Risk Assessment of an Existing School to the Effects from an LPG Vapor Cloud Explosion

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ABSTRACT

This work had two objectives, the first of which was to assess the risk of injury to humans at an existing school facility from the effects of the accidental explosion of a distant, unconfined LPG vapor cloud. The second objective was to recommend ways of reducing the risk of human injury to acceptable levels. Potential injury from the explosion effects was investigated for the case when the overpressure acts directly to cause injury and for the case where facility failure is the direct cause of injury. The effects of an enhancing atmosphere, such as inversion layer that could trap blast energy near the ground, were considered.

The risks to humans when the explosion effects act directly on persons included ear damage, lung damage, skull fracture and whole-body impacts, skin burns, and eye-retinal burns. The resistance of structural components of the school facility to the blast overpressure were investigated including structural systems, window glass, doors, and upset/failure of building contents. Risk mitigation measures were recommended for strengthening specific structural and nonstructural building component.

1. INTRODUCTION

The primary objective of this study was to assess the risk of injury to humans on the Smith Site School Grounds from the effects of the explosion of a distant, unconfined Liquid Petroleum Gas (LPG) vapor cloud. Potential injury from the explosion effects was investigated for the case when the blast overpressure acts directly to cause injury and for the case where facility structural or nonstructural failure/upset is the direct

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cause of injury. A second objective was to recommend ways of reducing the risk of human injury.

2. GIVEN EXPLOSION EVENT

Figure 1 is a topographic map that shows the relationship of the Smith Site property with school facilities to the Chevron U.S.A. - managed Gaviota Oil and Gas Plant. The map contours indicate the general features of the terrain. Note the east-west orientation of the coastline and location of the school in close proximity to adjacent California State Highway 101, Southern Pacific railroad tracts and shore line. Figures 2 thru 5 show the intervening terrain and the rise of the nearby coastal mountain range. This area is approximately 30 miles west of the City of Santa Barbara, California.

The source of the given explosion event was taken as the easterly wind translated, unconfined vapor cloud that would be formed by 100% vaporization of the contents of the eastern most 105,000-gal capacity butane vessel. The distance between the center line of this tank and the west edge of the school building is 7700 ft. The unconfined vapor cloud was assumed to be ignited at its eastern most flammable edge, and to detonate, to produce the given explosion event. The explosion source is characterized below based primarily on information published by Arthur D. Little, Inc. (References 1 and 2). Note that two conditions were investigated - one for a vessel 86% full and the other for a vessel 40% full.

Parameter	86%-Full Vessel	40%-Full Vessel
Weight of Butane Vapor, lb (@ SG = 0.6)	450,000	210,000
Downwind Range of Effective Center of Explosion from Butane Vessel, ft	3,000	2,100
Vapor Cloud Dimensions at Time of Explosion, ft	3,000 x 300	2,100 x 300
TNT Explosion Equivalence of Butane Vapor Cloud Explosion, lb of TNT		
Half-Space Release	170,000	79,000
Half-Space Less 15 Deg Release	200,000	92,000

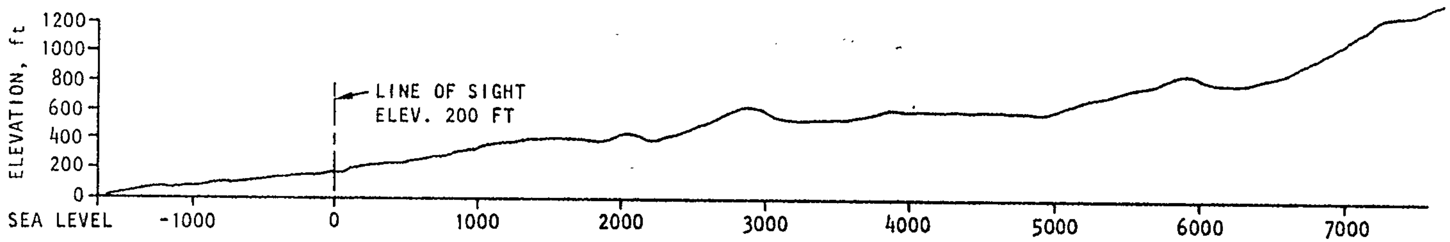

FIGURE 1-3. SECTION B-B 3000 FEET EAST OF LPG VESSEL

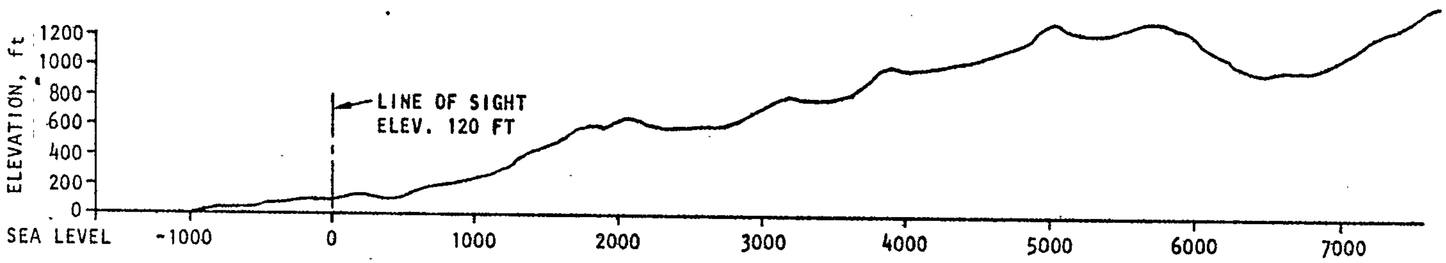

FIGURE 1-4. SECTION C-C 5500 FEET EAST OF LPG VESSEL

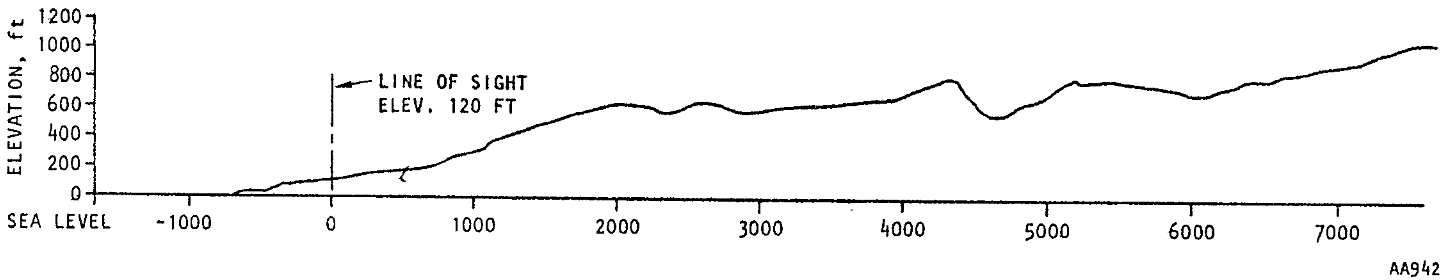

FIGURE 1-5. SECTION D-D AT WEST FACE OF SCHOOL BUILDING ON SMITH SITE

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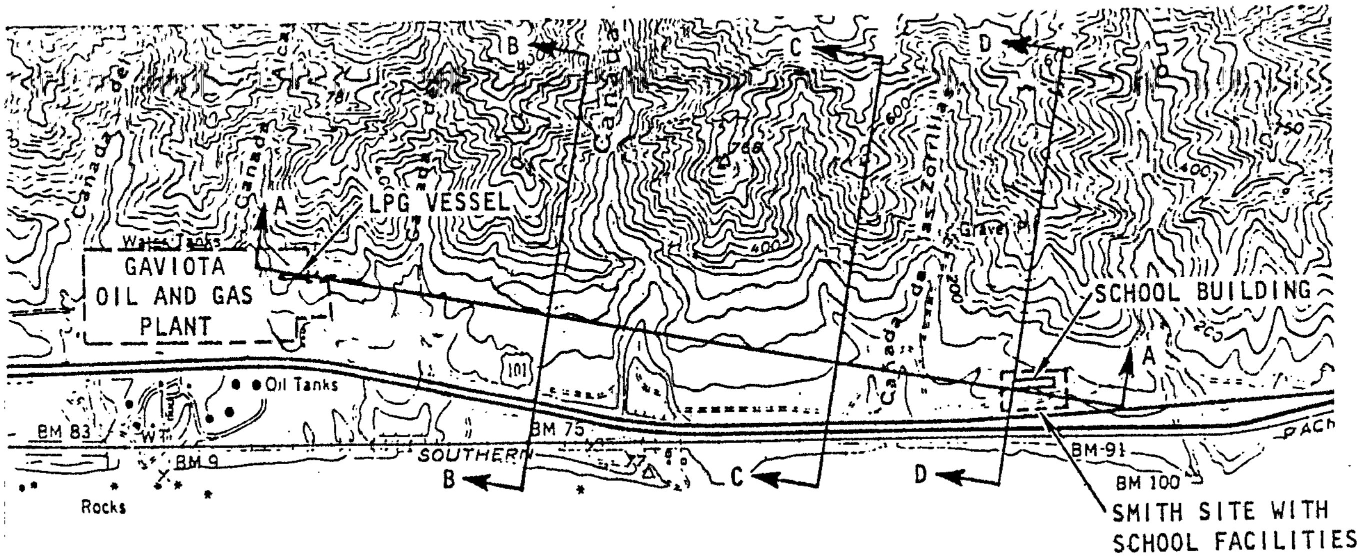


FIGURE 1. TOPOGRAPHIC MAP

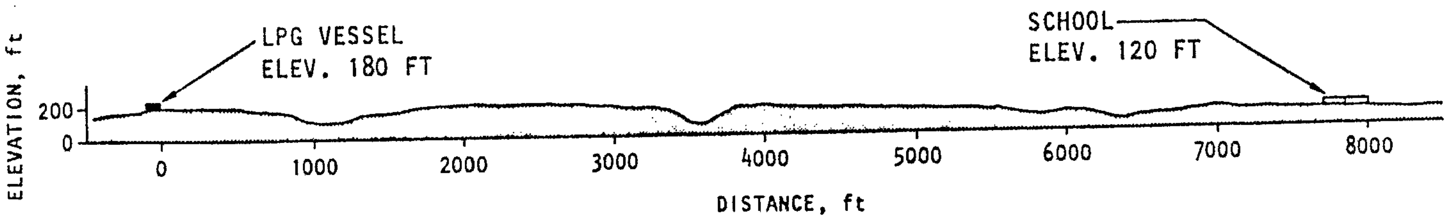


FIGURE 2. SECTION A-A, LINE-OF-SIGHT CROSS SECTION

Two TNT equivalent explosions are given-one for a half-space release of energy, i.e., for flat topography, and the other for a half-space minus 15 deg release of energy. This latter case, which simulates the effects of the approximately 15-deg slope of the nearby costal mountain range has been used as the basis for this study. The effect of the terrain that lies between the explosion source and the Smith Site (See Fig. 2) is expected to have little influence on the attenuation of overpressure. This terrain effect was therefore neglected.

