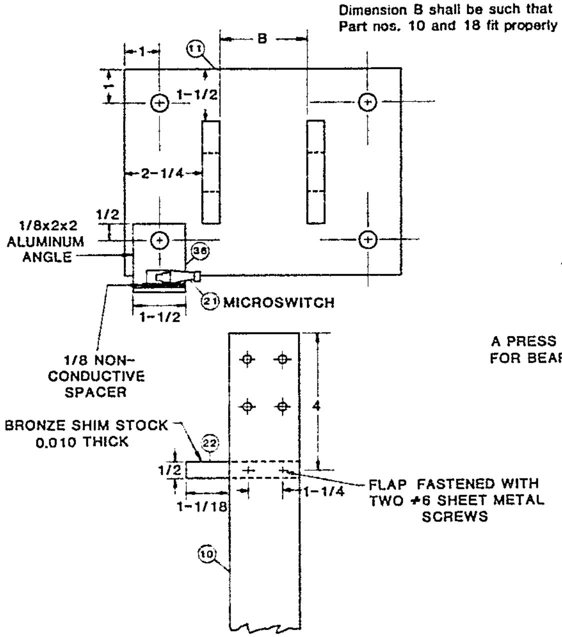


(c) TOP VIEW OF PARTS 2 AND 4

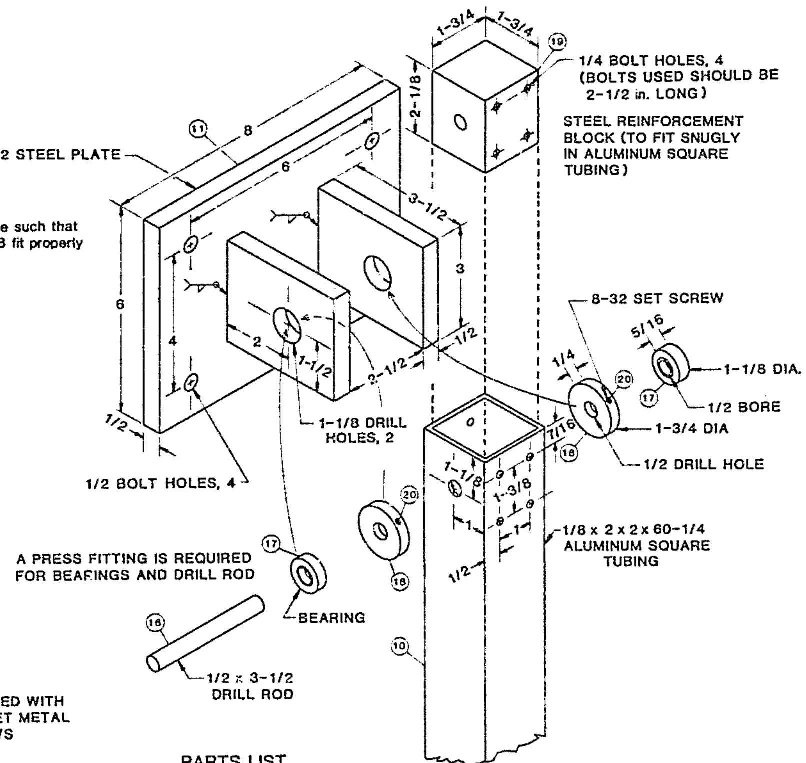
All dimensions in inches

All welds shall be of adequate strength to withstand impact loading during testing.

FIGURE A1. *Pendulum apparatus.*



FRONT VIEW OF
MICROSWITCH AND FLAP MOUNTING



PARTS LIST

PART NO.	PART NAME	NO. PIECES
10	Pendulum Arm *	1
11	Pendulum Shaft Support	1
16	Pendulum Shaft	1
17	Bearing**	2
18	Brass Bushing	2
19	Reinforcement Block	1
20	Set Screw	2
21	Microswitch	1
22	Flap	1
36	Microswitch Mount	1

