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NEW CONCEPTS IN THE DESIGN OF STRUCTURES TO RESIST THE EFFECTS OF EXPLOSIVE-TOXIC DETONATIONS

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DOVER, NEW JERSEY

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TABLE OF CONTENTS

SUMMARY

To insure that full protection is afforded in the event of an explosion, modern day explosive-toxic facilities must be designed to fully contain the explosive output of a detonation. The design procedures necessary to achieve this structural containment are described; additionally, several case studies are discussed in which these structural procedures were tested. These studies include both single- and multi-cell arrangements.

This presentation was made at a seminar on Disaster Hazards sponsored by the Central States Section of the Combustion Institute (and co-sponsored by Illinois Institute of Technology Research Institute) at the Manned Spacecraft Center, Houston, Texas on 7-8 April 1970.

NEW CONCEPTS IN THE DESIGN OF STRUCTURES TO RESIST THE EFFECTS OF EXPLOSIVE - TOXIC DETONATIONS

INTRODUCTION

For the last half-century, military and commercial explosive facilities have been designed utilizing criteria and methods based upon results of catastrophic events. So called safe distances were established for separation of explosive materials from other explosives, personnel, buildings, roads, etc. In many cases these separation distances were far in excess of those which can be tolerated in modern, economically efficient manufacturing facilities of explosives and explosive like materials. Furthermore, in many cases the use of the above separation distances are not truly applicable particularly where toxic and/or chemical incapacitating materials are involved in the explosive operation.

Therefore, extensive research and development programs are underway to establish procedures which are in general adequate for current and future design requirements. The procedures which have already evolved from these programs are contained in the tri-service technical manual "Structures to Resist the Effects of Accidental Explosions" (TM5-1300) and are directed primarily towards those facilities where venting of the explosive output to the atmosphere can be tolerated. In those production facilities where incapacitating materials, in addition to explosives are involved, this venting is not permitted and, thereby, necessitates the further development of these new procedures for full explosive containment protective structures. These procedures along with several case studies which were reviewed to "test" the application of the new design techniques are contained in subsequent sections of this paper.

The data reported was developed by Ammann & Whitney and Picatinny Arsenal in connection with contracts DAAA-21-67-0941 and DAAA-21-70-C-0088 as part of Picatinny Arsenal's Supporting Studies Program for the Armed Services Explosives Safety Board and the U.S. Army Munition Command.

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DESIGN TECHNIQUES

1. General

Most explosive protection systems (Fig. 1) consist of three components which must be defined in order to assess the safety of the overall system. These components include: (1) the donor system (explosive materials) which produces the damaging output; (2) the protective structure, walls and/or distances which reduce the donor output to a tolerable level; (3) the receiver system which may be personnel, valuable equipment or other explosives.

In explosive-toxic protective systems the receiver portion is not a factor in the design since full protection is always required. This is achieved by providing full containment of the explosive output of the donor within the protective structure and, therefore, the principal factors to be considered in the design of the protective system are the donor system and the protective structure.

2. Donor System

The potential output of the donor system includes blast pressures, primary and secondary fragments from the explosive container and processing equipment, respectively, and secondary effects consisting of heat, dust, toxic fumes, etc. The blast pressure is the most significant factor in the design of the protective structure. However, fragments may be of equal importance in the design of the entire system. Except for the necessity of containing toxic materials, secondary effects are seldom governing factors affecting the integrity of the structure.

a. Blast Pressures

When an explosion occurs within a confined volume, the peak pressures associated with the initial blast output (free air pressures) will be extremely high. These pressures in turn will be amplified due to their multiple reflections within the structure. In addition the accumulation of gases from the explosion will exert additional pressures and increased durations of the internal loads. The combined effects of both pressures may eventually destroy the protective structure unless adequate strength is provided. A typical pressure-time history of a confined explosion is illustrated in Figure 2.

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Although the intensity of the blast pressures associated with the initial output is extremely high, the duration of these pressures are relatively short in comparison to that of gas accumulation. Therefore, this portion of the internal blast environment may be treated as impulse loadings rather than as peak pressure loadings which are associated with relatively long-duration loads.

As the initial blast output propagates away from the center of the explosion, the initial wave (free air pressure) will contact an interior surface of the structure at which point it will be reinforced and reflected to other surfaces where they are again amplified and reflected. At any given point on a particular reflecting surface, the total impulse loading is a combination of the contributions from the initial shock and from the shock reflected from adjacent surfaces (Fig.2). The pressures will eventually decay to the more steady state gas pressure.

Although little data is presently available pertaining to the magnitude of impulse loads produced in a fully confined area, some recent tests have indicated that these loads will be similar in magnitude to those impulse loads associated with explosions in cubicle-type structures where full venting of the internal blast environment is accomplished with the use of surfaces which are either sufficiently frangible or open to the atmosphere. These loadings have been adequately defined in recent years and are contained in reports of which Reference 1 is one of many. In the interim it is suggested that impulse loads computed in accordance with the procedures for cubicle type structures where full venting is provided, be utilized for determining the impulse portion of the blast environment occurring in confined cells.

A significant amount of work has been accomplished in the evaluation of the magnitude of the gas pressure accumulation associated with partially and fully confined explosions. A major portion of this work was accomplished in Sweden (Ref. 2) where confined H.E. tests were performed to simulate the blast environment of nuclear events. These tests were performed both on a full and model scale bases. In the case of the former, the tests took place in abandoned mines and tunnels. The cumulative data obtained from both the model and full scale tests indicated that the relationship for the variation of maximum mean pressure versus the charge-volume ratio is:

$$P_{mo} = 2410 \, \frac{W}{V}^{0.72}$$

Where: P_{mo} - maximum mean pressure (psi)

W - equivalent weight of TNT (lbs)

V - volume of chamber (cu. ft.)

This relationship is plotted in Figure 3.

Unfortunately, the integrated effects of the initial blast output and the longer duration gas pressures have not as yet been fully established. However, for design purposes it is suggested that the duration of the gas pressures be assumed very long insofar as the response of the structure is concerned. This assumption is fully valid when full containment is required. Furthermore, it is suggested that the total impulse used in the design of a structure be taken as a combination of the contribution from the initial shock wave and its reflections, and the pressures caused by the gas accumulation. In the case of the former, the effects of the added reflections of the initial wave will be accounted for by utilizing the cubicle-type structure blast environment previously suggested.

The above evaluation of the interior blast environment is based on close-in impulse loads associated with an explosion in a rectangular shape structure while the pressures produced by the gas accumulation is applicable to both rectangular and cylindrical shape chambers. Therefore, in order to evaluate the entire blast environment in fully contained cylindrical cells, it is suggested that the assumption be made that the impulse loads produced in a cylindrical cell be taken equal to those produced in an equivalent rectangular cell whose length and cross-sectional area are the same as those of the cylindrical cells. Because the reflections of the blast wave within a rectangular structure are more numerous than in an equivalent circular structure, the above assumed internal blast environment of circular shaped cells is probably conservative. The performance of tests to verify the above hypothesis is contemplated in the near future.

b. Fragmentation

The damage resulting from flying fragments is usually significantly less than that produced by blast overpressures. However, the effects of the fragments on the overall integrity of the structure may be as severe as that of the blast. In the event that full penetration of the structure shell occurs, the internal pressures resulting from the explosion would leak through the opening and into the atmosphere and, thereby, produce the same intolerable situation which would occur if failure of one or more of the structure elements was produced by the blast effects. Therefore, in order to provide the necessary full protection, fragment perforation of the structure shell must be prevented.

As previously mentioned, two types of fragmentation are associated with explosions in processing cells, namely; (a) primary fragments which are produced by the break up of the container or casing (as in the case of military items) of the explosive and,

(b) secondary fragments which are formed by the structural failure of the equipment used in the process and/or interior portions of the structure. The weight of the primary fragments will usually be small (several ounces or less), however, the magnitude of their initial velocity will generally be in the order of several thousand feet per second. On the other hand, secondary fragments are generally much larger than primary fragments although in some cases such as bolts, rivets, etc. the sizes of the secondary fragments will be similar to those of primary fragments. Because they are heavier, the larger secondary fragments will generally have an initial velocity which is less than those of both primary and small secondary fragments. In the case of the latter, the initial velocity of those fragments will deperd upon their location at the time of the explosion. Those fragments which are situated immediately adjacent to the explosion will experience velocities which are in the order of magnitude of those of the primary fragments while the velocities of the smaller fragments further removed from the point of detonation will approach the velocities of the high speed larger fragments.

Because of the dependency that secondary fragment velocities have on the physical layout and strength of the equipment as well as the initial location of the equipment relative to the explosion, a general evaluation of secondary fragment size and/or velocity can not be made. However, a simple series of explosive tests could be performed whereby the required data could be obtained. These tests would consist of detonating the explosive item in question while situated in the midst of a pile of selected structural steel debris, or a mock-up of the equipment. The debris would represent the fragments which are formed from the break up of the equipment. The fragment velocities can be obtained by utilizing high speed camera techniques. These tests may be performed in an open area rather than in a confined space which will exist in the structure.

On the other hand, empirical data is presently available whereby an upper limit of the initial velocity and the weights of primary fragments can be determined. This data, which was originally developed for military items (Ref. 1), can be readily adapted for most metal containers of explosives. These relationships involve the weight and shape of both the container and the explosive as well as the type of the explosive under consideration. To illustrate the effects that these parameters have upon the initial velocity, number and sizes of the fragments formed, consider the three cased explosives presented in Figure 4 and the results of their container fragmentation given in Figure 5. In the case of Items 1 and 2 the maximum size fragment formed from each is approximately the same whereas the maximum size fragment produced from Item 3 is approximately eight times as large. This variation in fragment size is primarily due to the difference in the container wall thicknesses; the wall thickness of Item 3 is 5/8 inches while that of Items 1 and 2 is 1/8 inches. On the other hand, the number of smaller fragments formed from an explosion of either Items 1 or 2 are larger than the number of fragments produced by a detonation of Item 3. Here, the larger quantity of explosive material involved in the first two items will require the use of larger size containers than needed for Item 3 and, thereby, provide more metal material to contribute to the formation of the fragments. It should be noted that the variation in the number of given size fragments produced by an explosion of Items 1 and 2 is due to the variation in the lengths of the cylindrical portion of their containers. If the results of the fragmentation analysis presented in Figure 5 also included the fragments formed by the end sections of the cylinders then the variation in the number of fragments formed from these items would be even larger than that shown.

Based upon the above illustrative example it can be concluded that the governing factor in determining the sizes of container fragments is the thickness of the container whereas the number of fragments formed is predominately affected by the size of the overall container. Furthermore, in order to limit the number of container fragments for a given quantity of explosive material, the container should be formed in the shape of a sphere which will present the smallest exposed container surface to the explosive.

Although to some extent the initial velocities of primary fragments are dependent upon the individual physical characteristics of the explosive and its container, they are more dependent upon the ratio of the total weight of the explosive to that of its container. In general, it may be said that as the container weight increases relative to that of the explosive the resulting initial velocity of the fragments decreases. As may be seen from Table 1, this tendency was consistent with results obtained from initial velocity calculations performed for the three explosive items previously discussed.

In performing calculations for the initial velocity of fragments, it is suggested that the quantity of explosive be increased by 20 percent to account for unknown factors which may be involved. This increase need not be applied to those calculations for determining the number and size of fragments.

3. Protective Structure

The protective structure of most explosive protection systems consists of either a shelter, where full protection for the structure's contents is provided from an exterior blast environment, or a barrier which serves as a shield between two or more potentially detonating explosives. When toxic materials are involved, however, only the shelter type configuration may be utilized (Fig. 6). Furthermore, the exterior of the structure must be protected from the internal blast environment rather than the reverse situation as described above.

Because explosive-toxic shelters are fully enclosed structures, entrances must be sealed with blast doors during all hazardous operations or, in certain instances, the use of blast locks (two blast doors, one of which is always closed) is required. Other openings required for toxic facility operations, such as ventilation openings, equipment access openings, etc. may be sealed with blast valves or blast shields. In most cases all closure systems for openings will require blast seals around their periphery to prevent uncontrolled leakage of the internal blast pressures into the atmosphere.

Re-entry into a protective structure after the occurrence of an explosive-toxic incident can not be accomplished until all internal blast pressures have been evacuated and contaminates removed. In the case of the latter, particulate filters must be provided to purify contaminated air before it is released to the atmosphere. Because the blast resistant capabilities of filters are extremely low, the pressure "exhaust system" must be provided with pressure release valves whereby the velocity of the air flow through the filter can be maintained at a safe level. Both the valve and filter usually are located exterior of the shelter and, therefore, all piping between the valve and the structure's interior must be hardened.

a. Blast Pressure Response

The design of protective structures to resist the blast effects of fully confined internal explosions must consider both the high- and intermediate- pressure design ranges as described in Reference 1. In the case of the high pressure range, the impulse capacity of each structural element must be sufficient to resist the high intensity pressures associated with the initial output of the explosion. In addition, the strength of the individual elements must be greater than the maximum mean pressure produced by the gas accumulation within the structure. However, in order to maintain an economically feasible facility, the structural elements should be permitted to attain plastic deformations.