3. SMITH SCHOOL SITE OVERPRESSURE CONTOURS

Figure 6 shows contours of free-field overpressure on the Smith Site for the two vessel ullages defined in the previous paragraph and for two atmospheric conditions. The quoted distances are from the effective center of the explosion (point of ignition). The first overpressure quoted in each set has been calculated for a uniform, or standard, atmosphere. A uniform atmospheric condition is generally assumed when estimating the attenuation of airblast effects with distance. The second overpressure quoted in each set has been calculated for an enhancing atmosphere, which traps blast energy back to the ground, or bends blast energy back to the ground, or both. An invasion layer is the most common example of an enhancing atmosphere - such as the early morning coastal cloud and fog covers common for the school site. Estimates for overpressure for the enhancing atmosphere were made using the upper-bound enhancement factors that are typically used by the DoD to help manage the far-field effects of large explosions in remote areas. The estimates of overpressure for the standard atmosphere were taken from a DoE handbook (See Reference 3).

As shown in Figure 6, the overpressure is more-or-less constant over the site and equal to about 0.4/0.65 psi and 0.25/0.5 psi for the 86% and 40% - full vessel accidents, respectively. Also note that the overpressure difference between the two ullage conditions narrows for the enhancing atmosphere.

The free-field airblast parameters of importance at the range of the west end of the school building are shown below:

Blast Parameter	86% Full	40% Full
Overpressure		
Peak Pressure	0.43/0.67 psi 163/167 db	0.25/0.53 158/165
Impulse	0.065/0.11 psi-sec	0.032/0.068

Duration (positive)	0.31/0.31 sec	0.27/0.27
Dynamic Pressure		
Peak Pressure	0.64/1.6 psf	0.22/0.98
"Wind" Velocity	15/24 mph 23/35 fps	9/19 13/28

These particular values are representative of the entire site, as noted earlier. If nothing else, the peak overpressure presents a tremendously loud noise, as indicated by its 158 to 167 decibel (db) level. The overpressure impulse is the area under the overpressure-time curve out to the time when the overpressure goes negative, which in this case is about three-tenth of a second. The impulse, or equivalently the duration, can be critical to the response of humans and facilities to airblast effects. The dynamic pressure, or the force of the blast winds, is benign for this study. The school structure was designed for a 15-psf pressure, which corresponds to about a 75-mph wind. The air blast arrives at the school site about 3 sec after detonation of the vapor cloud.

4. RISK OF INJURY WHEN EXPLOSION EFFECTS ACT DIRECTLY

Hazard Scenarios

The following hazard scenarios are postulated for the case where the explosion effects act directly on a person to cause injury.

Air Blast

Ear Damage
- Eardrum Rupture
- Temporary Hearing Loss

Lung Damage

Whole-Body Displacement
- Skull Fracture
- Whole-Body Impact

Fireball Thermal Radiation

Burn
- Skin
- Eye

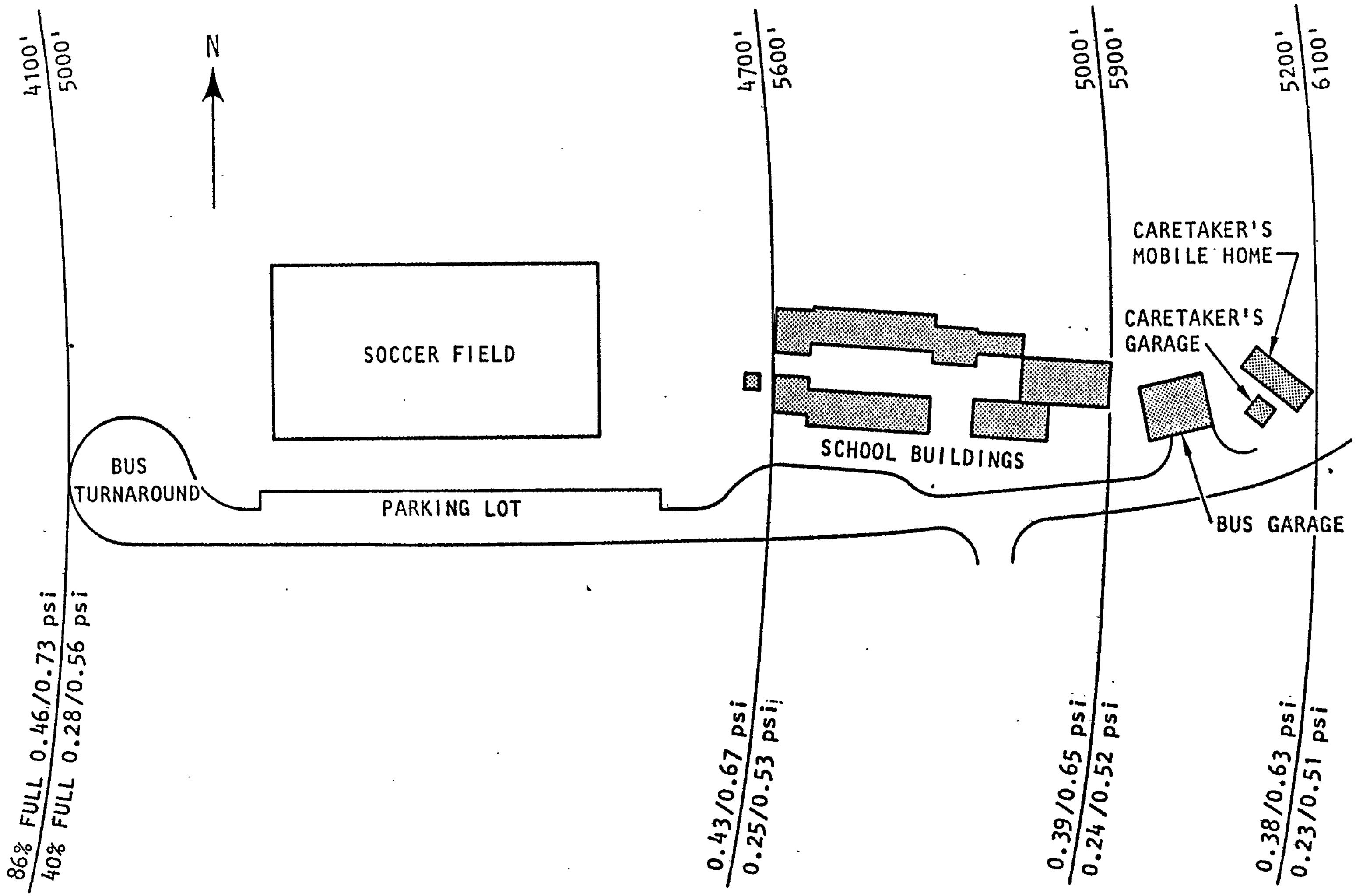


FIGURE 6. SMITH SITE OVERPRESSURE CONTOURS

The hazard of impact of debris and crater ejecta thrown from the explosion source region was not considered. The energy density of the vapor cloud is insufficient to scour the ground under the cloud or to throw the debris of any facilities that may be developed by the cloud to the Smith Site school grounds.

Summary

The risk of injury when the explosion effects act directly on persons located at the Smith Site school grounds are summarized as follows:

(1) There will be no damage to the ear other than a temporary partial hearing loss, which will be restored in a day or two.

(2) There will be no lung damage, no injury from knockdown, no skin burns, and no chorioretinal burns.

This conclusion is applicable for the 86%-full vessel accident and an enhancing atmosphere, and for all lesser threats.

The figures and tolerance data used in this evaluation are taken from Reference 4, a readily available reference on explosion hazards. Each hazard scenario is discussed below.

Ear Damage

Figure 7 shows the dependence of ear damage on the peak pressure and impulse of a fast-rising overpressure. The curve labeled TTS, is the threshold of a temporary loss of hearing. This loss, which is partial, would be reversed within a day or so. The full range of Smith Site overpressures are indicated on the figure as the cross-hatched area. It is seen that the Site overpressures are far too weak to rupture eardrums, but are strong enough to cause a temporary loss of hearing.

The TTS, asymptotic overpressure corresponds to a sound level intensity of about 155 db (By comparison, artillery fire is about 145 db). Since typical building construction attenuates sound levels by at least 20 db, those persons inside the school building and caretaker's trailer will not experience a temporary loss of hearing, provided the doors and windows are closed.