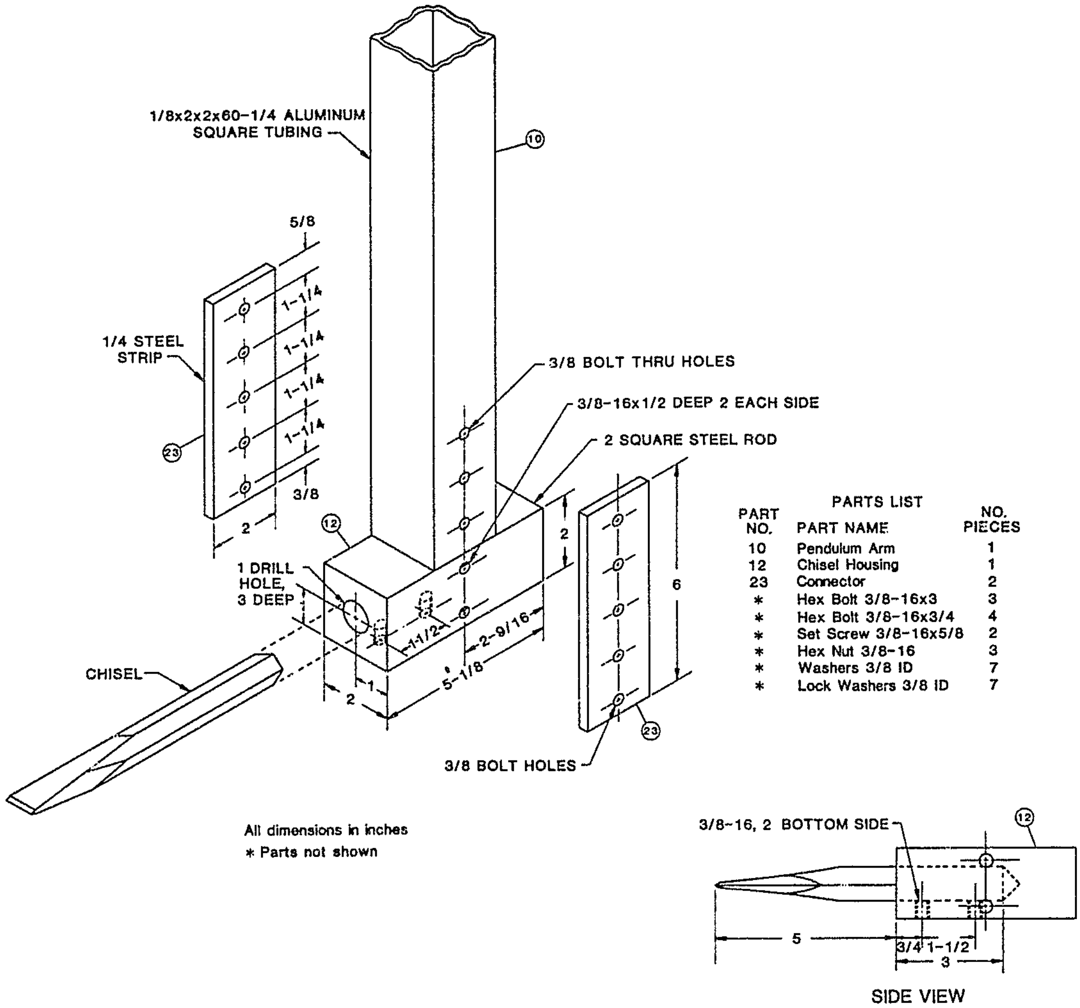
All dimensions in inches

All welds shall be of adequate strength to withstand impact loading during testing.

* Aluminum alloy 6063-T52 used.

** Bearings were single row, radial, inch dimensioned, extra light series, retainer type, with two shields. Dimensions: bore = 0.5000 in., O.D. = 1.125 in., width = 0.3125 in.
Examples of two manufacturers are: Fafnir (No. S5KDD) and New Departure (No. 77R8).