To illustrate the above blast resistant characteristics consider an element of a typical cell which is subjected to an internal blast load defined by the curve A-B-D-G of Figure 7 and has a resistance-time relationship corresponding to the curve A-C-E-G of the above mentioned illustration. In order for the element to remain intact, the area C-D-E-F must be equivalent to the area A-B-C and the ultimate resistance (R_{ULT}) of the element must be larger than the maximum mean pressure (P_{mo}) of the accumulated gas. It should be noted that if the ultimate resistance is increased relative to the value of P_{mo} then the time to reach maximum deflection is decreased. This decrease in response time will then correspond to a smaller deflection than would otherwise have occurred with the reduced value of the resistance. The magnitude of the permissible deflections should be such as to insure that all blast seals are maintained and, thereby, prevent the escape of toxic fumes.

Once the maximum deflection (Fig. 7) of an element is reached, its response curve (resistance-time) will vibrate about the long duration (flat-top) portion of the load curve until structural damping brings the vibrating system to rest. Because of their physical characteristics, reinforced concrete elements will usually attain steady state conditions in a significantly shorter period of time than structural steel elements.

In the analysis of structural elements subjected to the blast effects of an internal explosion, an approximation has been devised whereby an element is initially analyzed only for the impulse portion of the applied blast loads. Once the structural response (resistance and deflection) is determined for this loading then the calculated ultimate strength (ΔR_{ULT}) is added to the value of the maximum mean pressure to obtain the overall ultimate strength (R_{ULT}) required of the element. It should be realized, however, that the above procedure only applies to those elements whose mass is not increased with the increase of strength. For reinforced concrete members this increased strength may be furnished merely by providing an increased amount of reinforcement whereas for structural steel an increase in strength without providing a heavier member can usually only be achieved by utilizing a higher strength steel. This latter method is not usually applicable and, therefore, adjustments in both the mass and strength will have to be made to produce the desired structure response.

The use of single cell arrangements to resist the full effects of gas accumulation are generally applicable to explosive quantities less than 50 pounds. For the full containment of gases from larger quantities of explosives, however, the magnitude of the gas pressures may be so high as to make the use of a single cell arrangement impractical. In this case a multiple cell arrangement may be utilized; one cell serves as the operating area while the second (or more) cell is utilized as a plenum chamber (Fig. 8). In the event of an explosion within the operating area the initial shock wave will propagate until the interior of the cell is engulfed at which time a frangible element (or elements) between the operating cell and the plenum will fail and allow the accumulated gas pressures in the cell to expand into the plenum. This expansion will result in a reduction of the required capacity (strength) of the shell of the operating cell since the gas pressures in the cell are reduced.

For the use of the plenum system to be economically feasible, the cost incurred by the addition of the plenum must be less than the additional cost associated with the increased strength required when only an operating cell is utilized. For the case where several operating cells are involved, the use of a common plenum chamber (Fig. 8) appears to be the most economical arrangement possible. The operating areas and the plenum chamber are connected by blast doors which are allowed to blow into the plenum chamber due to pressures occurring in the operating areas but are designed to resist pressures occurring in the plenum chamber. Therefore, when an explosion occurs in one operating area (donor cell), the blast door between that cell and the plenum will fail and thereby allow the accumulated gas pressures in the donor cell to expand into the plenum.

b. Fragment Response

Upon contact with a barrier, a fragment will either pass through (perforate), be embedded in, or be deflected by the structural element depending upon: (1) the magnitude of the initial velocity of the fragment, (2) the distance between the explosion and element, (3) the physical properties of the fragment (weight, shape, material strength and hardness, dimensions, etc.), and (4) the angle at which the fragment strikes the barrier (angle of obliquity).

For most facilities which fully contain an explosion the distance between the explosion and the barrier (shell of structure) is relatively small and therefore, the second aspect affecting fragment penetration will not be a significant factor in determining the thickness of the structure shell. Here, the striking velocity of the fragment may be assumed to be equal to its initial velocity.

As will be shown later this initial (or striking) velocity will be one of the major factors affecting fragment penetration.

The other major contributing factor which will regulate fragment penetration is the physical characteristics of the fragment and barrier. Fragments which are formed from mild steel containers will penetrate a barrier less than armor-piercing fragments. On the other hand, fragment penetrations into mild steel barriers will be larger than the penetration of fragments into armor plate barriers. These variations will tend to offset one another when the same type of steel is used for both the fragments and barriers, i.e., the penetration of armor-piercing fragments into armor plate is approximately the same as that of mild steel fragments into a mild steel barrier where the mass (weight), shape and striking velocity of the two fragments are the same. Another interesting aspect of the effects that the barrier's physical properties have on fragment penetration is the fact that the penetration of mild steel fragments through concrete will be equal to approximately three times the penetration of these fragments through mild steel and thereby indicates a linear relationship between the magnitude of the fragment penetration and the density of the barrier material. It should be noted, however, that this relationship does not hold for other materials such as armor plate, lead, aluminum, etc. where the hardness of the material is significantly different from that of mild steel.

The degree to which the angle of obliquity affects fragment penetration will be less than that of both the initial velocity and physical properties. Here, the lowest striking velocity which will cause perforation of a barrier of a given thickness will occur when the fragment approaches the barrier from a normal direction (90 degree angle). If the fragment approaches the barrier at a direction other than normal then the velocity necessary to cause perforation will be higher than the normal direction perforation velocity, e.g., when a fragment approaches a barrier at a angle 30 degrees from the normal, the velocity to cause perforation will be approximately 30 percent larger than the perforation velocity associated with normal impact of the fragment. Although this velocity increase is appreciable, its effect on the overall design of the barrier is less significant than the fact that as the angle of obliquity increases the phenomenon of ricochet will take place. Here, some fragments will be deflected by the structural element and/or other fragments and thereby minimize the number of fragment penetrations. It is estimated that more than half the fragments formed will be deflected by the structure shell.

Based upon the above discussion, a series of charts have been developed, based on the procedures of Reference 1 and 3, which relate the fragment weight and striking velocity, and the physical properties of the fragment and the barrier to the fragment penetration into the barrier. These charts have been developed for both armor-piercing and mild steel fragments and for barriers constructed of mild steel and reinforced concrete. The charts are presented in Figures 9 through 12 and are based upon an assumed fragment shape "A" as indicated in Figure 13. The assumed shape is probably more severe than the shapes of 90 percent of the fragment formed. However, this shape will give a good indication of the protection required.

The above fragment shape is typical of primary fragments whereas fragment shape "B" (Fig. 13) is more representative of small secondary fragments. Although the initial velocities of both fragments are essentially the same, their penetrations will be significantly different, e.g., a one ounce armor-piercing fragment having shape "B" and an initial velocity of 4400 fps will penetrate 6 inches into concrete (Fig. 9) whereas a shape "A" fragment having the same weight and velocity will penetrate 9 inches (Fig. 9). The variation in the magnitude of this penetration is typical for fragments of other weights and velocities.

CASE STUDIES

1. Case 1 - Single Cell Arrangement

This facility consists of a single cell whose shell is constructed of structural steel. The cell is formed from three sections; a 12 ft. - 0 in. exterior diameter cylindrical center section and two enclosing end sections (Fig. 14). One of the end sections is monolithically attached to the center section of the structure while the other end section can be removed and, therefor, this section may be considered as a component element. Use of the component end section is predetermined by the need for providing a means of access for equipment into the cell.

This structure is designed to resist the combined effects of the internal explosion of the three contained explosive items previously discussed (Fig. 4). The combined explosive weight of the three items is equal to 23.5 pounds of H.E.

The central section of the cell consists of a bent one-inch thick structural steel plate which is welded along a longitudinal seam to form a 20 ft. - 0 in. long cylinder. The inside diameter of the cylinder is 11 ft. - 6 in. while the cylinder length is equal to the length of the operating area.

Personnel entrance into the cell is accomplished through an opening situated in the component end of the structure. This end section consists of a circular structural steel plate which is bolted around its periphery to a circular flange which in turn is butt welded to one end of the cylindrical plate. The flange section consists of a one inch thick circular steel ring having an interior and exterior diameter of 11 ft. - 0 in. and 12 ft. - 0 in., respectively. A total of 72-7/8 inch diameter bolts are required to form the connection between the two sections of the structure (Fig. 15). The bolts are positioned in two rows; half are situated at each side of the cylindrical plate. This double bolt arrangement will provide a smooth transfer of stress through the joint in addition to reducing the flange thickness from that which would be required if a one row bolt arrangement was used.

Because the joint between the flange and end plate will tend to open as a result of the interaction between the bolts, flanges and cylindrical plate due to the longitudinal blast loads, the joint must be equipped with a blast seal to prevent the escape of toxic materials. Here a tongue and groove system is used which utilizes a neoprene or comparable gasket (Fig. 15). However the separation occurring between the flange and the end plate as a result of their bending and bolt elongation must be held to a minimum of less than one-fiftieth of the distance between the interior and exterior rows of bolts in order to make the seal effective.

The access opening for personnel entrance into the cell is by means of a 3 ft. - 0 in. wide by 6 ft. - 8 in. high opening located in one of the cell end walls. This opening is sealed by means of a structural steel plate door (Fig. 16). The plate thickness required for the door is 2-1/2 inches. The door is hinged and upon opening will swing in a horizontal direction into the cell. This arrangement will permit the edges of the door to bear against the cell wall when it is loaded as a result of an internal explosion. The door is designed to permit plastic deformations corresponding to support rotations equal to 2 degrees.

The door may be subjected to negative loads as a result of the blast environment within the cell. Unless adequate means are provided the door will open and thereby permit the escape of toxic materials to the atmosphere. To prevent this possible gas leakage, a reversal mechanism is provided to resist the inward motion of the door resulting from the negative blast loads and/or the elastic rebound of the door due to the positive blast pressure effects. The mechanism consists of four reversal bolts which are attached to the door proper. When the door is closed and the cell is in a "button-up" situation, the bolts penetrate into recesses provided in the cell wall immediately adjacent to the bolts. The interaction between the door bolts and recesses provide the means to prevent the door from opening. The movement of the bolts in and out of the recesses can be either mechanically or manually operated from the exterior of the cell.

To insure that leakage of toxic agents to the atmosphere does not occur around the periphery of the door, a gas seal consisting of a tongue and groove interface with a neoprene gasket is provided. The function of this seal is similar to that described for the seal between the interface of the end plate and the cylinder flange.

The monolithic end section of the cell may consist either of a steel plate similar to the component section described above or a dished head steel plate similar to that used to enclose the ends of conventional boilers and/or unfired pressure vessels. The use of a dished head configuration is however predicated on the assumption that the number and size of openings in the dished head will be limited. Because this end section need not be disconnected from the remainder of the cell, the dished head or plate may be welded directly to the cylindrical plate.

The description of the structure up to this point was primarily directed towards blast overpressures. However, as mentioned previously, the effects produced by the occurrence of primary and secondary fragments may be equally important in the structure design as the blast effects. To illustrate the effects of fragments, a comparison of the fragment penetration through mild steel and/or concrete was made for the maximum weight fragment and initial fragment velocities corresponding to the three contained explosive items housed in the cell. These penetrations are listed in Table 2 along with those penetrations which are produced by fragments whose weights are equal to one-half the weight of the maximum size fragment. As may be seen from Table 2, both weight fragments penetrate both the cylindrical and the dished head section of the structure while only the maximum weight fragment will penetrate the steel door. Therefore, in order to prevent perforation of the structural steel shell by fragments, a flat circular end section should be used in place of the dished head section and the thickness of the door should be increased. However, in the case of the cylindrical plate, rather than increasing the plate thickness, a more economical solution to prevent fragment penetration would be to utilize a 7-1/2 inch concrete liner in conjuction with the 1 inch steel plate. The concrete liner need not be fabricated in one unit and therefore could be installed in sections after the structural steel portion of the cell is constructed. The use of the concrete liner may require a slight increase in the steel cylinder diameter in order to provide the necessary operating space within the structure.

2. Case 2 - Multi-Cell Arrangement

This facility consists of three structures. However, all three buildings contain very similar processes and therefore a description of the design of anyone of the structures will also describe the designs of the other two buildings. For the purpose of discussion the design of the building to be described in this paper will be referred to as Building A (Fig. 17).