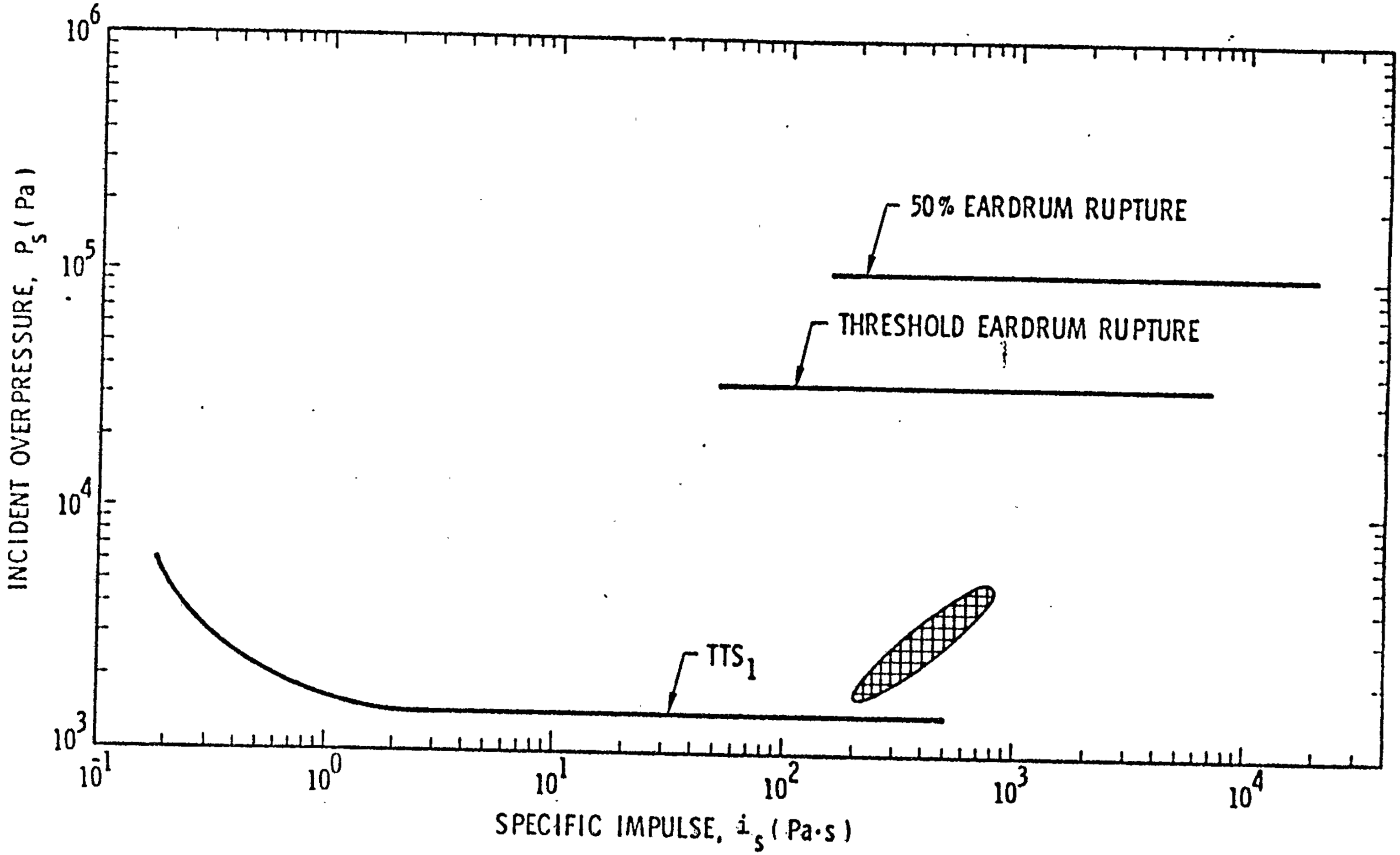


FIGURE 7. HUMAN EAR DAMAGE CURVES FOR BLAST WAVES ARRIVING AT NORMAL ANGLE ON INCIDENCE

Lung Damage

Figure 8 shows lung damage as a function of the peak pressure divided by ambient atmospheric pressure and the impulse of a fast-rising overpressure. The impulse is seen to be divided by the square root of the ambient atmospheric pressure (p_o) and the cube root of the mass of the person (m). The arrow indicates where the interaction of the Smith Site worst-case overpressure and an infant (m = 3 kg) falls (off the plot). Clearly, there will be no lung damage on the Smith Site school grounds.

Skull Fracture and Whole-Body Impacts

A sufficiently strong airblast can knock a person down and even carry them downrange. The attained maximum velocity has been related to impact injury. Shown below are the skull fracture and whole-body impact tolerances that have been derived from primate and cadaver experiments.

Skull Fracture	Related Impact Velocity, m/s	(ft/sec)
Mostly "safe"	3.05	(10)
Threshold	3.96	(13)
50%	5.49	(18)
Near 100%	7.01	(23)

Whole-Body Impact	Related Impact Velocity m/s	(ft/sec)
Mostly "safe"	3.05	(10)
Lethality threshold	6.40	(21)
Lethality 50%	16.46	(54)
Lethality near 100%	42.06	(138)

For purpose of reference, it is noted that an impact velocity of about 5.3 m/s (17fps) results from falling out of an upper bunk, and a whole-body impact velocity of about 27 m/s (88 fps) results from exiting a car traveling 60 mph.

The above data have been used to construct Figure 9. The figure indicates tolerance levels for skull fracture plotted against the peak pressure and impulse of the overpressure. The impulse is divided by the cube root of the mass of the person (m). The lighter the body, the higher the attained velocity and the more likely skull fracture. The full range of the Smith Site overpressure acting on a toddler (m=10kg) is indicated by the cross-hatched oval. It is seen that the Smith Site airblast is far too weak to cause skull fracture. This same conclusion also applies for whole-body impact. The maximum blast-induced velocity