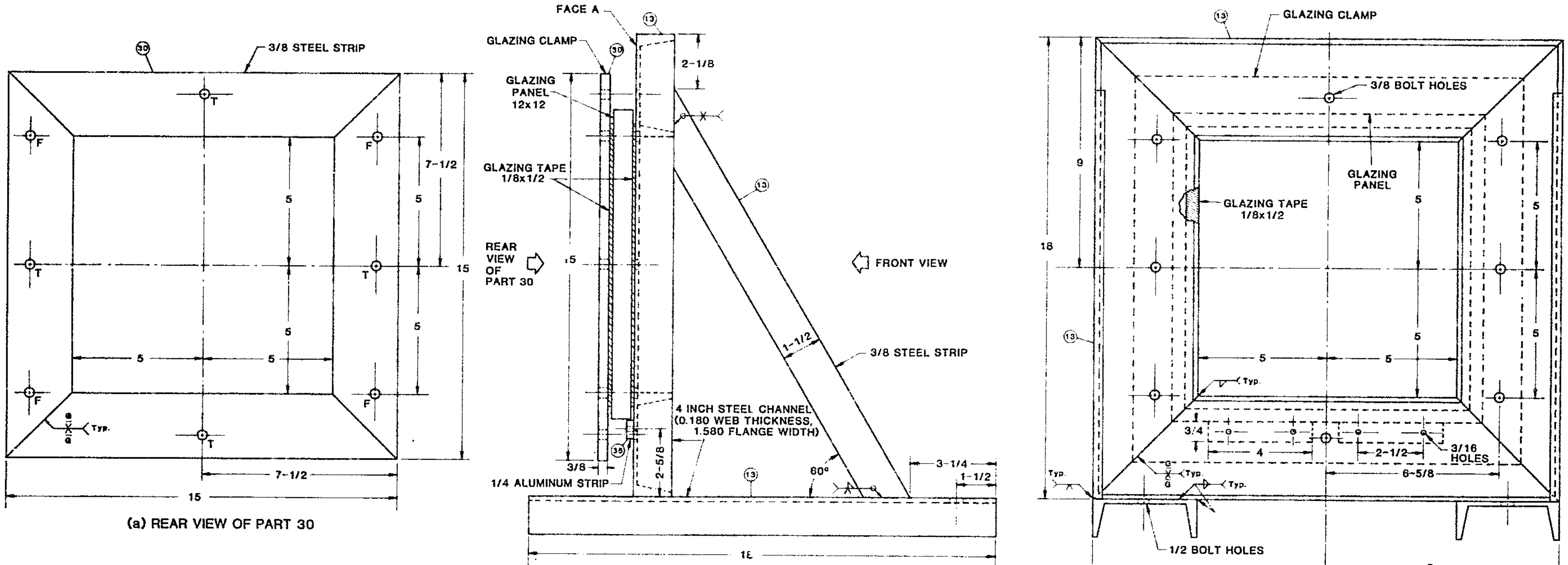
FIGURE A2. *Pendulum support system and upper section of pendulum arm.*



PARTS LIST

PART NO.	PART NAME	NO. PIECES
10	Pendulum Arm	1
12	Chisel Housing	1
23	Connector	2
*	Hex Bolt 3/8-16x3	3
*	Hex Bolt 3/8-16x3/4	4
*	Set Screw 3/8-16x5/8	2
*	Hex Nut 3/8-16	3
*	Washers 3/8 ID	7
*	Lock Washers 3/8 ID	7