Building A is a one story structure having a plan shape similar to that of the letter E where three parallel wings lead from a common end portion of the building. This latter section of the building is used for access between the various wings in addition to housing a portion of the operating facilities of the building.

The structure is subdivided into 65 compartments or cells and six major corridors. The cells are used for processing of the hazardous material or administrative purposes while the corridors are used for personnel access and/or movement of equipment. A minimum ceiling height of 12 feet is required throughout the structure except in Compartment 6, 7 and 8 where a ceiling height of 8 feet may be used. These latter three compartments are administrative areas. All corridors are 12 feet wide to provide room for movement of equipment about the building.

The various cells have been classified based upon the operation performed in the individual areas, namely: (a) Non-hazardous or N-Area, (b) Toxic or T-Area, (c) Explosive or E-Area and (d) Toxic and Explosive or T&E-Areas. The first area classification pertains to those compartments of the building which serve as support for the processing areas and include offices, laboratories, washrooms, toilets, locker rooms, dining area, etc. The other three area types are classified as hazardous areas where processing of toxic and explosive materials is performed in T-Areas and E-Areas, respectively, and a combination of toxic and explosive materials are handled in the T&E-Areas. The maximum quantity of explosive materials contained in each cell is 50 pounds of HE equivalent. The hazardous portions of the structure are constructed of reinforced concrete while the non-hazardous areas have walls and roofs constructed of light metal panels and light metal joists and metal decking, respectively.

The compartments containing the toxic and explosive material and several administrative areas are located in the three wings of the building while the cells containing the other hazardous processes are located in the end portion of the building. Eight cells are used for each of the toxic material and explosive material processes whereas a total of 35 cells contain the combined toxic-explosive material process.

The toxic material cells are fully enclosed compartments. Two adjoining cells have a common decontamination chamber (Fig. 1b). Contaminated clothing used in the process cells is removed in the chamber and showers are provided for the operating personnel. The interior of the toxic material cells is either painted with an epoxy paint or a steel liner is provided to insure hard smooth surfaces which can be thoroughly cleaned between operations.

The eight cells containing explosives are divided into two groups; each group consists of four cells. As previously mentioned, each cell contains 50 pounds of explosive and therefore Building A is separated from other on-site structures by Intraline Distances corresponding to the amount of explosive contained in each cell. Each group of cells is located at the end of each exterior wing where it intersects with the common end of the building. The individual cells of each group are arranged in a line with the end wall of the first cell forming a part of the exterior wall of the building. Similar to the toxic material cells, those compartments containng explosives are fully enclosed units.

Access to two adjoining cells containing explosives is through a common blast lock; the arrangement of which is similar to that of the deontamination chamber of the toxic cells (Fig. 18). The opening between each cell and the blast lock is sealed with a 2-5/8 inch thick steel plate blast door. A third opening, leading from the blast lock to the corridor, is also sealed with a blast door. All three doors are mechanically and/or electrically interlocked and are provided with reversal mechanism to insure, in the event of an explosion in one of the cells, that the blast will not proceed beyond the lock either to the corridor or to the other cell. The reversal mechanisms for the door leading to the cells are designed to resist the full impact of the blast.

Most facilities of this type require periodic modification either of the structure and/or equipment. In the case of new equipment, provisions are made to allow movement of the equipment into the individual cells. An opening 6 feet wide by 8 feet high is located in the wall separating the cells from the exterior corridor. These openings are sealed with 3 1/8 inch thick steel plates which are bolted to the walls around the periphery of the openings. Because of the occurrence of the high non-uniform pressures as a result of the interior explosion, solid steel plates are used in lieu of the less expensive built-up doors.

In case of an explosion in one of the cells containing explosive materials, both the initial portion of the blast wave and the pressures associated with the gas build-up as a result of its confinement are vented through an opening in the roof of the cell (Fig. 18). This opening leads to a concrete duct which focuses the blast along the roofs of the other cells and down the exterior wall of the first cell. At this point the concrete duct is connected to an undergound culvert through which the pressures will pass until they reach a point where they are released to the atmosphere. The duct located on the roof is semi-cylindrical in shape and common to all four cells. The opening from each cell is sealed with a blast cover. In the event of an explosion in one of the cells, the cover of the opening in that cell will be displaced upward thereby allowing the pressures to be vented from the cell. However, the covers over the openings of the other cells will remain in place thereby providing the protection required for the interior of these cells.

The design of the toxic and explosive areas of the building is similar to that of the explosive areas. However, because of the presence of the toxic material, the measures taken to provide the required protection are more elaborate than previously described. Two cubicle sizes are used in the T&E-Areas of the building; one having a usable floor area of 144 square feet while the second size cubicle has twice the floor area of the first cell.

Figure 19 illustrates two adjoining cells. Access to each cell through a common blast lock which also serves as a decontamination chamber. Blast doors used to seal the openings in the lock of the small cells are the same as those used for the locks of the explosive material cells while the blast doors sealing the openings in the locks of the larger cells have a reduced thickness equal to 2 inches. All doors are mechanically and/or electrically interlocked and are provided with reversal mechanisms.

The blast walls protecting the blast lock also serve as a portion of the wall separating the two adjoining cells. The remainder of this wall is a single wall and connects the back wall of the blast lock to the exterior wall of the cells. A 2 ft. wide by 3 ft. high opening is located in this wall to provide a means of pass-thru from one cell to another. The pass-thru will only be used in the event a production operation is initiated. At the present time the pass-thrus are sealed with steel plates. However, provisions have been made such that blast doors can be installed in the future.

Located in the exterior wall of each cell is the 6 ft. wide by 8 ft. high opening required for movement of equipment into the cells. Closure of this opening is similar to that used for the large openings in the walls of the explosive material cells. The thickness of the steel plate doors used in the smaller cells is 3-1/8 inch while the door thickness for the large openings in the larger cells is 2 inches. The thicknesses of the exterior walls are 2 ft. - 8 in. and 2 ft. - 2 in. for the small and large cells, respectively. The thickness of the other two walls, roof and floor slab of each small cubicle is 1 ft. - 9 in. while for the larger cells, the thickness of the above elements is 1 ft. - 7 in. In order to provide protection against spalling for personnel in the corridors and adjacent cells, steel plates are attached to the receiver surface of each interior wall of each cubicle. The attachment of these plates to the wall is shown in Figure 20. The plates are also utilized to provide the hard surfaces required for periodic washdown. These plates may also be used as forms during construction.

Venting of the blast pressures is provided through an opening in the floor slab located adjacent to the dividing wall which is a continuation of the blast lock walls. The plan dimensions of the opening are 2 ft. wide by 4 ft. long. The opening leads to a below ground tunnel which in turn leads to a plenum chamber. The tunnel in combination with the plenum serves as an expansion chamber to reduce pressures resulting from the gases produced by the explosion to a tolerable level. In the case of an explosion in one of the smaller cells, the magnitude of the peak gas pressure would be in the order of 150 psi. With the size of the expansion chamber and the area of the opening considered in this design, this peak gas pressure would be reduced to approximately 40 psi after approximately 750 milliseconds. The peak gas pressure in the larger cells would be approximately 90 psi and would decay to 40 psi in approximately 400 milliseconds. Once the gas pressure in the expansion chamber has stabilized at the 40 psi level then the gases may be vented very slowly by control valves to the purification structure at which time the exhaust is completely detoxified by such processes as scrubbing, filtration and/or incineration.

The top of the opening in the cubicle floor slab is covered with a wooden-frame-sheet metal skin platform. This platform will prevent water, which may accumulate as a result of scrubbing of the cubicle, from seeping down onto the steel plate blast hatch located at the bottom of the opening at the underside of the floor slab. In the event of an explosion, the platform will be destroyed and the blast hatch propelled downward to provide the space required for the expansion of the pressures to the relief tunnel below the cell.

The purpose of the blast hatch below the floor opening is to provide protection for receiver cells. Although the blast pressures will "blow" the hatch downward at the donor cell, similar covers on other openings in other cells will prevent the pressures within the relief tunnel from leaking up into the receiver cubicles. Each hatch is bolted to the floor slab and provided with a gas seal to insure that toxic material does not flow past the blast hatch and into the cubicles above. The blast hatch bolts are so designed that they will fail as a result of downward pressures from the donor cell but will withstand any rebound effects produced by the blast load from the tunnel pressures impinging on the underside of the hatch.

Below the relief openings of each two adjoining cubicles is a concrete chamber. At the bottom of the chamber is a debris pit to provide room for the ejected relief opening hatch of the donor cell. The pit will prevent blockage of the tunnnel by the hatch. The chamber also provides room for partial expansion of the blast pressures before they enter the relief tunnel. The relief tunnel is constructed of reinforced concrete pipe and forms the connection between the various concrete chambers below the relief openings. The inside diameter of the pipe is 4 or 5 feet depending upon the number of cells the tunnel services.

Each wing of the building has two relief tunnels; one servicing each series of cubicles on each side of the central corridor. All tunnels lead to the expansion chamber located adjacent to the ends of the wings of the building. The expansion chamber consists of three below ground cubicles which are interconnected by reinforced concrete pipes. Each tunnel terminates in one of the cubicles. Blast doors are used to seal the ends of the tunnels at the cubicles. In the event of an explosion, the door sealing the tunnel leading from the donor cell will be blown out into the expansion chamber as a result of the blast pressures in the tunnel. However, the doors sealing the other tunnels will remain intact thereby preventing pressure feedback to the other tunnels. Entrance to the expansion chamber is through manholes located at the top of the concrete cubicles. The interior doors of the tunnels may be removed and thereby provide access to the blast relief system under the individual cubicles.

Because of the requirement of full confinement of the toxic material, an air distribution system had to be developed (Fig. 21) which prevents the blast pressures, with contaminated material, from leaking into the atmosphere through the air supply and exhaust system. Here a Breckenridge (Ref. 4) type blast-actuated valve may be used to delay the propagation of the blast for a sufficient length of time to insure a "bottom-up" condition and thereby prevent the spread of the toxic material. Both the air supply and the exhaust systems for each cell would require individual valves. As the blast wave propagates through the ventilation opening (end of valve which is indicated to or from compartment, Fig. 21), it will pass the "V-flap" valve and proceed along the delay path until the wave reaches the far end of the valve at which time the other side of the V-flap will have closed against the opening. The system should be self-locking and thereby prevent leakage of the pressures past the valve. The springs attached to the V-flap valve are for the regulation of the normal flow of air through the distribution system.

The use of the Breckenridge blast valve enables the remainder of the ventilation system beyond the valves to be unhardened. The exhaust system which may have contaminated air as a result of normal use is ducted to the air purification structure where detoxification takes place. All ventilation systems of other portions of the structure are independent of the air distribution system of the toxic-explosive areas. Similar independent distribution systems are required for the toxic areas and the explosive areas.

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2. Weibull, H.R.W., Pressures Recorded in Partially Closed Chambers at Explosion of TNT Charges, Royal Swedish Fortifications Administration, Stockholm, Seden, Annals of the New York Academy of Sciences, Conference on Prevention of and Protection Against Accidental Explosion of Munitions, Fuels and Other Hazardous Mixtures, Volume 152, Art. 1, October 1966.

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4. Breckenridge, T.A., Preliminary Development and Tests of a Blast-Closure Valve, Technical Note N-460, U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, September 1962.

APPENDICES

APPENDIX A

Tables

TABLE 1

INITIAL VELOCITY OF PRIMARY FRAGMENTS

ITEM	EXPLOSIVE TYPE	EXPLOSIVE* WEIGHT(W) (lbs)	CONTAINER WEIGHT(W_c) (lbs)	W/W_c	INITIAL VELOCITY OF FRAGMENTS (fps)
1	Propellant	19.3(18.5)	12.2	1.52	6,450
2	A	3.2(3.8)	8.0	0.48	4,900
3	B	1.0(1.2)	5.4	0.22	3,190

* Numbers in ( ) indicate explosive weight used for calculation of initial fragment velocities (includes a 20% factor of safety and TNT equivalency for propellant).

Table 2

FRAGMENT PENETRATIONS

DESCRIPTION		CASED EXPLOSIVES		
		Item 1	**Item 2**	**Item 3**
Type of Explosive		Propellant	**Explosive A**	**Explosive B**
Weight of Explosive (lbs.)		19.4	3.2	1.0
Initial Velocity of Fragments (fps)		6,450	4,900	3,190
Maximum Fragment Weight W_f (oz.)		0.52	0.48	4.10
Thickness to prevent perforation of Maximum Fragment Weight W_f (in.)	Steel Plate	3-1/4	2	2
	Concrete	10-1/2	6	6-3/4
	1 in. Steel Plate + Concrete	7-1/2	3	3-1/2
	2 in. Steel Plate + Concrete	4-1/2	None Req'd.	None Req'd.
Thickness to prevent perforation of one-half Maximum Fragment Weight (in.)	Steel Plate	2-5/8	1-5/8	1-1/2
	Concrete	7-3/4	4-3/4	5-1/4
	1 in. Steel Plate + Concrete	5	2	2
	2 in. Steel Plate + Concrete	2	None Req'd.	None Req'd.