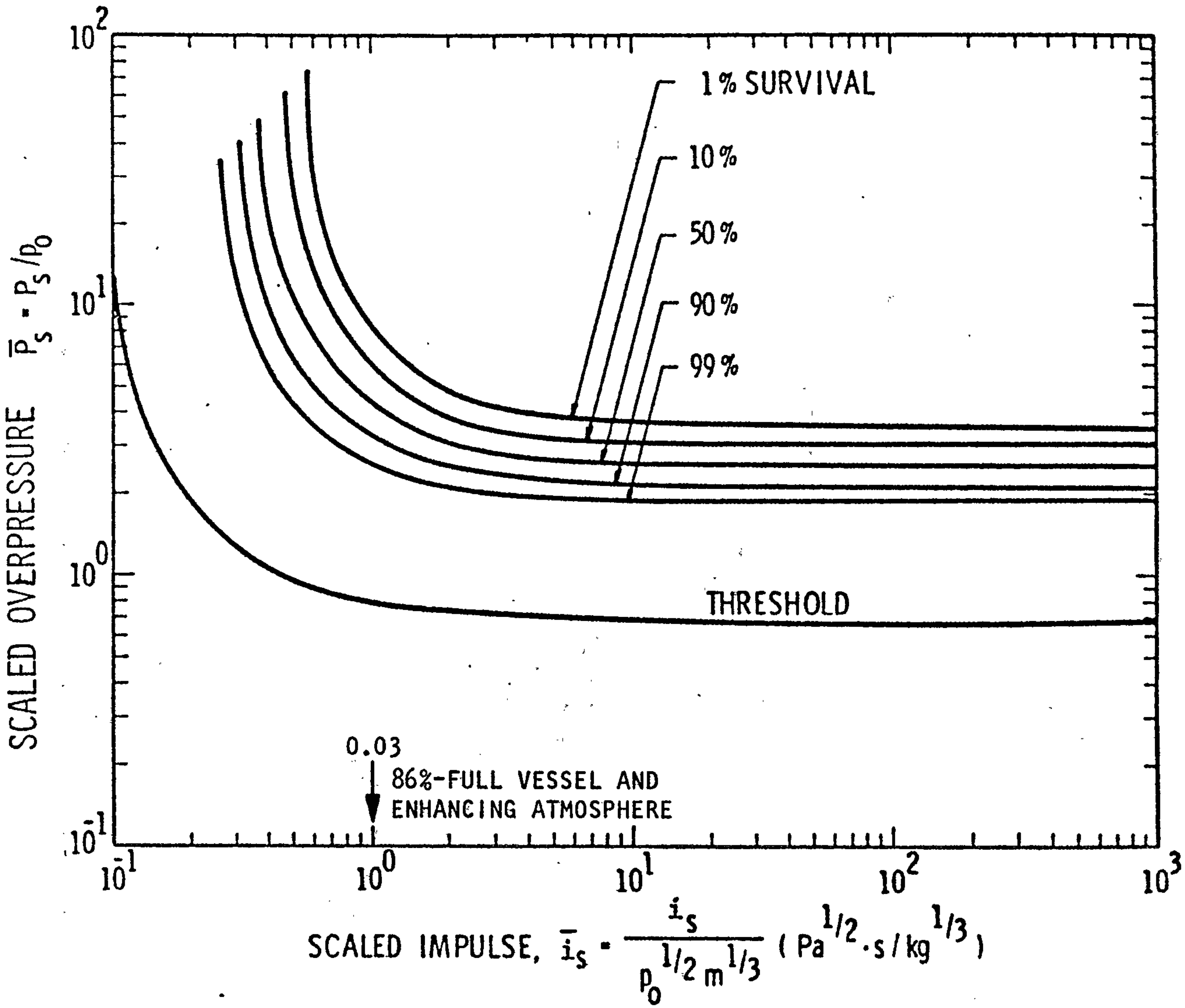


FIGURE 8. SURVIVAL CURVES FOR LUNG DAMAGE TO MAN

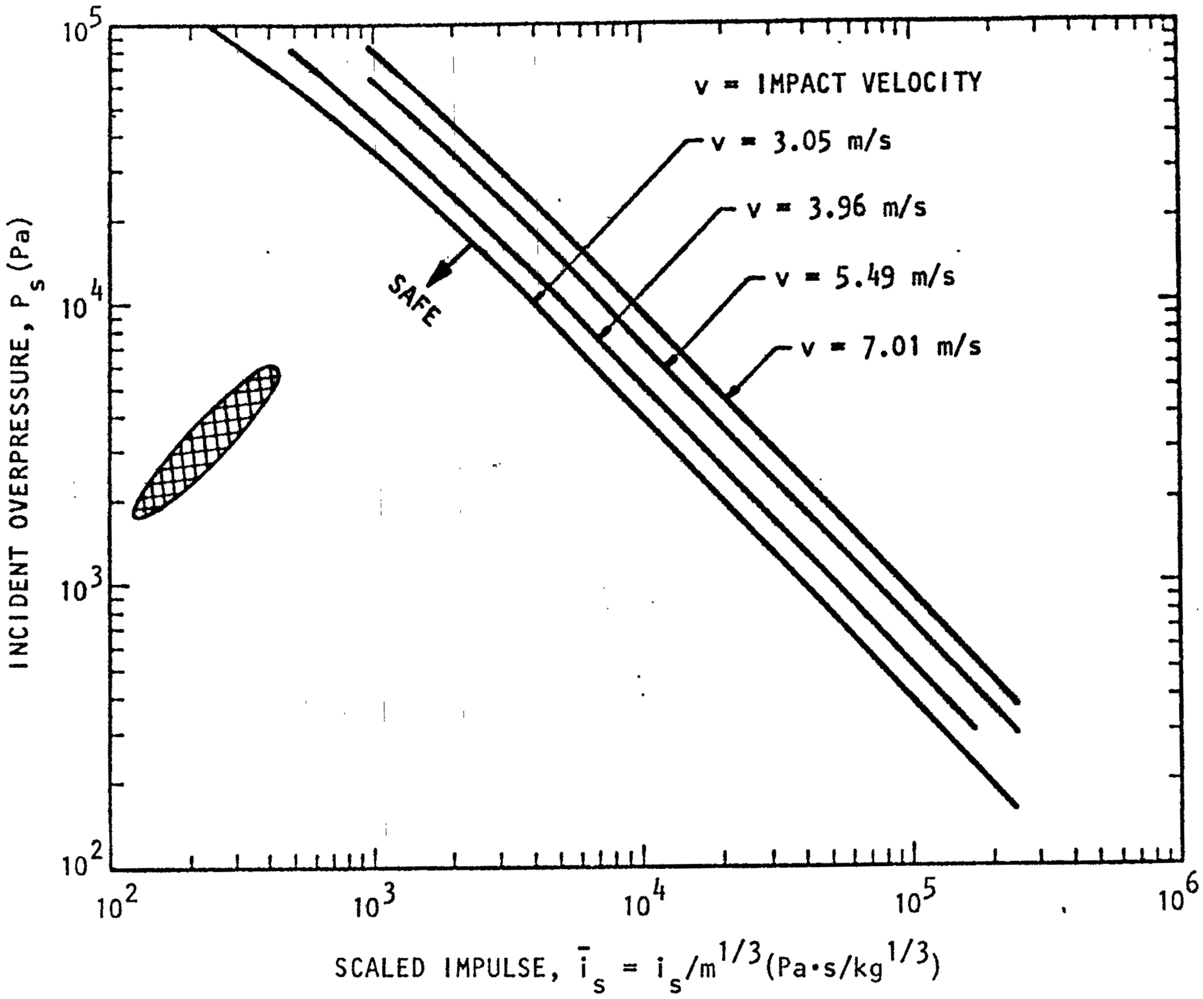


FIGURE 9. SKULL FRACTURE

that a person attains on the Smith Site school grounds is less than about 2 fps.

Skin Burns

Figure 10 shows how much and how fast thermal radiation must be delivered to human skin to cause unbearable pain, i.e., to burn. It is seen from the figure that the thermal radiation falling on the Smith Site school grounds for the 86%-full vessel accident and enhancing atmosphere is so low that it falls off the plot.

Chorioretinal Burn

As shown in Figure 11, the thermal radiation delivered to the Smith Site school ground is too low to cause chorioretinal damage, even to the indicated wide-eyed observer of the entire fireball burn. For an explanation of the derivations of geometrical image diameter and Foveal threshold for chorioretinal burns, Reference 4 should be consulted.

5. RISK OF INJURY WHEN EXPLOSION EFFECTS ACT INDIRECTLY

Hazard Scenarios

The following hazard scenarios are postulated for the case where the explosion effects act indirectly to cause injury through structural failure of the facilities or by failure/upset of equipment or nonstructural components.

Air Blast

Facility Structural Failure
Impact
Fire

Facility and Vehicle Window Glass Breakage
Impact / Penetration

Facility Door Failure
Impact

Facility Contents and Nonstructural Systems Failure/Upset
Impact
Fire
Chemical Spill