FIGURE A3. *Chisel housing assembly.*



(a) REAR VIEW OF PART 30

(b) SIDE VIEW

(c) FRONT VIEW

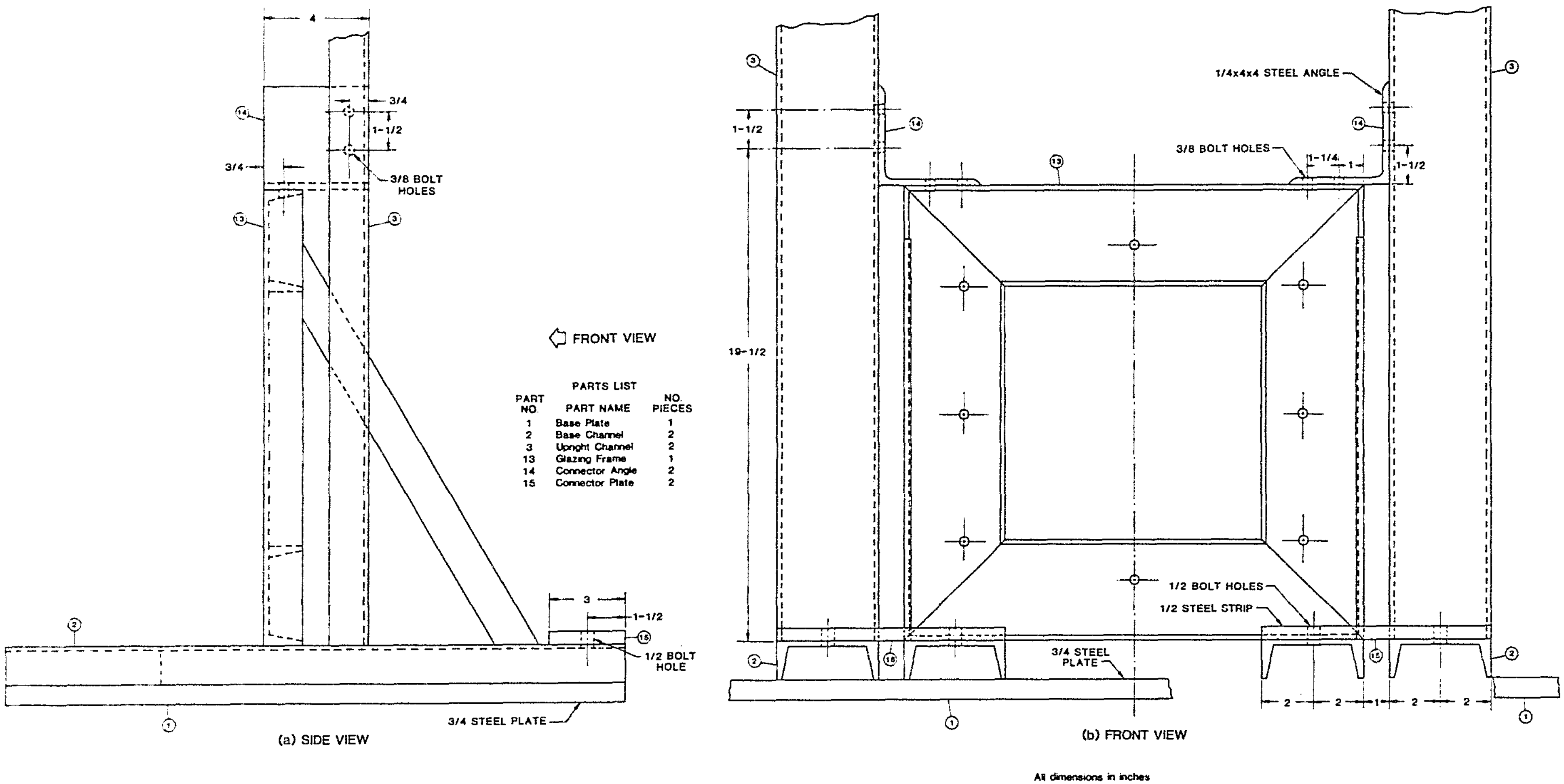
T = Torque Bolts to about 28 in-lbs.
F = Finger Tighten Bolts (No Tools)
All dimensions in inches

All welds shall be of adequate strength to withstand impact loading during testing.

PARTS LIST

PART NO.	PART NAME	NO. PIECES
13	Glazing Frame	1
30	Glazing Clamp	1
35	Panel Seat	2