APPENDIX B

Figures

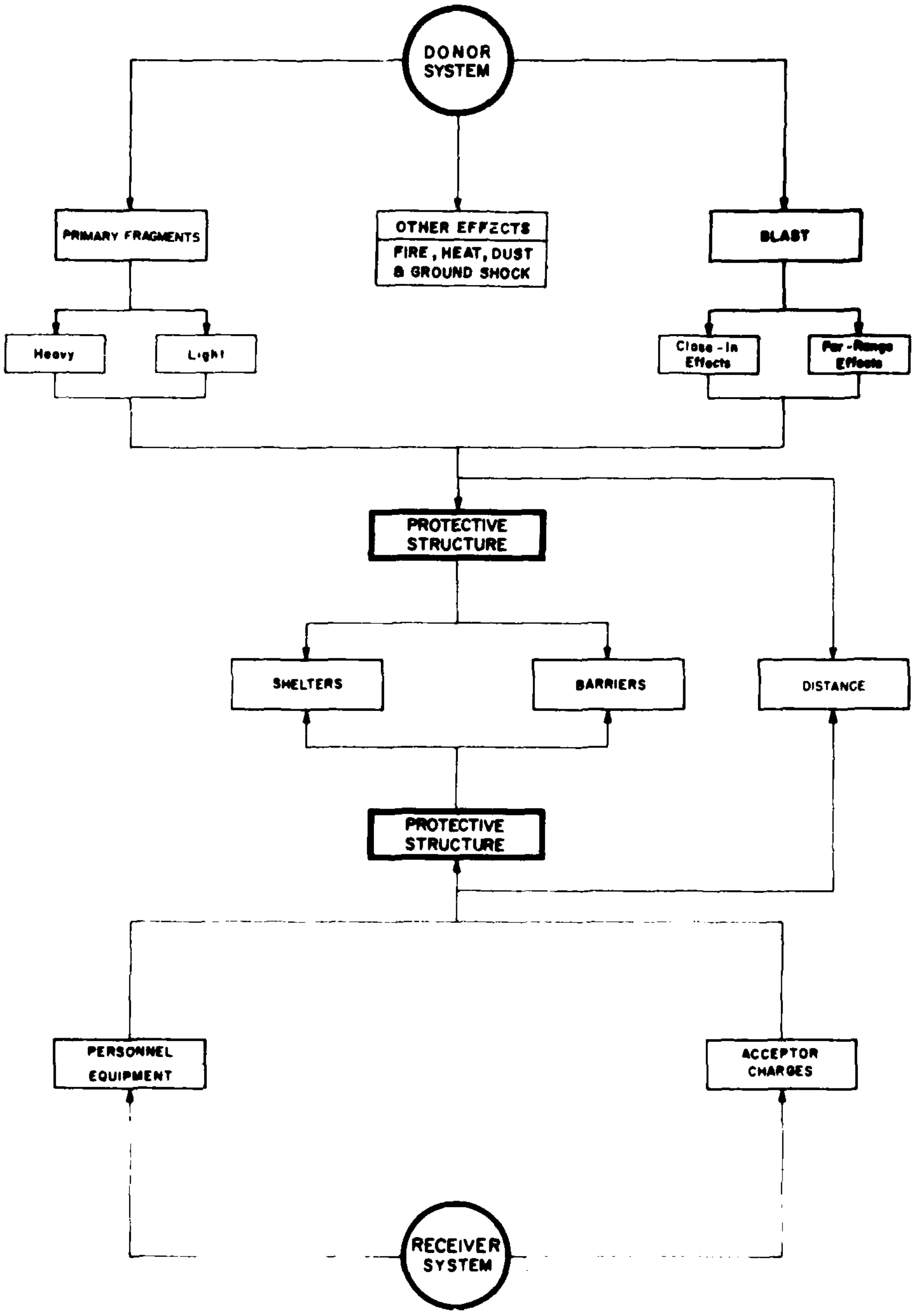


FIG. 1 EXPLOSION PROTECTIVE SYSTEM

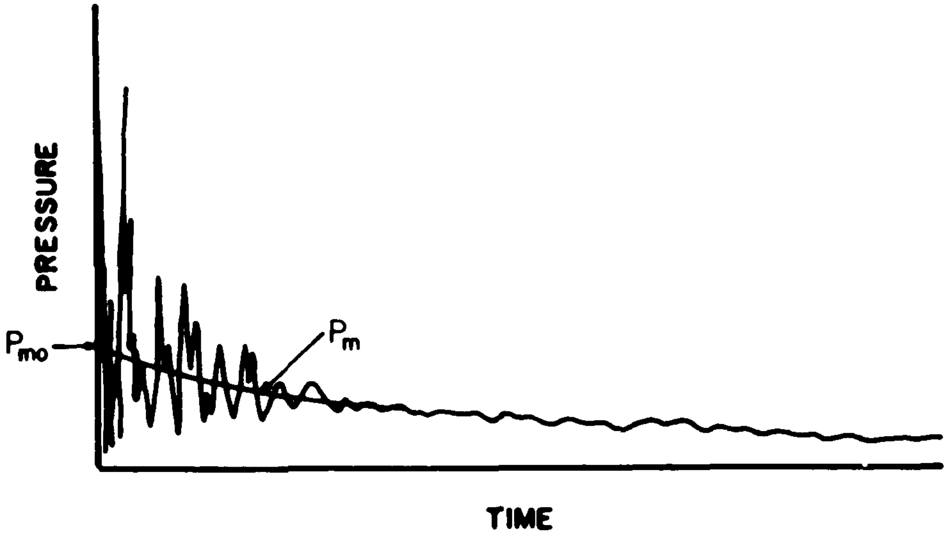


FIG. 2 PRESSURE-TIME VARIATION FOR A PARTIALLY VENTED EXPLOSION

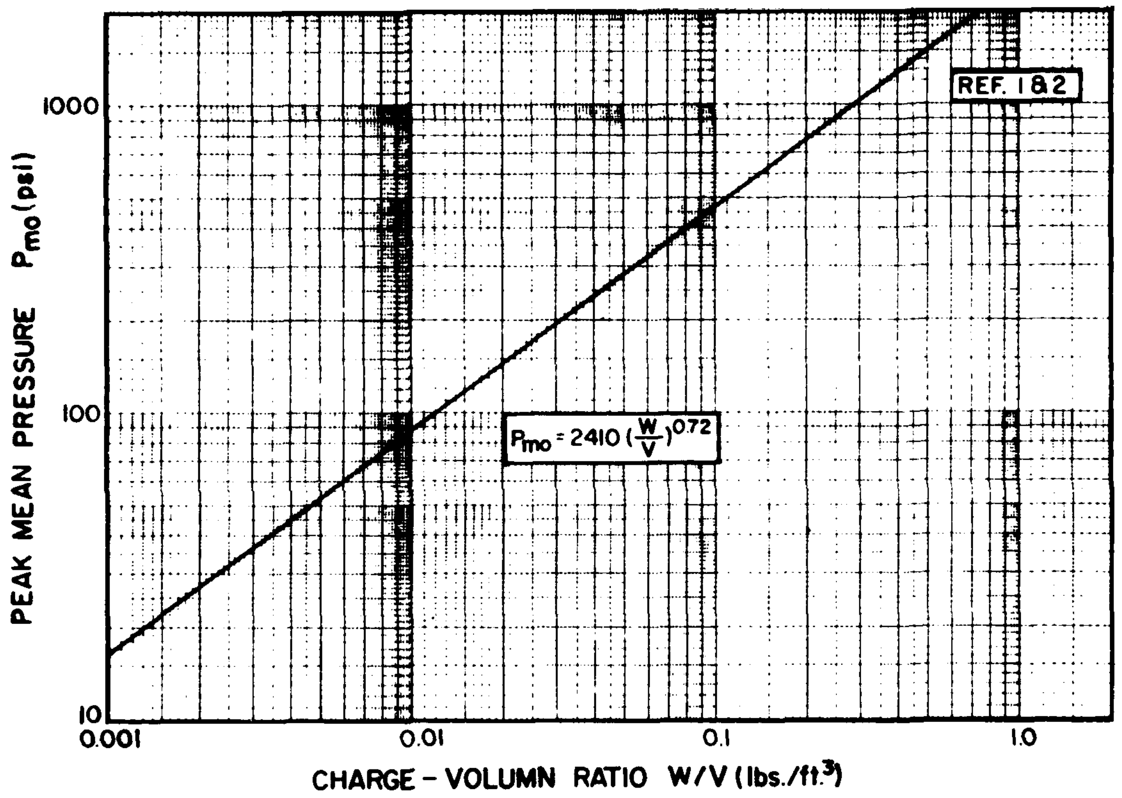


FIG. 3 PEAK MEAN PRESSURE IN A PARTIALLY VENTED CHAMBER

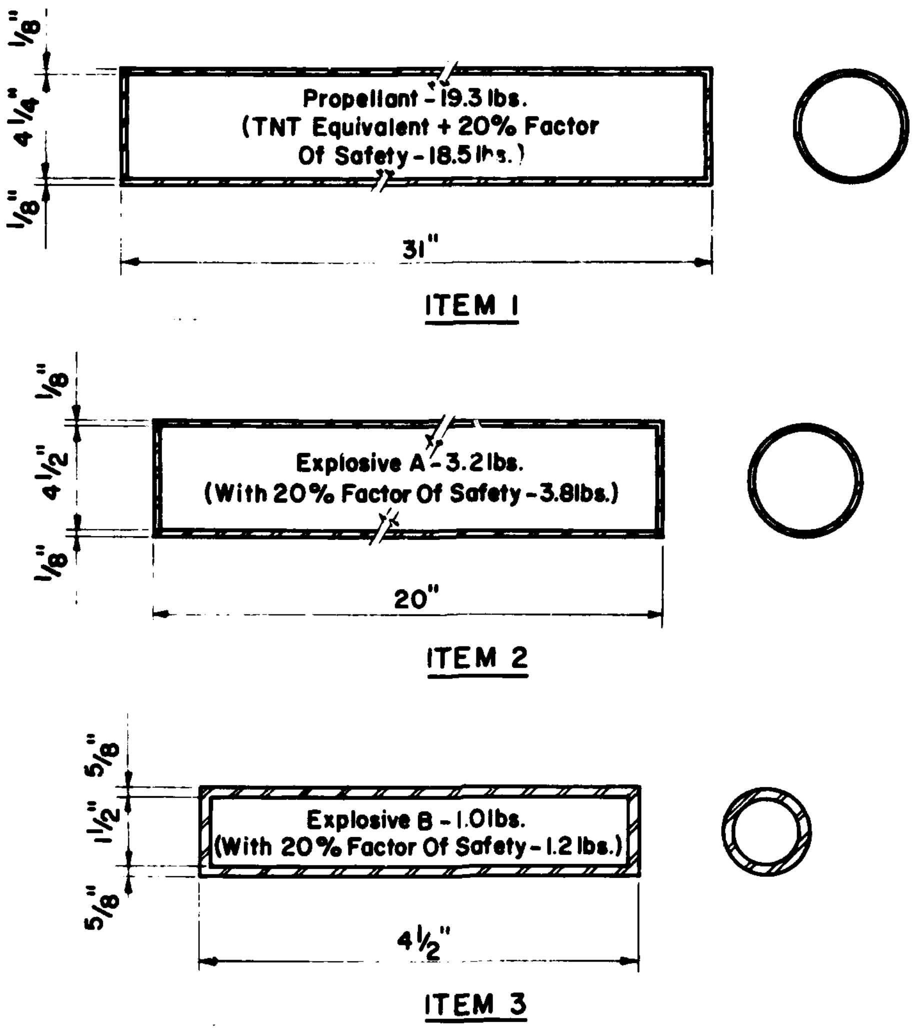