Appurtenance Failure
Impact

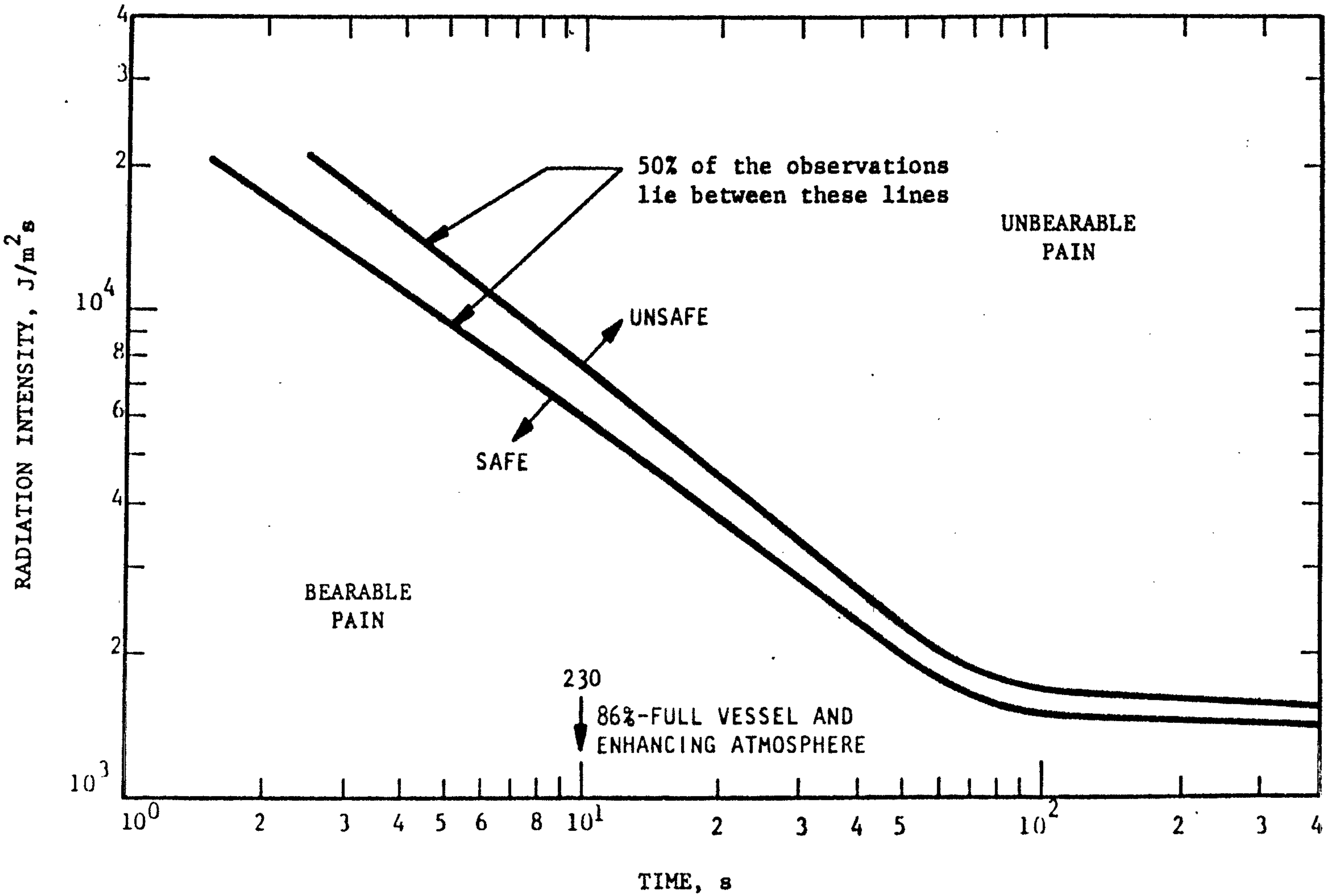


FIGURE 10. THRESHOLD OF PAIN FROM THERMAL RADIATION ON BARE SKIN

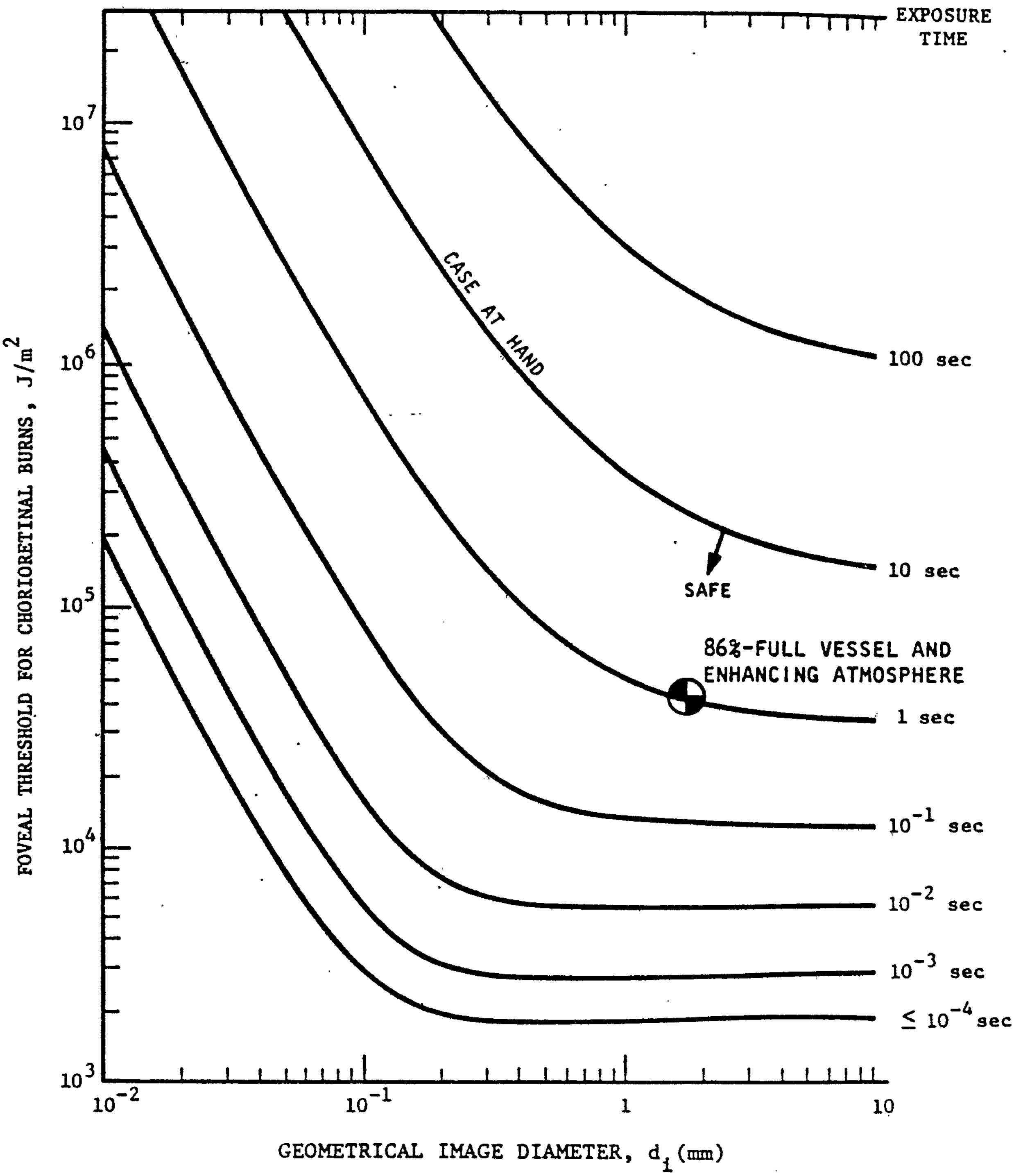


FIGURE 11. CHORIORETINAL BURN THRESHOLDS FOR PRIMATES

Airblast Loadings on Buildings

The airblast loads that act on the exterior surfaces of the various buildings are shown in Figure 12, where the typical values of P_S indicated by the overpressure contours indicated in Figure 6 are applicable. Note that the duration of the load has been standardized at 0.3 sec. The school building is optimally oriented, in that only one door and a few windows see a reflected pressure. Only the west-facing walls of the school building see a reflected overpressure.

At the overpressure levels being considered, the peak reflected overpressure, P_R, is double the peak free-field incident, or side-on, overpressure, P_S. The duration of the reflected overpressure has been standardized at 0.03 sec.

In the following sections, the facilities' capacity, or resistances, will be quoted for each considered failure mode in terms of a side-on pressure, P_S. Such specifications will account for reflected airblast, as applicable.

Basis for Analysis and Evaluation of Structures

In the evaluation of the school facilities, life-safety was the controlling consideration, i.e., insure that persons within or outside the buildings will not be injured by structural failures induced by the blast overpressures. Damage to the buildings as determined by permanent deformation of structural elements was permitted, but conservative limits on the amount of inelastic behavior (permanent displacement) were selected to insure safety of occupants and provide a margin of safety against collapse.

Dynamic, inelastic analyses were performed of the building roof and side wall structural framing systems to determine the amount of plastic deformation each will sustain under the appropriate airblast side-on overpressure indicated for the buildings in Fig. 6. The plastic deformations were compared with empirical data that relate deformation to damage levels and margin of safety against failure/collapse. Limits on inelastic behavior were based on the ratio of maximum allowable deflection of a structural element to the yield deflection depending on the ductile characteristics of the construction materials, time history of the loading, and yield strength of the material. Ultimate strength design procedures were utilized in the analyses to take advantage of the reserve strength in a member or structure that has been stressed beyond the elastic yield point.

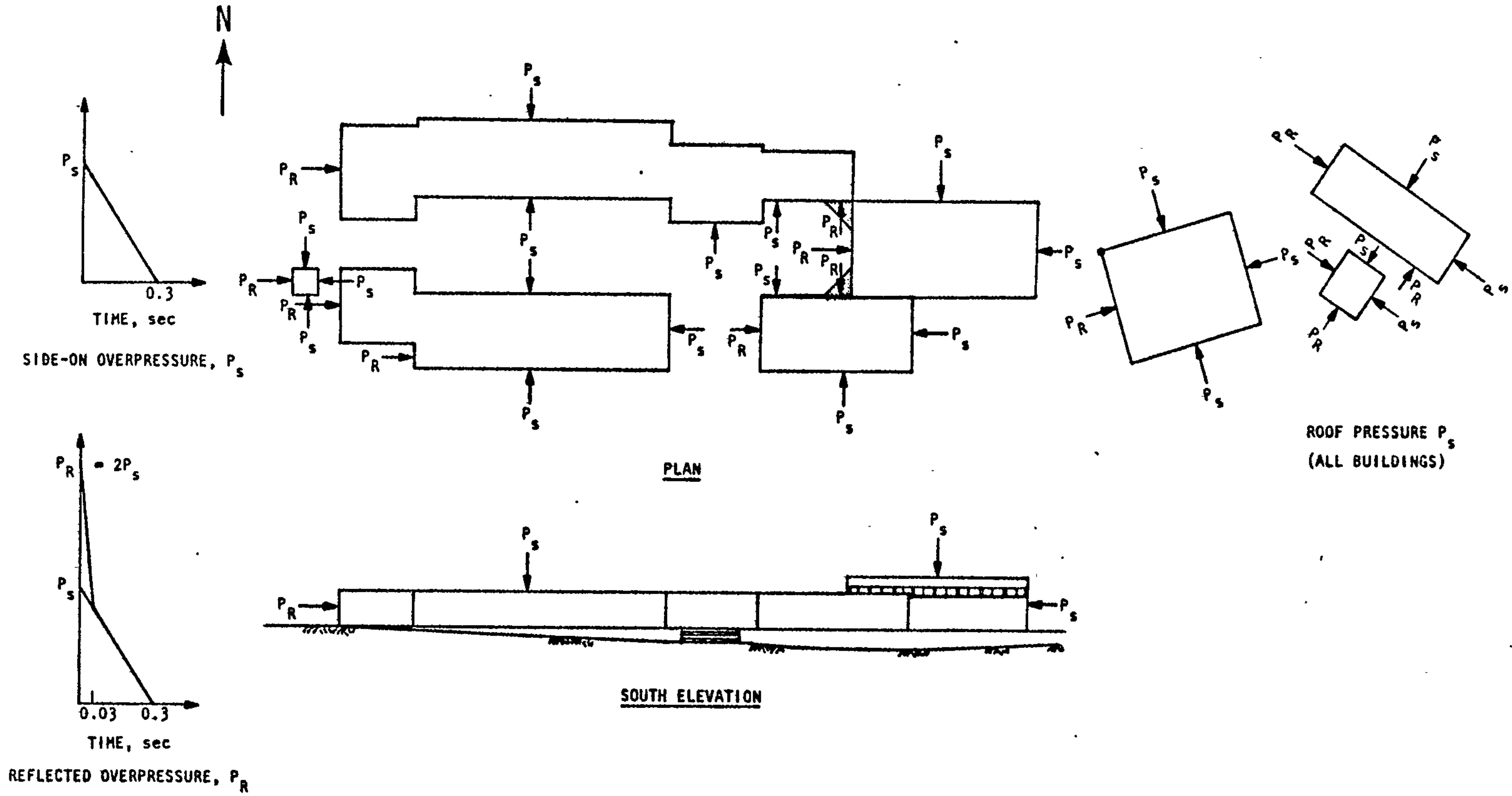


FIGURE 12. AIRBLAST LOADINGS ON SCHOOL AND ANCILLARY BUILDINGS

6. EVALUATION OF STRUCTURES

Structures evaluated at the Smith Site School consisted of the school building, caretaker's mobile home, the bus garage, a two-car garage, and a ball storage room. Results of the evaluations are summarized below, including a brief description of their construction.

6.1 School Structure Evaluation

Results of the evaluation of school building roof and sidewall structural systems are summarized below.