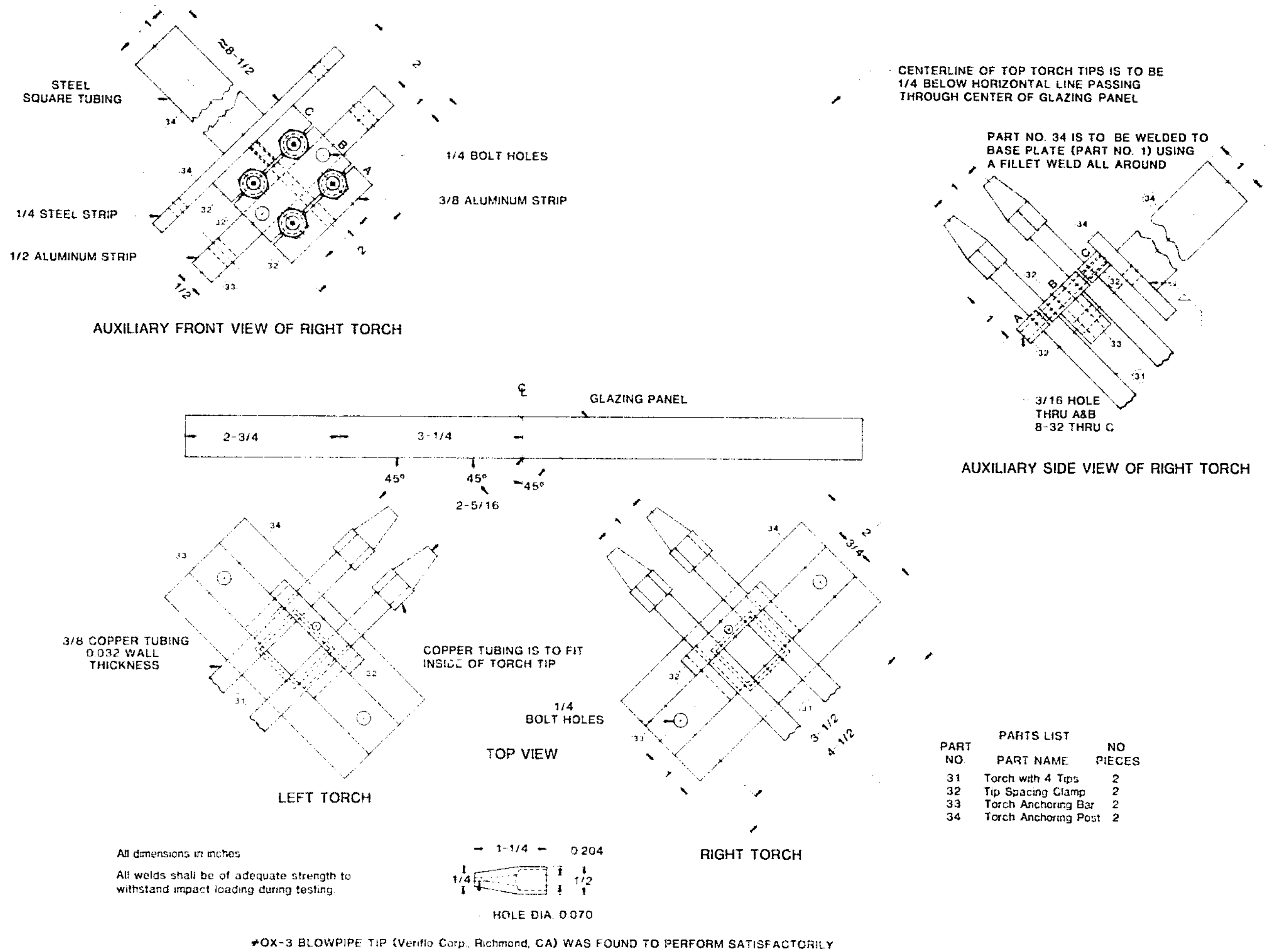
FIGURE A4. *Glazing housing assembly.*



PARTS LIST

PART NO.	PART NAME	NO. PIECES
1	Base Plate	1
2	Base Channel	2
3	Upright Channel	2
13	Glazing Frame	1
14	Connector Angle	2
15	Connector Plate	2

FIGURE A5. *Connection details for glazing frame.*



PARTS LIST

PART NO.	PART NAME	NO PIECES
31	Torch with 4 Tips	2
32	Tip Spacing Clamp	2
33	Torch Anchoring Bar	2
34	Torch Anchoring Post	2

FIGURE A6. *Mounting and positioning of torches.*

Appendix B—Moment of Inertia, Potential Energy, and Maximum Velocity of Chisel Impactor

APPENDIX B—*Moment of inertia, potential energy and maximum velocity of chisel impactor.*

Element			Mass moment of inertia of element about an axis which is: (a) through center of mass of element and (b) parallel to pendulum axis of rotation (fig. A1, app. A)	Distance from center of mass of element to pendulum axis of rotation,	Transfer	Mass moment of inertia of element about pendulum axis of rotation,	Decrease in height of element in cocked[a] position as compared to bottom of arc position just before impact	Potential energy in cocked position relative to bottom of arc position just before impact
Description	Weight, W (lb)	Mass, m (slug)	I_{cg} (slug-ft^2)	d (ft)	term, md^2 (slug-ft^2)	$I_o = I_{cg} + md^2$ (slug-ft^2)	Δd (ft)	$(\Delta d)(W)$ (ft-lb)
Chisel housing (part no. 12, fig. A3, app. A); chisel; and two set screws, 3/8 in-16 × 5/8 in long	6.404	0.1989	0.003	5.010	4.993	4.996	9.993	63.998
Two connectors (part no. 23, fig. A3, app. A)	1.582	0.0491	0.001	4.844	1.153	1.154	9.661	15.284
One hex bolt, 3/8 in-16×3 in long; one lock washer, 3/8 in ID; and one hex nut, 3/8 in-16.	0.120	0.0037	0.000	4.646	0.080	0.080	9.266	1.112

APPENDIX B—*Moment of inertia, potential energy and maximum velocity of chisel impactor (continued).*