Fig. 4 CONTAINED EXPLOSIVES

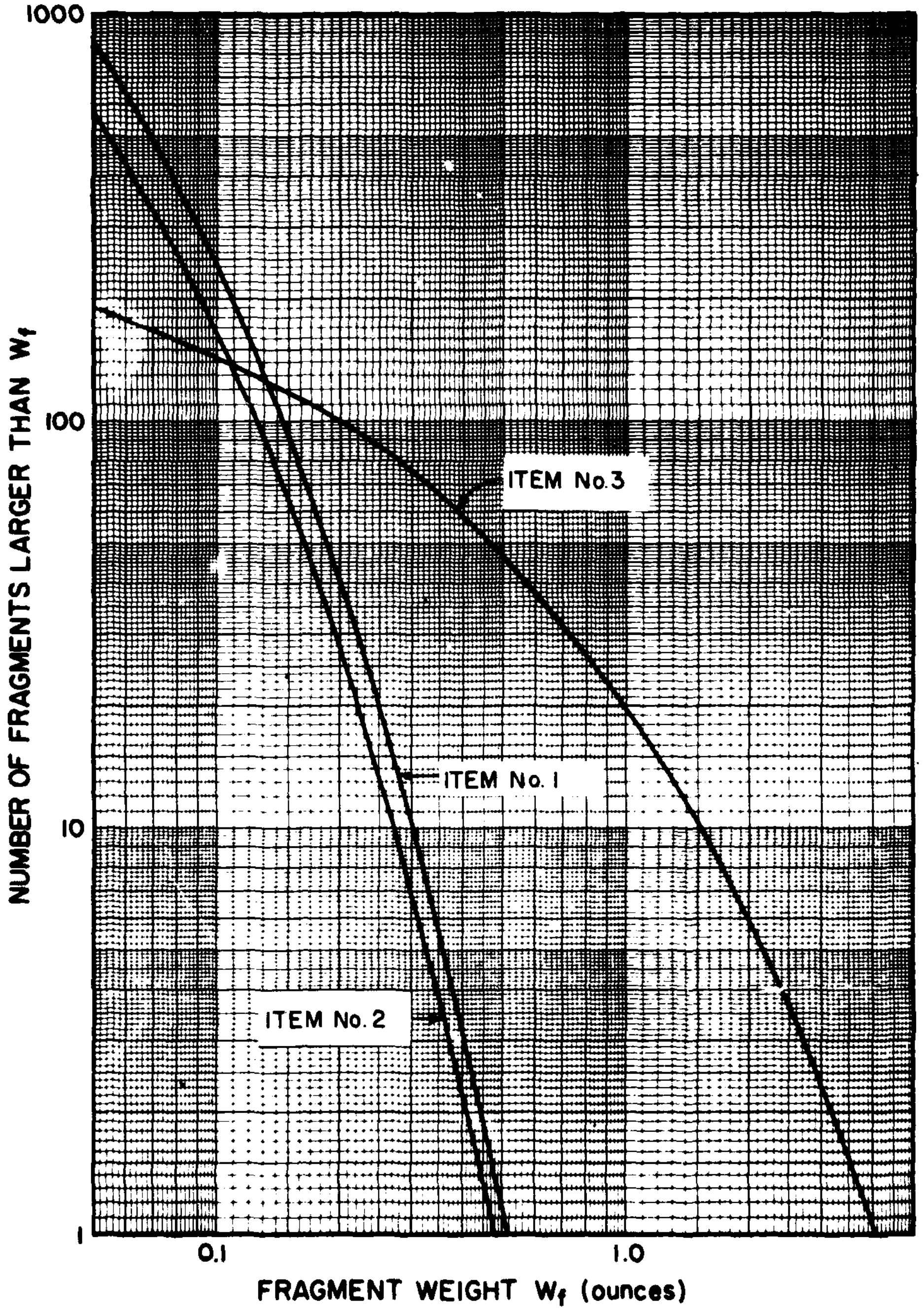


Fig. 5 FRAGMENT SIZE DISTRIBUTION

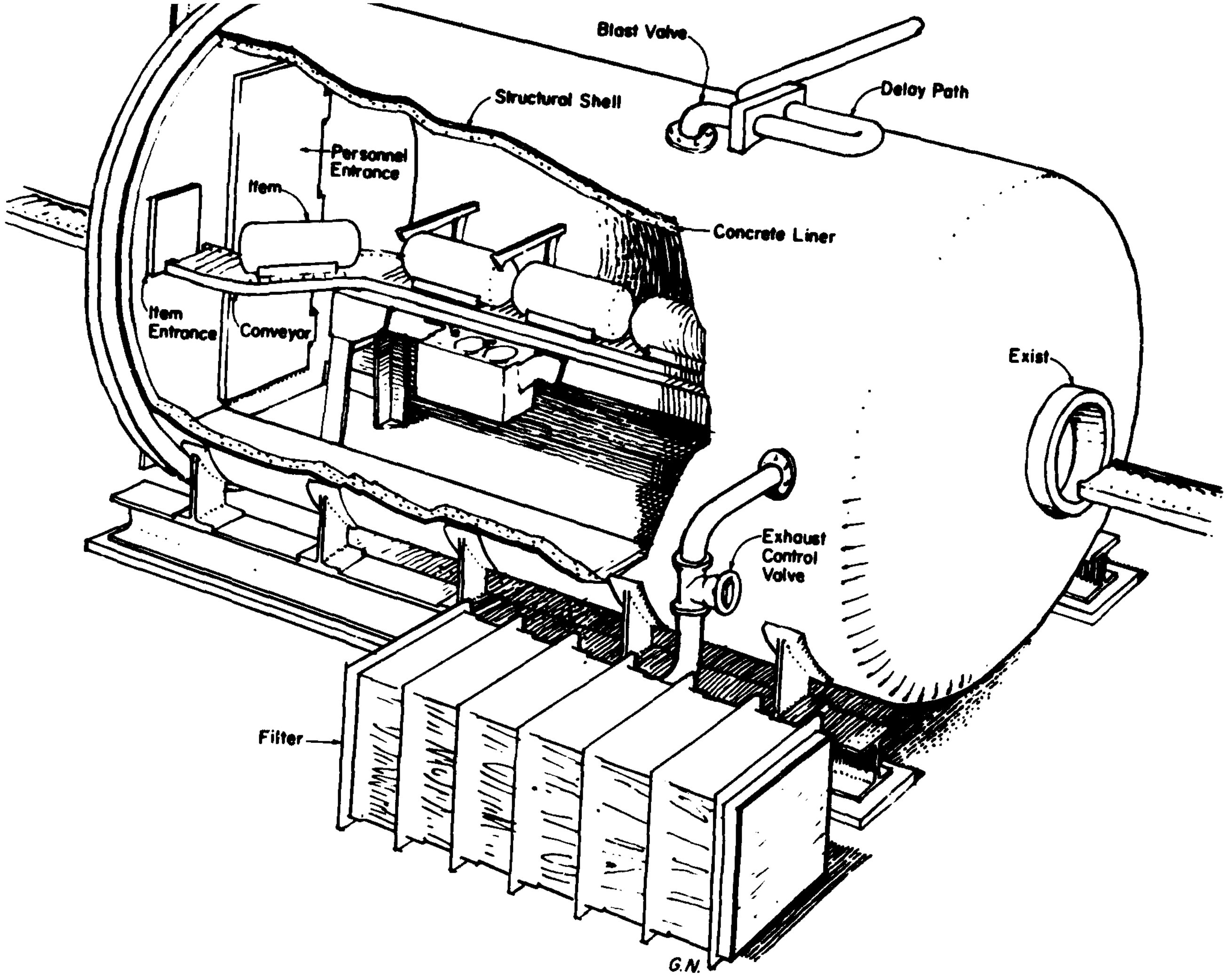


Fig. 6 FULLY CONTAINED EXPLOSIVE-TOXIC PROCESSING CELL

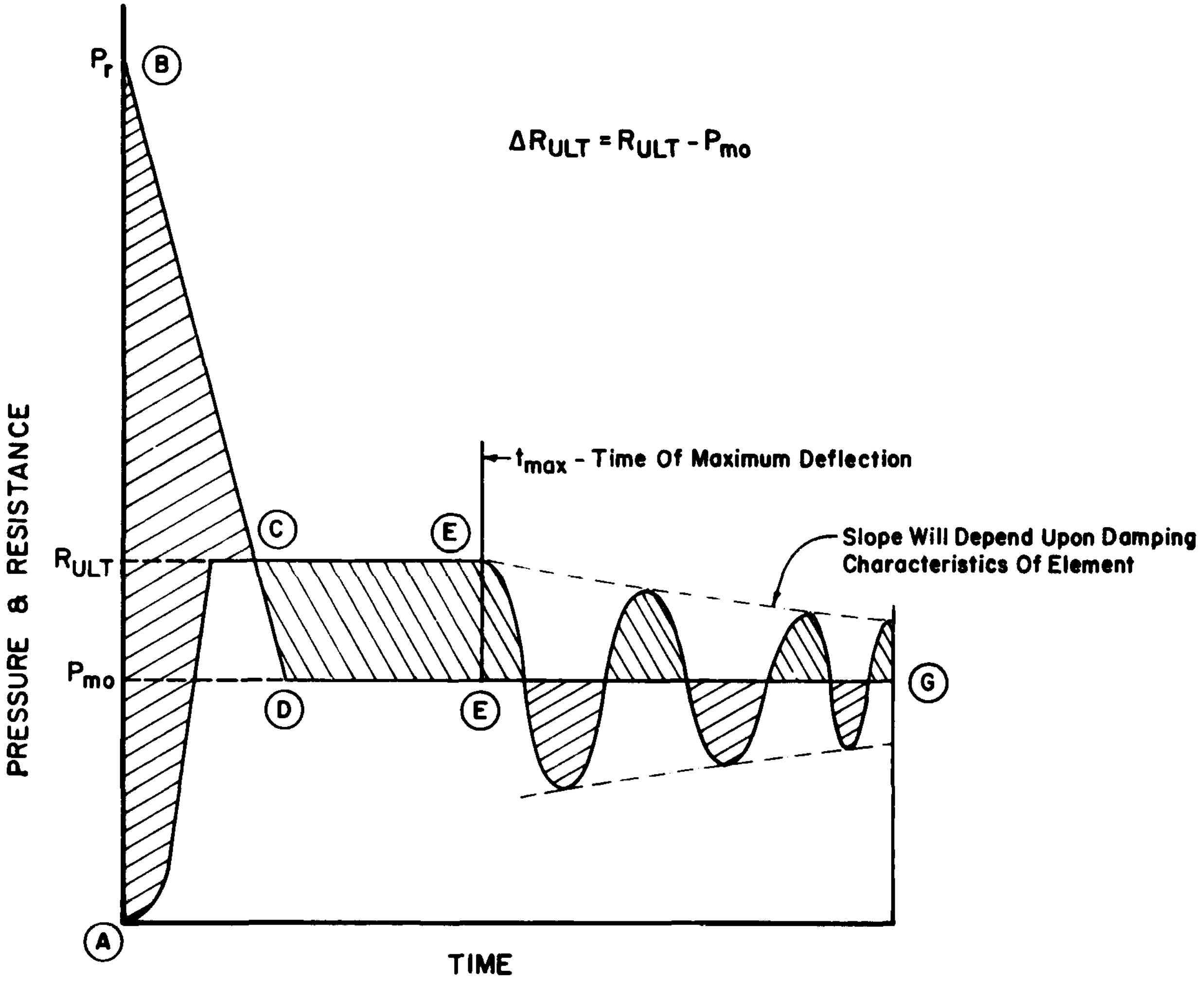
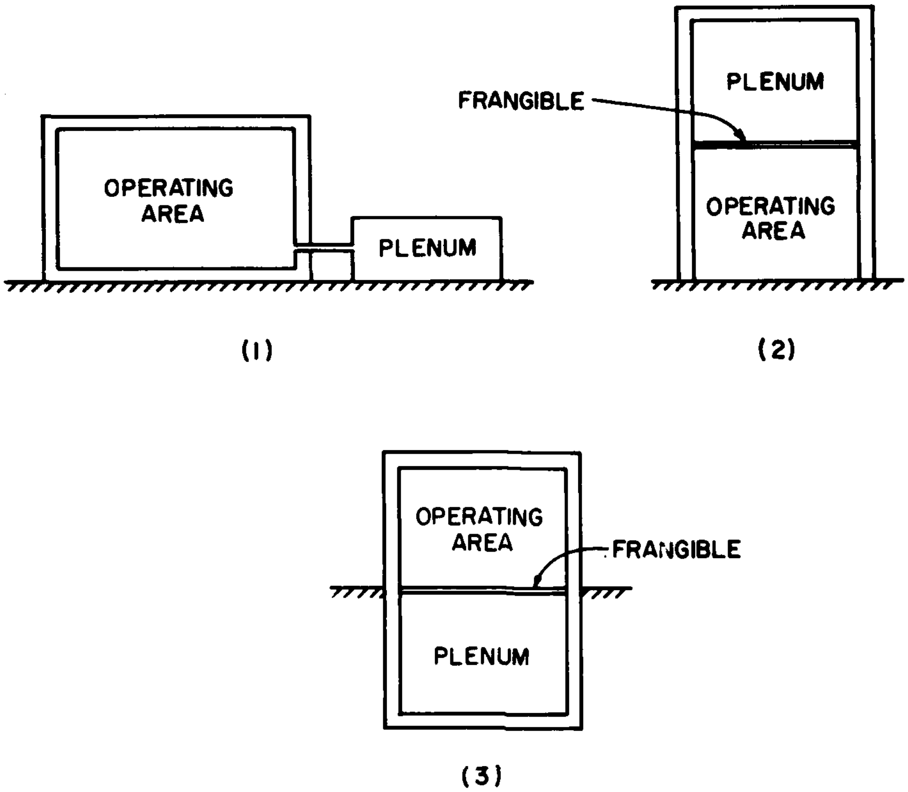
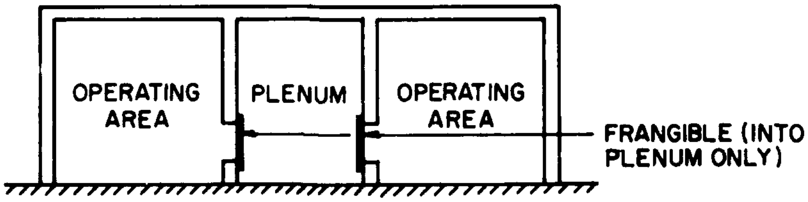