(a) Description of Construction

The school building is constructed using steel-framed, factory-assembled skeleton modules, nominally 10ft by 40ft, or 12ft by 40ft, in plan by 10ft or 17ft high. Modules are assembled in groups of 2, 3, 4, and 8 to form classrooms or other administrative support areas.

The grouping of modules for the school is shown below by module size.

10 x 32 Modules

30 x 32	Classroom Buildings (3-10x32)
40 x 32	Library (4-10x32)
40 x 32	Administration Building (4-10x32)
20 x 32	Toilet Building (2-10x32)
40 x 20	Faculty Building (4-10x20)

10 x 40 and 12 x 40 Modules

32 x 40 Kindergarten (10, 10, 12, x 40)

10 x 40 Modules

80 x 40 Multipurpose Building (8-10x40)

Roof: The roof structure comprises steel roof trusses spanning 32ft or 40ft supported on steel tubular columns with 6-in. by 14-gauge cold-formed steel C channel purlins at 4ft o.c., covered by 3/4-in. plywood sheathing.

Walls: Wall framing is nominally 2 x 4 wood studs at 16 in. on center or 2 x 6 wood studs at 16 in. on center depending on module height. Window and door openings are framed in the exterior walls as required following typical wood-frame construction details.

(b) Summary of Findings

Table 1 summarizes the maximum resistance, expressed in terms of a side-on overpressure, of school building elements to blast overpressure.

Roof System: The resistance of the roof construction is at least 0.60 psi.

Wall Framing for 10 Ft High Modules: The resistance of the 10 ft high side walls is limited to 0.31 psi because of the single stud used to frame a single window opening, as indicated in Figures 13a, 13b, and 13c. Double studs are used between two window openings when they occur in a single module, as indicated in Figure 13d, and they are reinforced with a flat 2 x 8 as shown in Figure 13e. Walls framed in this manner have a resistance of 0.74 psi. The resistance of the single-stud condition can be increased by nailing a flat 2 x 6 to the main and trimmer studs, in a manner similar to that shown in Figure 13e.

Wall Framing for the 17-ft High Multipurpose Room: The typical 2 x 6 stud framing (no openings) resistance is at least 0.67 psi. However, the resistance of this continuous framing is limited to 0.46 psi by the bolted wall to steel member connection at the top and bottom, when considering reflected overpressure.

The framing for the north wall is not subjected to reflected overpressures and has a resistance of at least 0.61 psi. However, the south wall framing, because of differences in how the wall is framed for the window openings, is limited by the connection detail used to attach the window sills to the steel module corner columns. This occurs at 9 locations. See Figure 14 for difference in framing for north and south walls. The 1985 Uniform Building Code (UBC), Section 2506(d) and (e), requires that the strength of bolted joints in a wood connection be evaluated not only for the bolt or load but also as a notched beam, considering the notch to extend from unloaded edge of the member to the center of the nearest bolt. This requirement limits the resistance of the wall framing to 0.14 psi. The joint should be reviewed for its adequacy to resist the static design wind load of 15 psf (0.1 psi). In any event, the connection can be strengthened by connecting adjacent window sills with a long steel strap attached to the beams by lag screws. This is required at 9 locations.

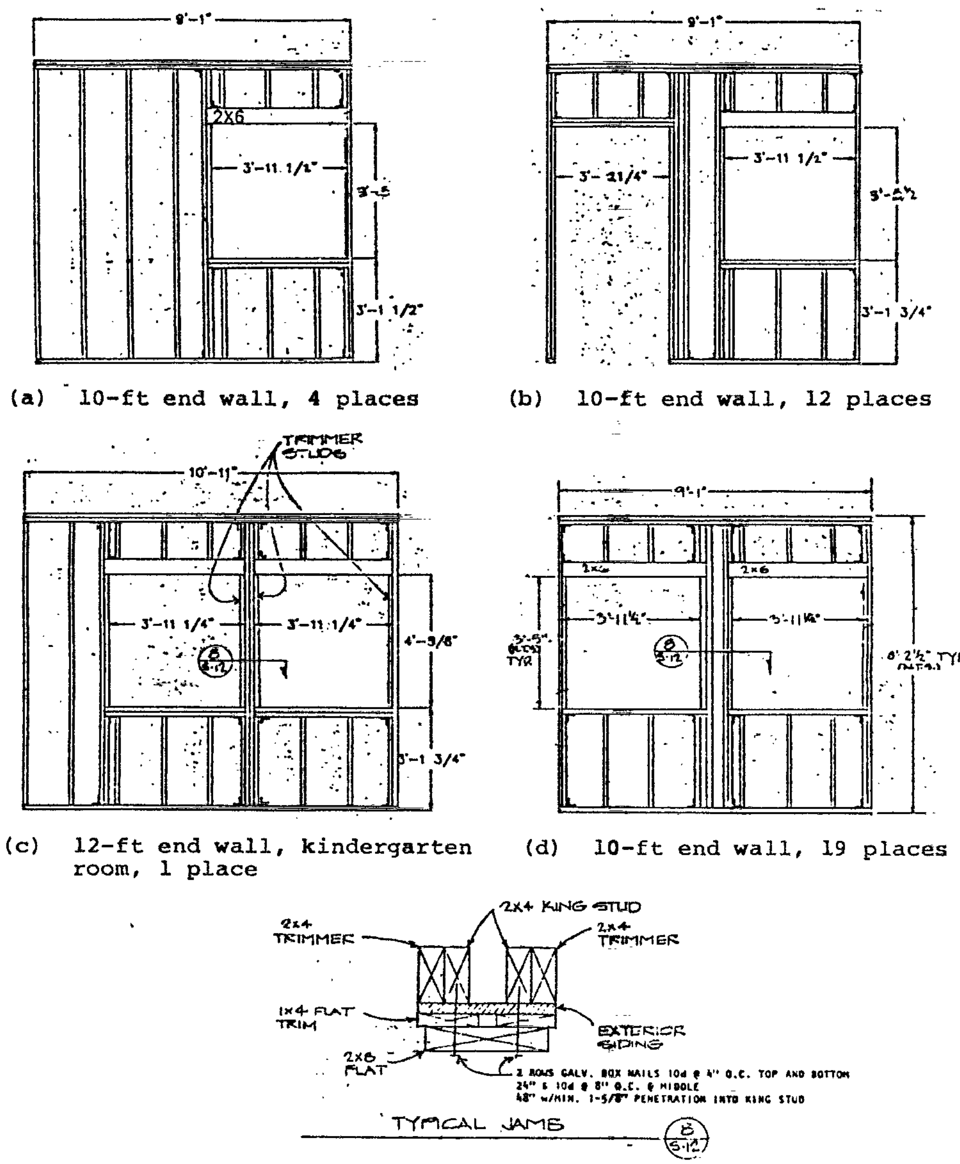
TABLE 1. MAXIMUM RESISTANCE OF SCHOOL BUILDING ELEMENTS TO BLAST OVERPRESSURE

ROOF		
Element	Failure Mode	Resistance, psi
3/4-in. Plywood Sheathing	Deflection	1.10
6-in. Steel Purlin	Bending	0.99
32-ft Steel Truss	Welding	0.70
40-ft Steel Truss	Welding	0.60

SIDE WALLS		
10-ft High Typical Construction		
Typical 2 x 4 studs @ 16" O.C.	Bending	0.58
Same as above subjected to reflected overpressure	Bending	0.42
Double 2 x 4 studs between 4' x 3-1/2' windows	Bending	0.74
Single 2 x 4 stud at side of single 4' x 3-1/2' window	Bending	0.31
3 x 3 x 1/4 L (bottom chord of roof truss) braced to roof purlin by knee-brace at 8 ft spacing	Bending	0.60

TABLE 1. (CONCLUDED)

Element	Failure Mode	Resistance, psi
<u>17-ft High Multipurpose Room</u> Typical 2 x 6 studs @ 16" O.C.	Bending	0.86
Same as above subjected to reflected overpressure	Bending	0.67
Typical wall bolted connections of top and bottom plates to steel members	Shear	0.59
Same as above subjected to reflected overpressure	Shear	0.46
North Wall, 3 – 2 x 6 studs between 4' x 2' windows	Bending	0.71
North Wall connections	Shear	0.61
South Wall – 4 x 6 window sill	Bending	0.86
South Wall – bolted connection of 4 x 6 window sill to steel tube roof column	Notch Shear	0.14
South Wall – bolted stud connection at floor at 6 ft wide door jamb	Notch Shear	0.13
3 x 3 x 1/4 L (bottom chord of roof truss) braced to roof purlin by knee-brace at 8' spacing	Bending	0.37
2 – 2 x 6 studs at 6' wide door jamb	Bending	0.60