Element			Mass moment of inertia of element about an axis which is: (a) through center of mass of element and (b) parallel to pendulum axis of rotation (fig. A1, app. A)	Distance from center of mass of element to pendulum axis of rotation,	Transfer	Mass moment of inertia of element about pendulum axis of rotation,	Decrease in height of element in cocked[a] position as compared to bottom of arc position just before impact	Potential energy in cocked position relative to bottom of arc position just before impact
Description	Weight, W (lb)	Mass, m (slug)	I_{cg} (slug-ft^2)	d (ft)	term, md^2 (slug-ft^2)	$I_o = I_{cg} + md^2$ (slug-ft^2)	Δd (ft)	$(\Delta d)(W)$ (ft-lb)
One hex bolt, 3/8 in-16×3 in long; one lock washer, 3/8 in ID; and one hex nut 3/8 in-16.	0.120	0.0037	0.000	4.750	0.084	0.084	9.474	1.137
One hex bolt, 3/8 in-16×3 in long; one lock washer, 3/8 in ID; and one hex nut, 3/8 in-16	0.119	0.0037	0.000	4.854	0.087	0.087	9.681	1.152
Two hex bolts, 3/8 in-16×3/4 in long, each with one washer, 3/8 in ID and one lock washer, 3/8 in ID	0.083	0.0026	0.000	4.958	0.063	0.063	9.889	0.821

APPENDIX B—*Moment of inertia, potential energy and maximum velocity of chisel impactor (continued).*

Element: Description	Element: Weight, W (lb)	Element: Mass, m (slug)	Mass moment of inertia of element about an axis which is: (a) through center of mass of element and (b) parallel to pendulum axis of rotation (fig. A1, app. A) I_{cg} (slug-ft^2)	Distance from center of mass of element to pendulum axis of rotation, d (ft)	Transfer term, md^2 (slug-ft^2)	Mass moment of inertia of element about pendulum axis of rotation, $I_o = I_{cg} + md^2$ (slug-ft^2)	Decrease in height of element in cocked[a] position as compared to bottom of arc position just before impact Δd (ft)	Potential energy in cocked position relative to bottom of arc position just before impact $(\Delta d)(W)$ (ft-lb)
Two hex bolts, 3/8 in-16 × 3/4 in long, each with one washer, 3/8 in ID and one lock washer, 3/8 in ID	0.084	0.0026	0.000	5.0625	0.067	0.067	10.097	0.848
Pendulum arm (part no. 10, fig. A1, app. A)	5.341	0.1659	0.348	2.406	0.960	1.308	4.799	25.630
Totals	13.853	0.4302	0.352		7.487	7.839		109.982

[a] Cocked position is described in section 4.1.

Note: Calculation neglects effects of friction
PE = Initial energy in cocked position of 109.98 ft-lb = Rotational kinetic energy at bottom of arc position just before impact

$$PE = \tfrac{1}{2} I_o \omega^2 ; \quad \omega = \text{Angular velocity}$$
$$109.98 \text{ ft-lb} = 1/2\ (7.839 \text{ slug-ft}^2)\omega^2$$
$$\omega = 5.297 \text{ rad/s}$$

Chisel velocity at bottom of arc = $V = r\omega$; r = distance from pendulum axis of rotation to chisel.
$$V = (5.010 \text{ ft})(5.297 \text{ rad/s})$$
$$V = 26.5 \text{ ft/s}$$

Appendix C—Student's t Statistic Values

The Student's t Statistic is defined* as

$$t = \frac{\bar{X}_2 - \bar{X}_1}{s_p\left[\frac{1}{N_1} + \frac{1}{N_2}\right]^{\frac{1}{2}}}$$

where

$$s_p = \left[\frac{(N_1-1)s_1^2 + (N_2-1)s_2^2}{N_1+N_2-2}\right]^{\frac{1}{2}}$$

$\bar{X}_1, \bar{X}_2$ = average number of impacts to penetration for two successive groups (e.g., $\bar{X}_1$ for Group A, $\bar{X}_2$ for Group B)

s_1, s_2 = standard deviation values of the number of impacts to penetration for two successive groups (e.g., s_1 for Group A, s_2 for Group B)

N_1, N_2 = number of panels tested in two successive groups (e.g., N_1 for Group A, N_2 for Group B)

TABLE C1. *t values for differences in the average number of impacts to penetration for successive groups.*

Groups compared (table 13)	A and B	B and C	C and D	D and E	E and F	F and G
$\bar{X}_2 - \bar{X}_1$	6.9	6.3	6.9	11.0	39.5	39.3
t	13.9	7.2	5.4	6.9	17.5	18.5

*Dixon, W. J., and Massey, F. J. Jr., *Introduction to Statistical Analysis*, 2nd Edition, McGraw Hill Book Co., New York, NY, 1957, 488 pp.