Fig. 7 TYPICAL PRESSURE - TIME AND RESISTANCE - TIME CURVES



a) SINGLE CELL AND PLENUM CHAMBER



b) MULTIPLE CELLS AND COMMON PLENUM CHAMBER

Fig. 8 PLENUM CHAMBER ARRANGEMENTS

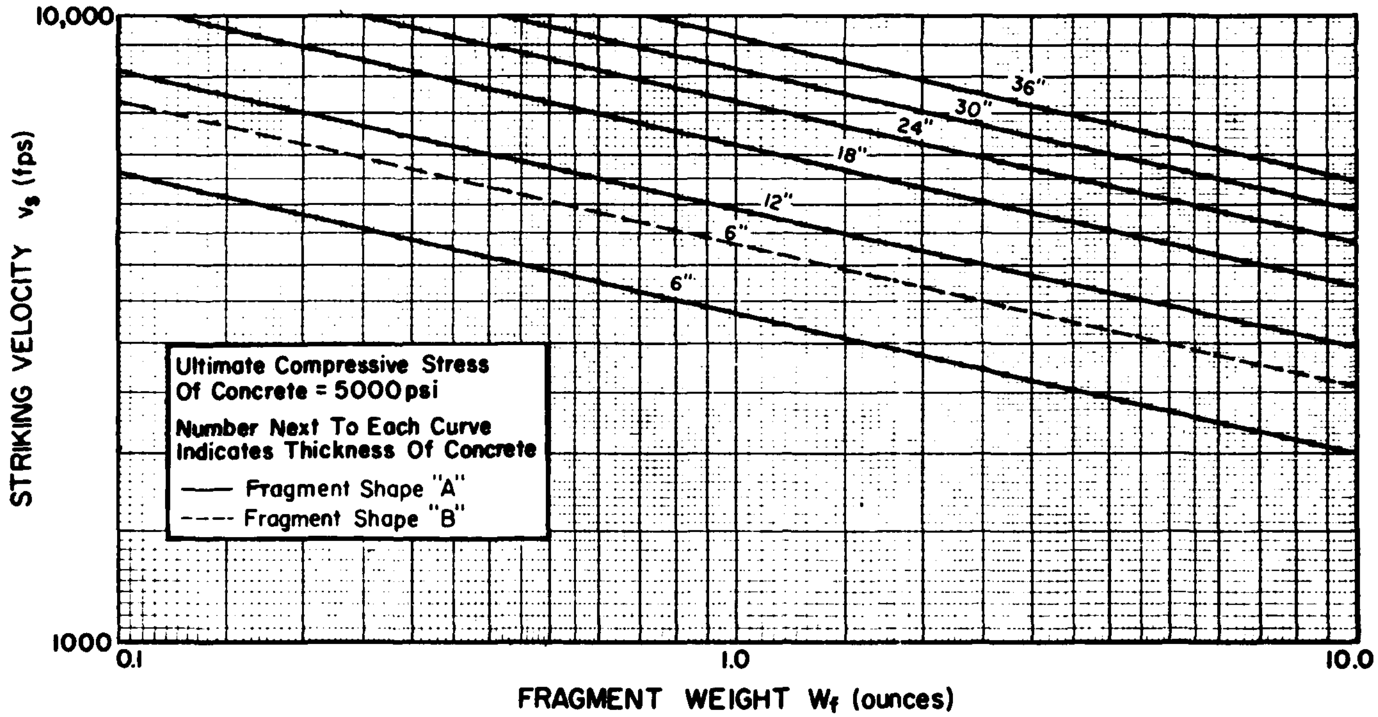


Fig. 9 PENETRATION OF ARMOR-PIERCING FRAGMENTS INTO CONCRETE

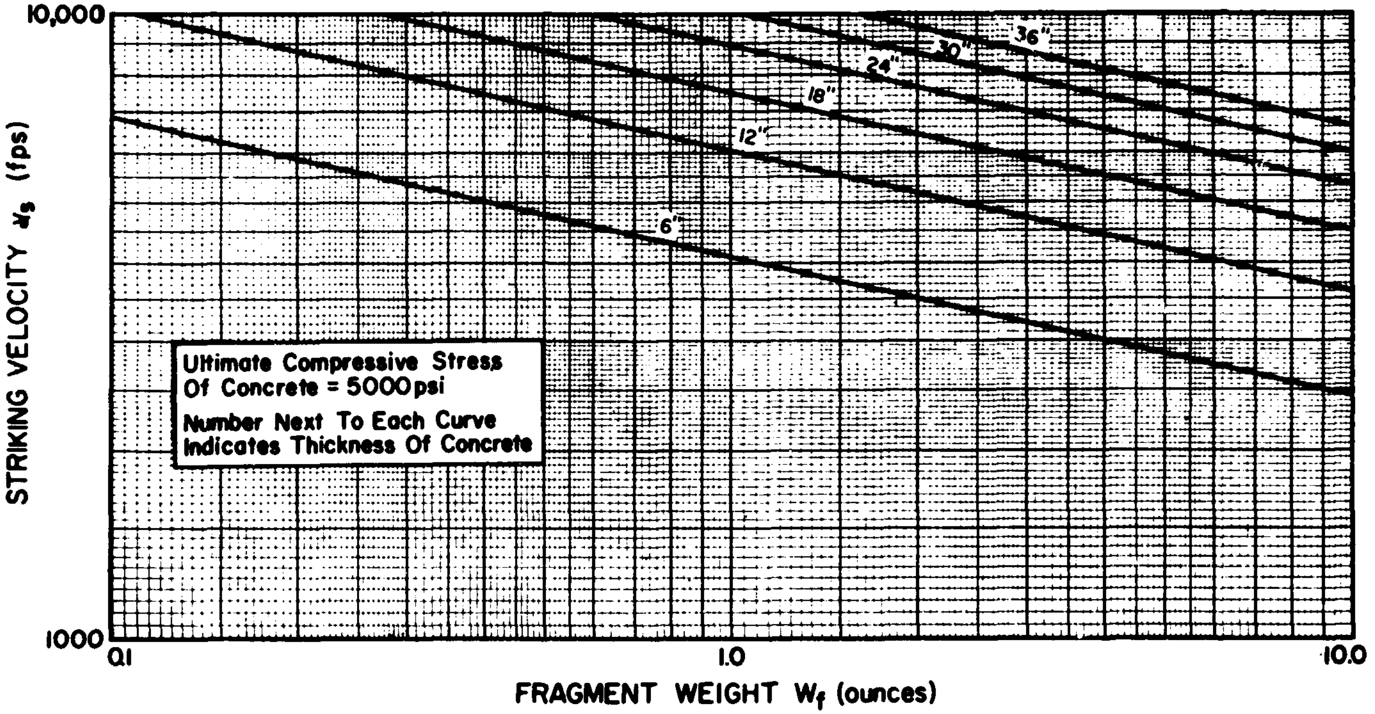


Fig. 10 PENETRATION OF MILD STEEL FRAGMENTS INTO CONCRETE

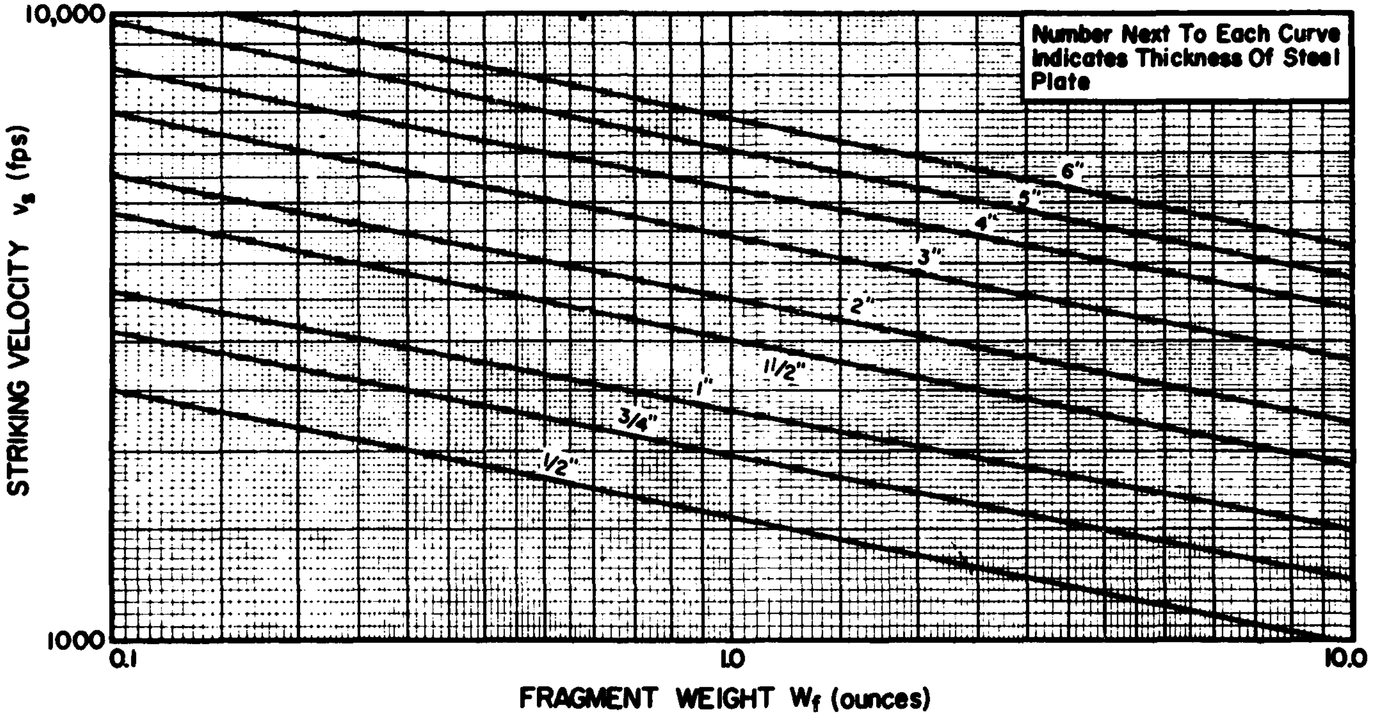


Fig.11 PENETRATION OF ARMOR-PIERCING FRAGMENTS INTO MILD STEEL PLATE

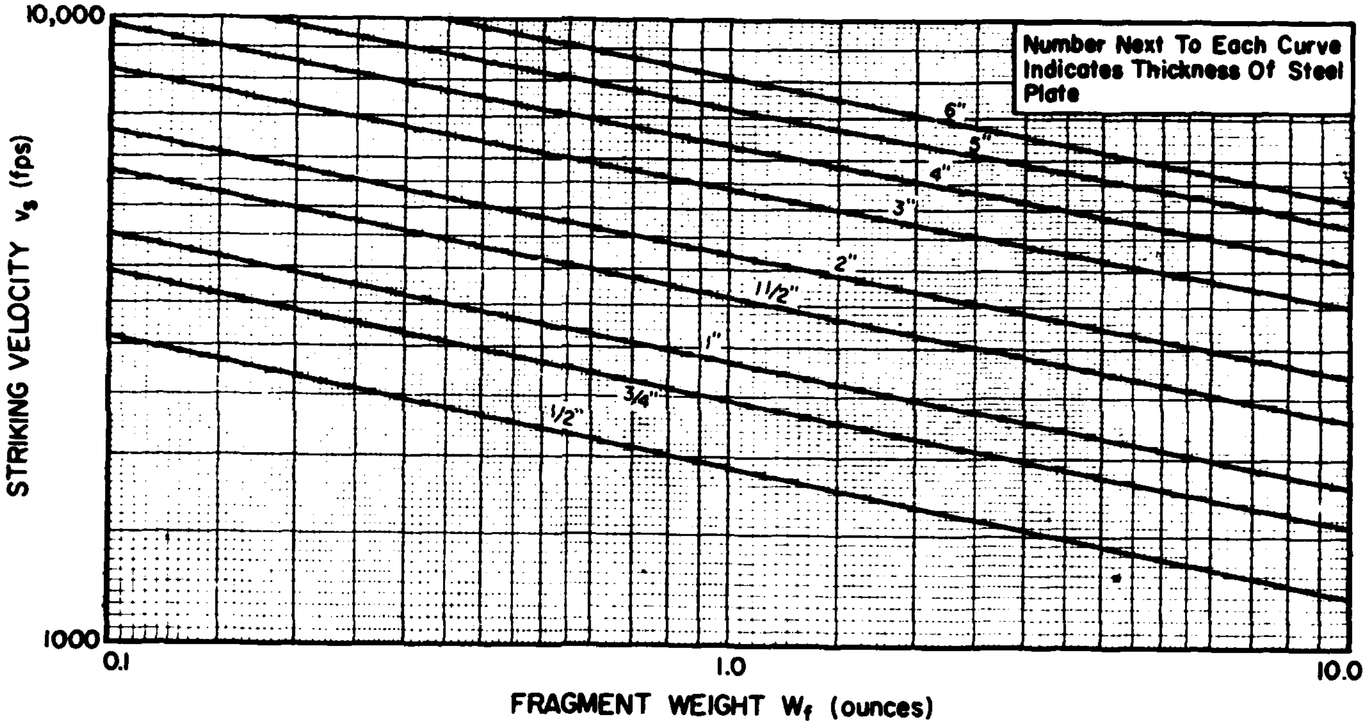