(a) 10-ft end wall, 4 places

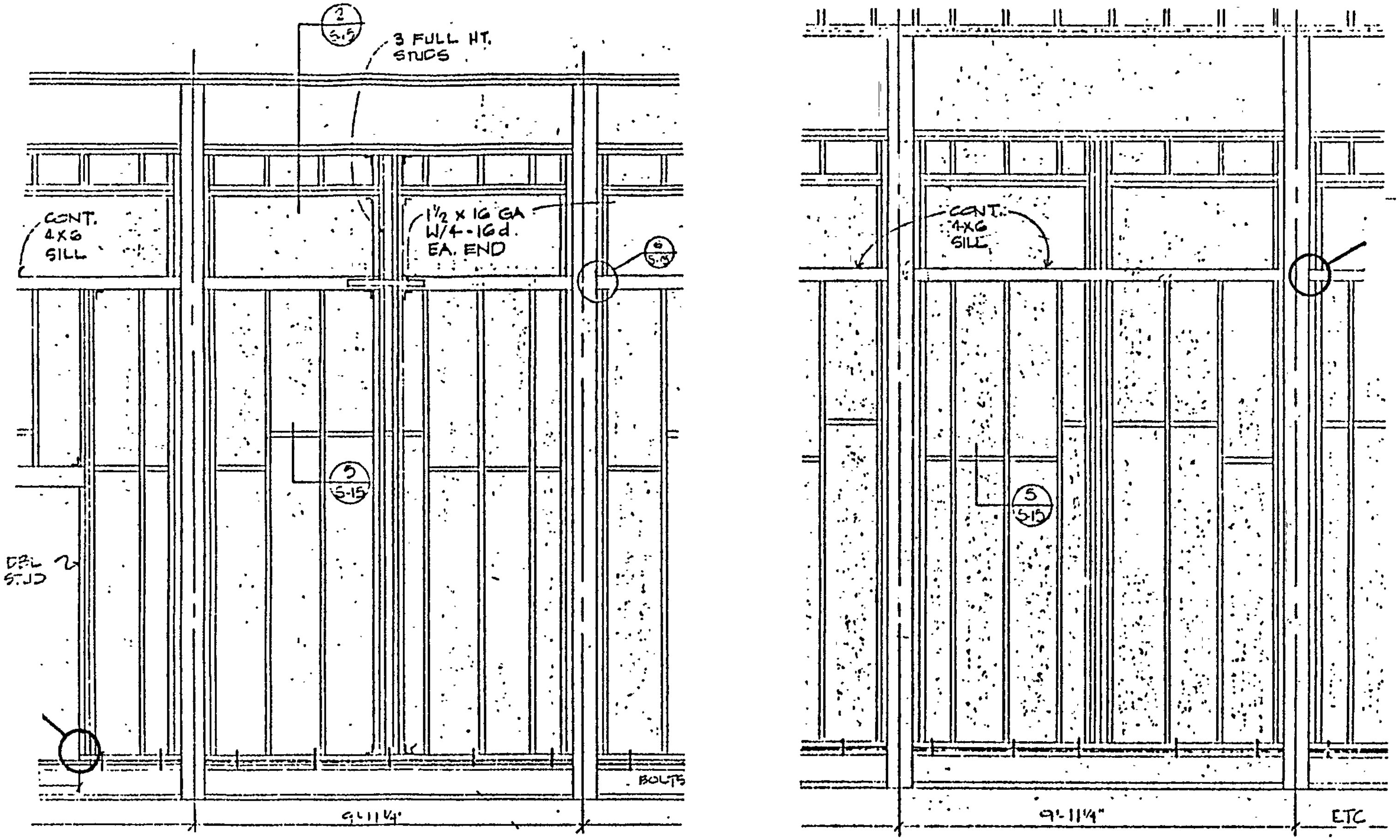
(b) 10-ft end wall, 12 places

(c) 12-ft end wall, kindergarten room, 1 place

(d) 10-ft end wall, 19 places

(e) Detail at double window

FIGURE 13. TYPICAL WALL FRAMING AT WINDOWS AND DOOR OPENINGS



(a) Multipurpose room, north wall framing

(b) Multipurpose room, south wall framing

FIGURE 14. MULTIPURPOSE ROOM WALL FRAMING

The notched-beam limitation on horizontal shear stress in bolted connections also limits the resistance of the wall framing because of the tie-down connection that anchors door jamb studs to the steel floor channels at double doors. This connection limits the resistance of the door jamb studs to 0.13 psi at 8 locations. The connection can be strengthened by using a variation of the detail described above for the window sill, but the steel strap has to extend below the floor and weld to the steel module frame.

The multipurpose room wall framing spans from the floor to the 3 x 3 x 1/4 steel angle that is the bottom chord of the module roof truss. This member must carry the wall reaction in horizontal bending between knee-braces that are spaced 8 ft apart. The spacing of the braces limits the overpressure that the walls can transmit to the bottom chord angle to 0.37 psi.

The resistance of the multipurpose room is currently limited to 0.13 psi by the bolted connections in wood members framing the south wall that must be treated as notched beams. If these connections are brought up to code, the resistance of the multipurpose room will be at least 0.4 psi. To further increase the resistance of the multipurpose room, the wall bolted connections at top and bottom (resistance of 0.46 psi) and the bottom chord of the roof truss (resistance of 0.37 psi), require strengthening.

(c) Special Reflected Pressure Condition at West Multipurpose Room Wall and Adjacent Classroom Buildings

There will be a reflected pressure build-up on the walls of the adjacent modules due to overpressure reflection on the west wall of the Multipurpose Room. The clearing of the reflected pressure from the Multipurpose Room is impeded by the walls of the adjacent buildings and the build-up of pressure on these walls will approximate the reflected pressures. This increase in side-on overpressure will extend back from the Multipurpose Room wall a distance about equal to the height of the wall.

The school room walls experiencing the increased loading includes three doors and two sliding windows. Two of the doors open inward and their resistance is limited by the strength of the door latch. Refer to Paragraph 8 for further discussion of the doors.

The resistance of the sliding classroom windows is controlled by the center aluminum mullion. The mullion resistance to reflected overpressure is 0.27 psi. The glazing resistance to reflected overpressure is 0.7 psi.

The single-stud framing condition at window openings in the area subjected to the reflected pressure should be reinforced using a flat 2 x 6 as discussed previously for similar situations.

6.2 Bus Garage Evaluation

Results of the evaluation of the bus garage roof and wall structural systems are summarized below.

(a) Description of Construction

The building is a clear span rigid frame steel structure 60 ft by 50 ft in plan and 14 ft high with a 12 ft by 24 ft roll-up door. The roof is framed with purlins covered by ribbed sheet metal panels and cross-braced by steel cables. The walls are framed by girts and wind columns and covered by ribbed sheet metal panels. The end walls are cross-braced by cable.

(b) Summary of Findings

Roof System: The roof panels and purlins and the tapered girder each have a resistance of at least 0.67 psi.

End Wall System (North and South Walls): The wall girt resistance is 0.41 psi, and the wall panel resistance in 0.48 psi.

Side Wall System (East and West Walls): The resistance of the wall girts and panels is at least 0.4 psi. The rigid frame column has a resistance of at least 0.7 psi.

6.3 Two-Car Garage Evaluation

Results of the evaluation of the two-car garage roof and wall structural systems are summarized below.

(a) Description of Construction

The building is a steel-framed structure 25 ft by 20 ft in plan by 10 ft high with a 7 ft by 16 ft door. The front and back walls are rigid frames. The side walls and roof are cross-braced by cables. Construction is similar to the bus garage. The building is covered by ribbed sheet metal panels.

(b) Summary of Findings

Roof System: The resistance of the roof purlins is 0.50 psi. The resistance of the roof panels and tapered steel rigid frames is at least 0.7 psi.

Wall Framing Systems: The resistance of the wall girts is at least 0.7 psi. The resistance of the wall panels is limited to 0.46 psi.

6.4 Caretaker's Mobile Home Evaluation

This structure is a conventional wood-framed double-wide unit mobile home approximately 26 ft by 66 ft supported on steel leveling piers. It was not possible to obtain fabrication drawings from the supplier, but it can be assured that the unit complies with Manufactured Home Construction and Safety Standards, Section 3280.404, issued by the Department of Housing and Urban Development. From a visual inspection of the mobile home, it appeared that the unit is sturdy and well constructed.

The adequacy of the wood-framed building was evaluated using the maximum resistances of the school building elements summarized in Table 1. The vulnerability of the window glazing is discussed in Paragraph 7. The building is supported off the ground on steel leveling piers approximately 18 to 24 in. high that are not braced or anchored to the ground. The building does not have a lateral force bracing system below the floor level and is vulnerable to being displaced and falling to the ground when subjected to earthquake ground motion or reflected blast overpressures.

6.5 Ball Storage Room Evaluation

This structure is a wood-framed building 10 ft by 12 ft in plan and 8 ft high. The walls are constructed with 2 x 4 studs covered by plywood sheathing. The roof is flat, framed with 2 x 8 rafters and covered by plywood and built-up roofing.

The adequacy of the structure was evaluated using the maximum resistances of school building structural elements summarized in Table 1. The top plates of the 10 ft long end walls have a resistance of 0.24 psi under wall loading and require bracing at the center to reduce their span.

7. WINDOW GLASS RESISTANCE TO OVERPRESSURE

All exterior glazing used in the school building is either tempered safety glass or laminated safety glass. Tempered safety glass is a single piece of specially heat-treated glass, which has a locked-in stress pattern that ensures that the piece will fracture into numerous granular, nonjagged fragments. This type of glass has a significantly higher impact strength than ordinary glass. The laminated safety glass consists of two pieces of glass held together by an intervening layer of plastic materials. It will not fall apart when cracked by impact, since splinters and sharp fragments will adhere to the plastic interlayer.

The resistances of the windows on the school site to overpressure are summarized in Table 2.

7.1 School Building Windows

The blast resistance of the sliding classroom windows is limited by the strength of the vertical aluminum mullion at the center of the window. Although the glazing itself will withstand overpressures of 1.3 psi, the mullion will fail under the tributary window loading imposed by an overpressure of 0.3 psi. The mullions can be strengthened by attaching an aluminum bar to the exterior flange of the mullion with self-tapping sheet metal screws.

The strength of the laminated safety glass in the multipurpose room windows is limited to 0.4 psi. Substitution of tempered safety glass would increase this resistance to at least 0.7 psi.

The exterior windows in the administration area are judged safe for all threats being considered since they will resist an overpressure of 0.9 psi. The windows in the administration restrooms are also adequate for the largest overpressure being considered.