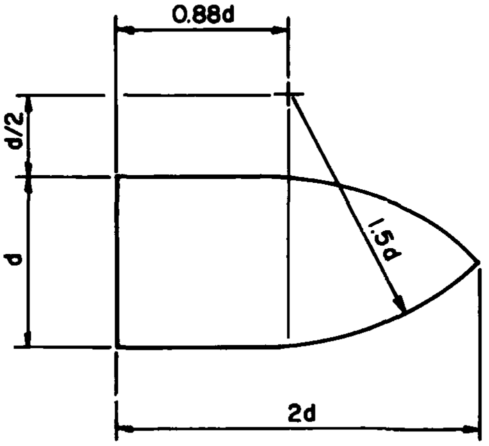
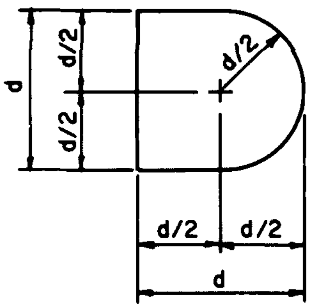


Fig. 12 PENETRATION OF MILD STEEL FRAGMENTS INTO MILD STEEL PLATE



TYPE "A"

d = DIAMETER OF CYLINDRICAL
PORTION OF FRAGMENT



TYPE "B"

Fig. 13 FRAGMENT SHAPE

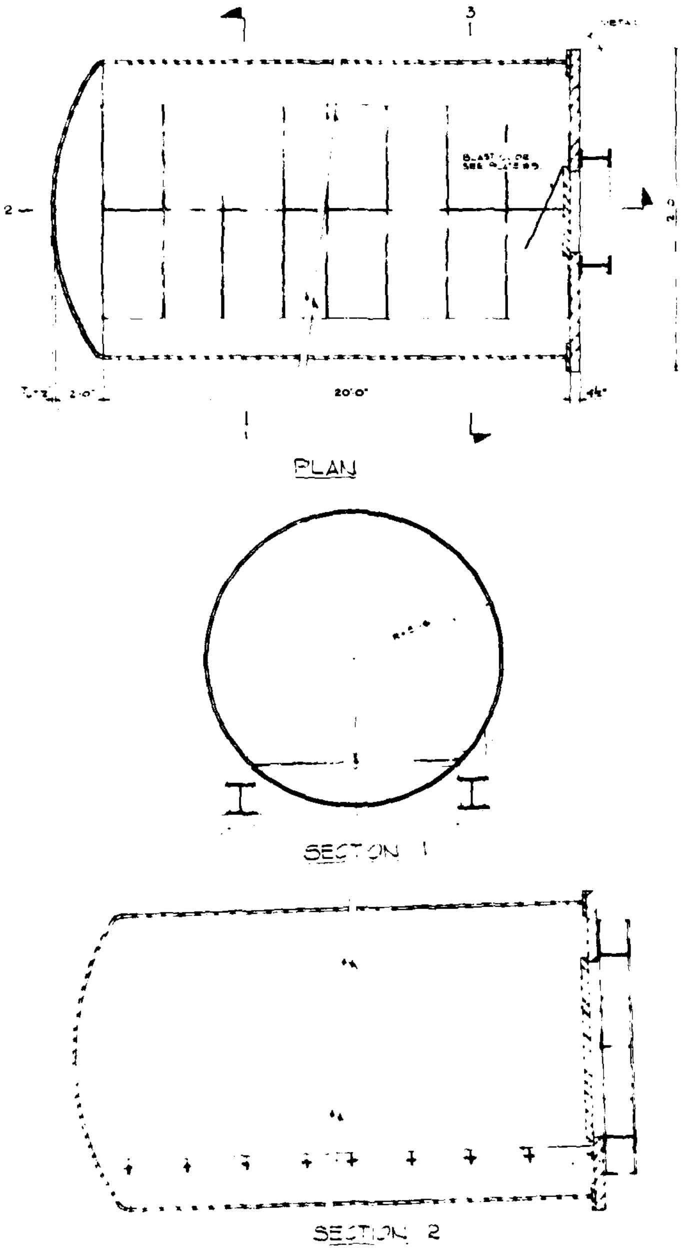
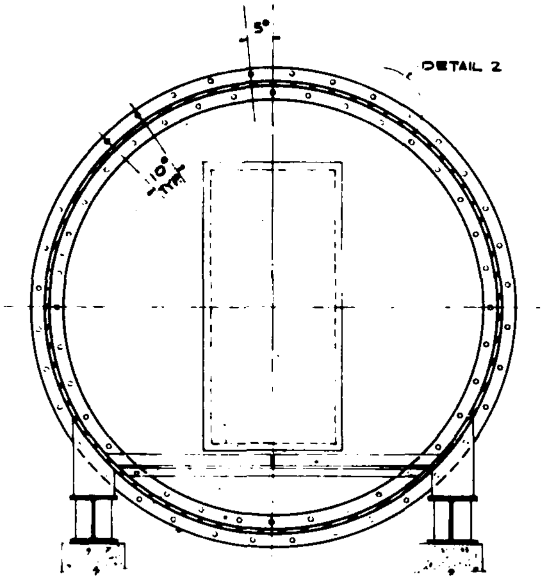


Fig. 14 - CASE I - SINGLE CELL ARRANGEMENT



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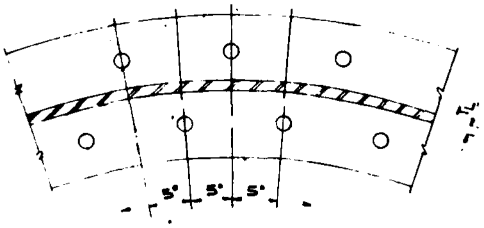
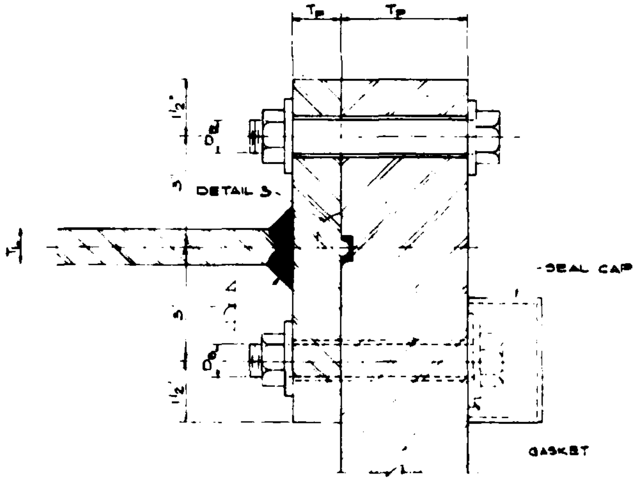
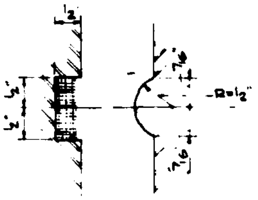


DETAIL 2
NOT TO SCALE



DETAIL 1
SCALE $\frac{1}{2}"=1"$



DETAIL 3
SCALE $\frac{1}{2}"=1"$

Fig. 15 - CASE I - TYPICAL STRUCTURAL DETAILS

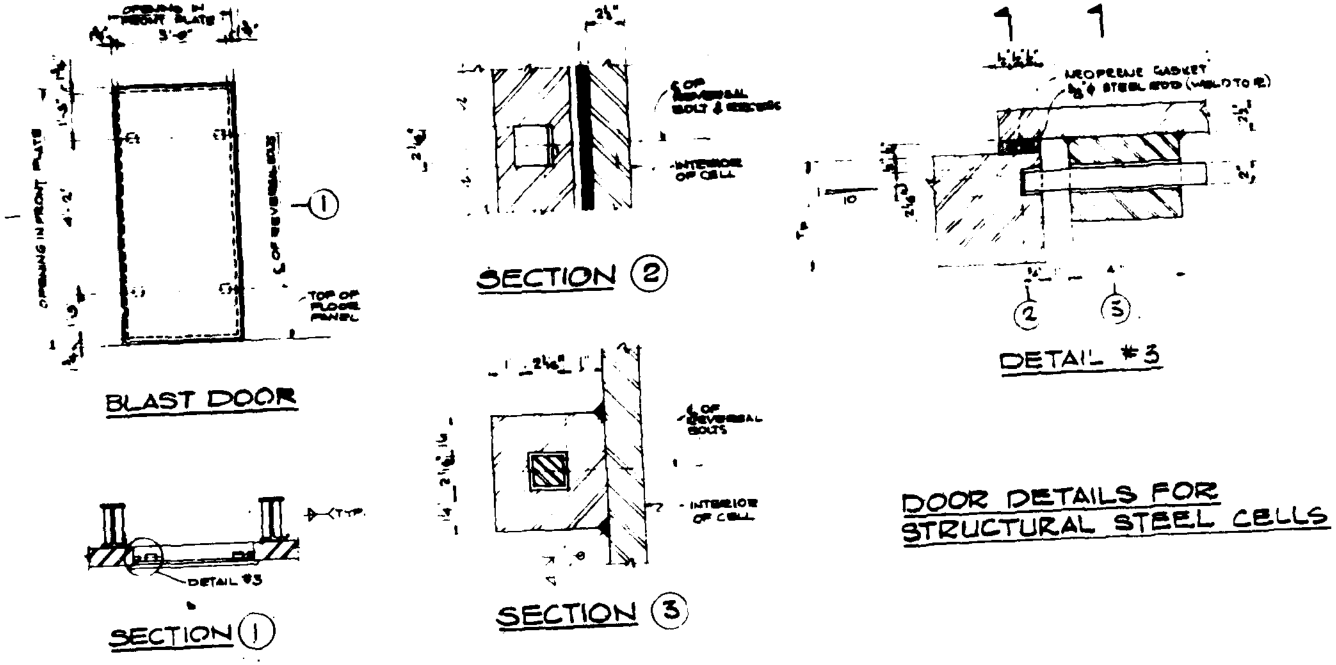


Fig. 16 TYPICAL PERSONNEL DOOR DETAILS

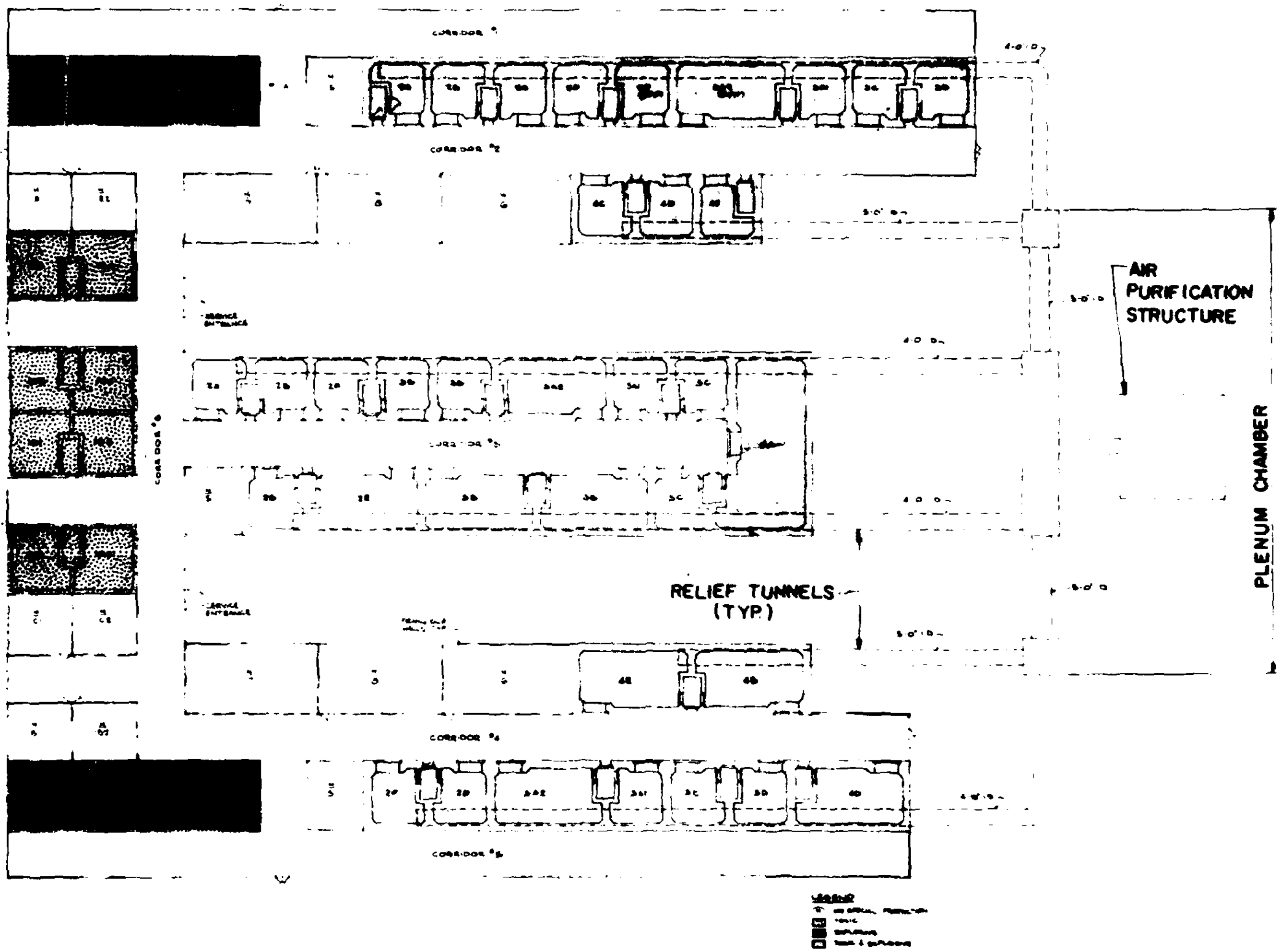
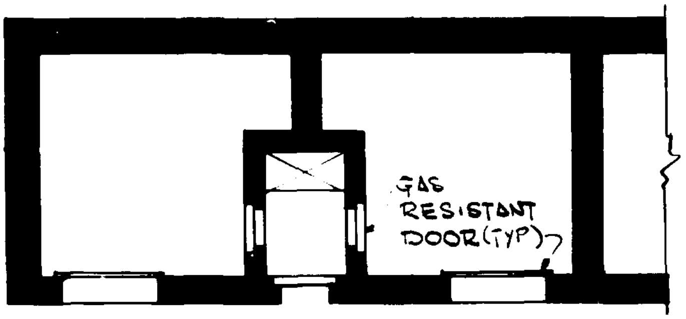
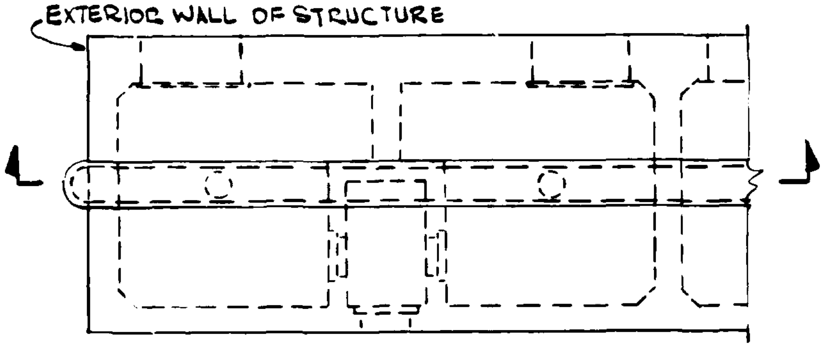


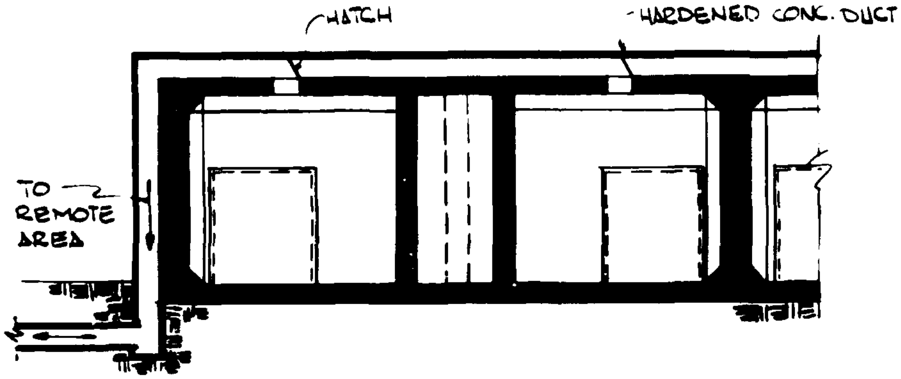
Fig. 17 CASE II - MULTI-CELL ARRANGEMENT



TOXIC CELL PLAN

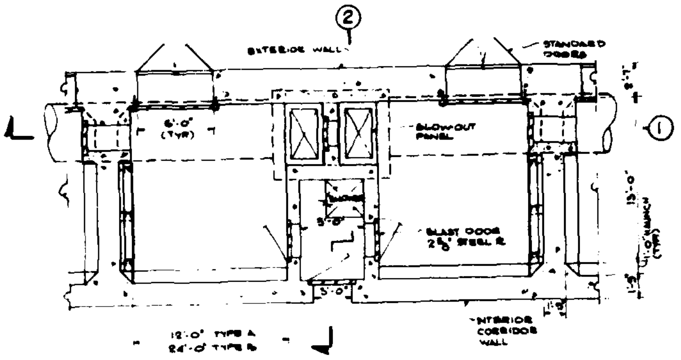


EXPLOSIVE CELL PLAN

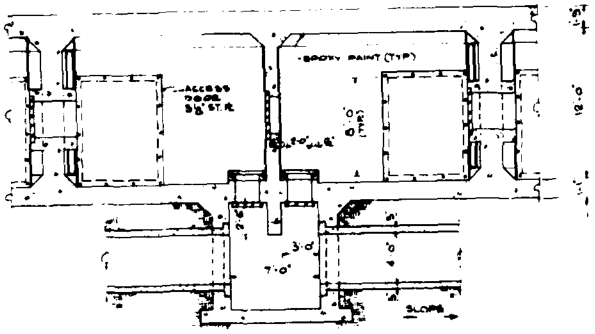


SECTION THRU EXPLOSIVE CELL

Fig. 18 TYPICAL TOXIC CELLS AND EXPLOSIVE CELLS



PLAN



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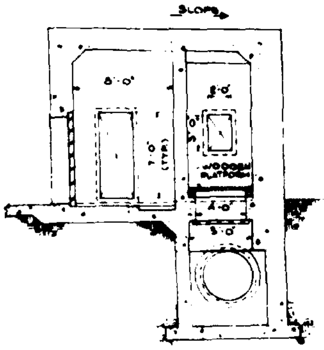

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Fig.19 DETAILS OF TOXIC AND EXPLOSIVE CELL

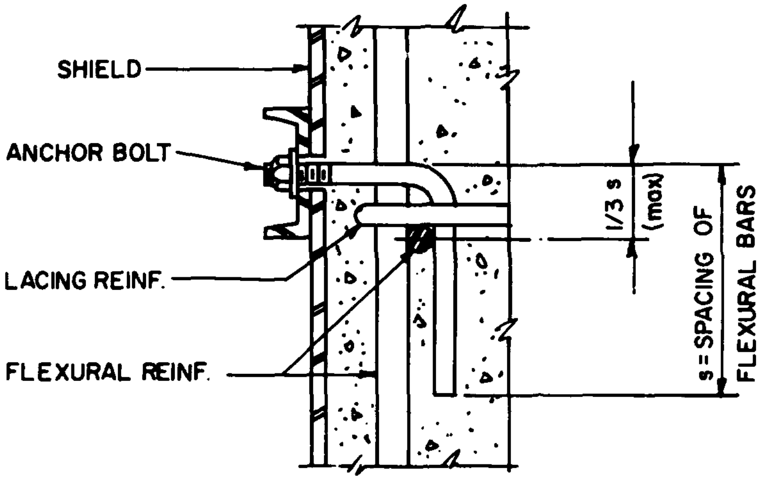
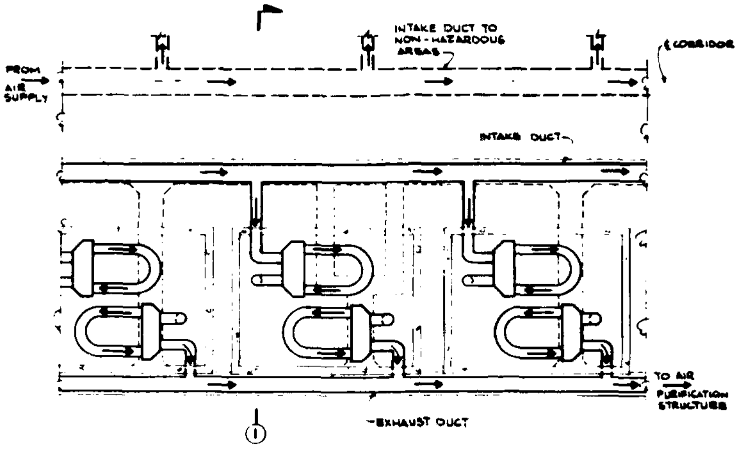
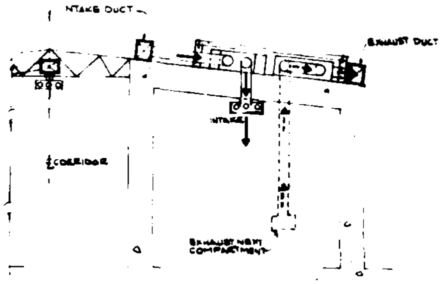


Fig. 20 RIGID ATTACHMENT OF FRAGMENT SHIELD TO DIVIDING WALL



POSSIBLE AIR DISTRIBUTION SYSTEM



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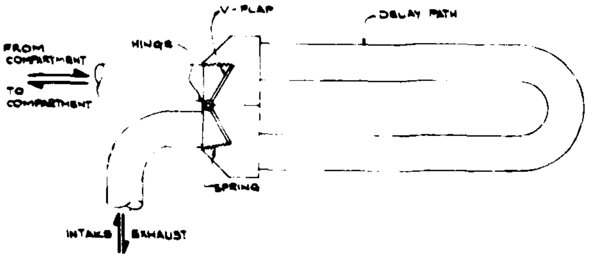

BLAST-ACTIVATED VALVE

Fig. 21 AIR DISTRIBUTION SYSTEM

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TO
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13. ABSTRACT

To insure that full protection is afforded in the event of an explosion, modern day explosive-toxic facilities must be designed to fully contain the explosive output of a detonation. The design procedures necessary to achieve this structural containment are described; additionally, several case studies are discussed in which these structural procedures were tested. These studies include both single- and multi-cell arrangements.

This presentation was made at a seminar on Disaster Hazards sponsored by the Central States Section of the Combustion Institute (and co-sponsored by Illinois Institute of Technology Research Institute) at the Manned Spacecraft Center, Houston, Texas on 7-8 April 1970.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Explosive-toxic facilities						
Detonation containment						
Structural containment						
Design procedures						
Single-cell arrangement						
Multi-cell arrangement						