7.2 Vehicle Windows

In the United States, vehicle window glazing is exclusively tempered safety glass. In a 175-ton high-explosive test conducted by the U.S. Department of Defense Explosive Safety Board at the Naval Weapons Center, China Lake, CA, automobiles were located at various distances from the center of the explosion and exposed to face-on (reflected) overpressures (Reference 5). The results of this test can be summarized as follows:

TABLE 2. MAXIMUM RESISTANCE OF WINDOWS

Window		Resistance, psi
Location	Description	
Classroom	4'-0" x 3'-6" Sliding – Dual Glaze with 3/16-in. Tempered Safety Glass	1.3
	Aluminum Mullion	0.3
Multipurpose Room	4'-0" x 2'-0" Projection – Single Glaze with 1/4-in. Safety Glass	0.4
Administration	2'-0" x 6'-0" Single Hung with 3/16-in. Tempered Safety Glass	0.9
Automobiles and Buses	Vehicle Glazing – Tempered Safety Glass	0.5 to 1.2
Caretaker's Home	Normal Residential Glazing – Annealed Glass	< 0.20

Overpressure	Range of Damage
0.5 psi	- No damage
0.9 psi	- No damage - Multiple fractures
1.2 psi	- No damage - Multiple fractures - Completely broken out

Therefore, it is judged that the windows in vehicles on the school property should sustain at most fracture of windows under the entertained overpressure threats.

7.3 Windows in Caretaker's Home

The windows in the caretaker's home are plain, annealed glass and will be easily fractured at the overpressures of interest, especially windows normal to the direction of the blast wave, which are subject to reflective overpressure. Typical breakage of annealed glass produces long, sharp-edged splinters. It is prudent to replace all windows in the caretaker's home with tempered safety glass.

8. DOOR RESISTANCE TO OVERPRESSURE

The school building door leaves are all 3 x 7 ft, of solid core wood construction, and hung by three hinges. Both inward and outward swinging leaves are used. Hollow metal door frames are used. The door leaves and hinges resist the applied overpressures with large margins of safety. The catches on leaves that swing inward, however, will probably fail, thus allowing the door leaf to sing open. The side-on overpressure that is required to accelerate the leaf to the 10-fps mostly safe impact velocity (see Paragraph 4) is about 0.6 psi, which is about equal to the largest overpressure being entertained.

For leaves that open outward and that are open when struck by the airblast, a peak side-on overpressure of 0.3 psi produces the 10-fps threshold velocity. This overpressure is lower than the above value because the leaf sees a reflected overpressure.

The inward swinging door leaves, with the two exceptions noted below, are judged safe for all threats being entertained. The outward swinging door leaves, however, have potential for inflicting injury. The Faculty Workroom and Music Room inward swinging doors are subjected to the same reflected pressure that the adjacent high wall is subjected. As a result, these two doors could be accelerated beyond the mostly safe 10-fps velocity.

All outward swinging doors and the two inward swinging doors identified above can be fitted with double-acting door closures to eliminate <u>all</u> risk of injury under the full range of threat conditions under consideration.

9. UPSET/FAILURE OF BUILDING CONTENTS

The airblast-induced shock created by the interaction of a blast wave with a structure and the resulting deformation of the building may upset contents, or upset or fail nonstructural systems, or both. These responses are similar to those induced by earthquake.

Free-standing equipment such as bookshelves, filing cabinets, lockers, vending machines, and storage racks can overturn due to floor motions and injure persons, damage contents, and impede egress from the facility. It was noted during visits to the school that bookshelves and lockers appear to be well anchored against overturning.

Chemical spills in the science laboratory and storage lockers can create hazardous conditions from mixing of chemicals. Containers on shelves or in cabinets should be constrained to prevent their falling on the floor. It was noted that chemicals in the Science Laboratory Room were stored in cabinets, but that the cabinet doors were not well secured. It is prudent to install positive latches or other means to prevent these cabinet doors from opening accidentally when not in use.

Suspended ceilings and light fixtures should be well secured to prevent them from falling and injuring persons or damaging equipment. Recessed light fixtures should be secured to the roof structure by hanger wires at corners of the fixture. T-bars supporting the suspended ceilings should be well anchored to the roof hangers. An examination of the construction drawings for the school indicate details for securing the suspended ceilings and light fixtures are sufficient for the largest overpressure being considered.

Anchorage of mechanical and electrical equipment is to prevent loss of the usage of the equipment and for life safety. Water heaters/boilers are well anchored to prevent translation and/or overturning. Transformers, switchgear, and electrical panels are anchored. Broken gas lines can create hazardous problems where sparks could result in fires or explosions. The installation of earthquake-activated shutoff valves can reduce this hazard. It was noted during the inspection that the LPG tank providing gas for the Science Laboratory was not tied down. It is prudent to secure this tank against movement.

There is an interior window and a trophy case within the administration area that is glazed with plain glass. It is prudent to replace these glazings with safety glass since they are vulnerable to accidental breakage and are a hazard to students and faculty. There is an outside bulletin board mounted to an exterior wall in the open court between classrooms. The bulletin board is covered by plain glass. The glass can be easily broken by students playing ball, roughhousing, etc., as well as by blast overpressure, and presents a hazardous condition. It is also prudent to replace this glazing with tempered safety glass.

10. RECOMMENDATIONS

The following recommendations were made for mitigating the risk of hazards to humans on the school site from the effects of the accidental explosion of an LPG vapor cloud or from a major earthquake in the vicinity of the school.

10.1 Prudent Risk Mitigation Measures

Implement the following seven prudent risk mitigation measures regardless of whether the tanks are filled to 40 or 86% capacity:

1. Replace all windows in the caretaker's home with tempered safety glass to mitigate explosion effects.

2. Install positive latches on cabinet doors in the Science Laboratory to mitigate explosion/ earthquake effects.

3. Secure the LPG tank that services the Science Laboratory to mitigate earthquake effects.

4. Replace the interior window and trophy-case glazings with tempered safety glass to mitigate explosion/mishap effects.

5. Replace the Bulletin Board glazing with tempered safety glass to mitigate explosion/mishap effects.

6. Correct all shear-notch deficiencies in the school building framing to mitigate wind/explosion effects.

7. Brace the caretaker's mobile home against lateral displacement to mitigate explosion/earthquake effects.

10.2 Optional Risk Mitigation Measures

Implement, on an optional basis, the following ten measures for either tank ullage condition based on descending order of importance:

1. Sliding Classroom Window Mullions. Strengthen the aluminum mullion used in all sliding classroom windows by attaching an aluminum bar to the exterior flange of the mullion with self-tapping sheet metal screws (40 bars).

2. Doors. Install double-acting door closures on all exterior outward swinging doors excepting the north and west double doors to the Multipurpose Room and the kitchen door (16 closures) and the exterior inward swinging doors to Rooms 24 and 27 (2 closures). Limit the door swing velocity to 10 fps.

3. Ball Storage Room. Install continuous blocking between the 2 x 8 roof rafters at the center of the building from end wall to end wall.

4. Multipurpose Room Windows. Substitute tempered safety glass for all the laminated safety glass in the Multipurpose Room windows (28 places).

5. West School Wall and West Ball Room Wall. Construct new walls of 2 x 6 studs at 16 in. on center directly over the existing wall and cover with plywood sheathing to match the existing architecture. The studs should extend the full height of the wall and attach to the upper chord of the roof truss at the roof diaphragm.

6. Window Jambs. Reinforce window jambs that are framed by a single stud by nailing a flat 2 x 6 to the main stud and trimmer studs, the full height of the wall, on the building exterior. This technique is similar to the typical detail that was used to reinforced existing double studs between two window openings. The addition of the flat 2 x 6 would be required at 36 locations.

7. Multipurpose Room Walls. Strengthen the bolted connections used to attach the top and bottom plates of the Multipurpose Room walls to the steel support members by using additional nailing. Pneumatic equipment is available that can attach wood members to steel by penetrating the steel framing with special pins. This can be used to provide additional shear resistance between the bottom plate and the steel channel. At the top of the wall, the bottom truss angle supporting the wall at the top should be accessible through the suspended ceiling for attaching to the top plates through the angle leg. Holes can be drilled in the angle leg for nailing or lag bolting; or pneumatic nailers can be used.

8. Multipurpose Room Wall Framing Support Angle. Add additional knee-braces to the 3 x 3 x 1/4 angle of the bottom chord of the roof truss to which the Multipurpose Room walls are framed. Weld or bolt diagonal angle struts between the bottom chord angle and the roof purlins so that the chord angle is braced every 4 ft.

9. Bus Garage. Except for the rigid frame, the building utilizes light-gage, cold-formed structural members for purlins, girts, and other framing members, and for exterior covering. Field tests of this type of construction subjected to blast overpressures in tests at the Nevada Test Site indicate that the building can accommodate large permanent deformations without failure, provided connections do not fail. Reference 6 concludes that presently designed structures of this type may be regarded as being repairable provided they are not exposed to blast pressures exceeding 1.0 psi. Based on this information, it is concluded that the framing for the Bus Garage is adequate for the maximum pressures entertained, even though the calculated resistances indicate that wall system members are only adequate for about 0.3 to 0.4 psi. However, connections should be inspected and those that appear to be marginal should be reinforced.

10. Two-Car Garage. The resistance of the building to overpressure loading is higher than the Bus Garage. Although the resistance of the purlins, girts, and wall panels is approximately 0.5 psi, it is concluded that the building is adequate for the maximum overpressure entertained, as discussed

in Measure 9. Connections should be inspected and reinforced as may be appropriate.

10.3 Implementation of Risk Mitigation Measures

All seven prudent risk mitigation measures and ten optional risk mitigation measures, recommended above have been implemented.

11. REFERENCES

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