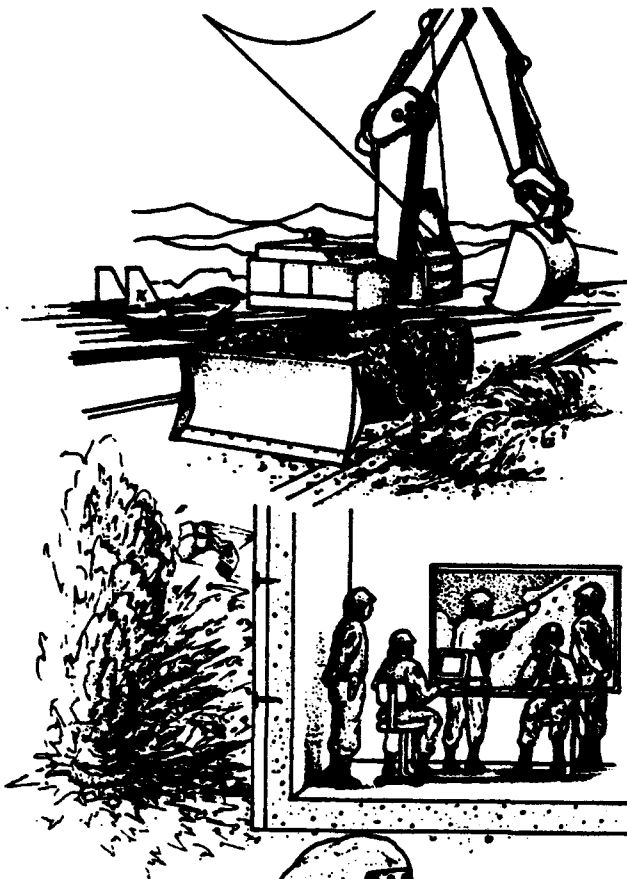


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QUANTITY-DISTANCE REQUIREMENTS FOR EARTH-BERMED AIRCRAFT SHELTERS

M.G. WHITNEY, K.H. SPIVEY

WILFRED BAKER ENGINEERING, INC.
8700 CROWNHILL, SUITE 310
SAN ANTONIO TX 78209-1128

JUNE 1993

FINAL REPORT

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ENGINEERING RESEARCH DIVISION
Air Force Civil Engineering Support Agency
Civil Engineering Laboratory
Tyndall Air Force Base, Florida 32403



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FIELD	GROUP	SUB-GROUP		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) The subject work has been performed under Phase I of an SBIR (small business innovative research) program sponsored by Tyndall AFB. The effort concentrated on development of methods to quantify debris hazards from accidental explosions inside earth-bermed and unbermed aircraft shelters. The Phase I effort addressed shock loading, gas loading, debris breakup, and debris throw. The prediction model, Quantity-Distance Requirements for Aircraft Shelters (QDRACS), includes new programming which uses image charges and ray-tracing of shocks for the specific geometry of an aircraft shelter. Interior surfaces are divided into a grid of rectangular elements. Shock loads are calculated at each element for up to 20 munition stacks. Existing data were utilized to determine structural breakup dependence on load intensity and the formation of small or large debris. Venting is calculated using the FRANG program as a subroutine to QDRACS, but with special treatment for defining vent area and vent perimeter based on the breakup pattern, and venting provided by the door. The velocity of all missiles is calculated based on contributions (Continued)				
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19. ABSTRACT (Concluded)

from both the shock and gas pressure loading. Debris dispersion is calculated using MUDEMIMP as a subroutine. Model results were compared to the Q-D criteria based on DISTANT RUNNER tests. Hazard distances for Event 4 were predicted within 20 percent, and for Event 5, within 5 percent of the DISTANT RUNNER data.

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EXECUTIVE SUMMARY

A. OBJECTIVE:

The project purpose is to develop a tool for the analysis and correction of hazards associated with accidental explosions inside Hardened Aircraft Shelters. This Phase I effort is directed toward a study of existing methods, software, and test data and the development of "first-generation" predictive software. This Phase I effort also identifies future needs to complete the project purpose.

B. BACKGROUND:

Explosions inside a structure can result in the throw of debris and fragments along with the venting of blast pressures. Debris are pieces of the destroyed structure which are thrown by the force of the explosion. The quantity of debris and the distances individual pieces are thrown are dependant on the construction of the building and the quantity of explosives involved. These hazards must be considered when siting these facilities and occupied areas nearby.

The quantity of debris and the distances of debris throw can be limited by either reducing the size of the explosive source or by improving the structure containing the explosive. This program investigates the development of an analysis tool to evaluate these variables.

C. SCOPE:

This program reviewed current literature related to the study of explosions and debris throw. Test data was also obtained to support model development. A number of analysis techniques and available computer programs were collected for evaluation of their potential use in the project. These analysis techniques and computer codes were modified to develop a user friendly program to analyze debris thrown from third generation aircraft shelters. Finally, the computer program output was validated using available test data.

D. METHODOLOGY:

Because of the limited scope of this effort, the methodology consisted of combining existing predictive tools into a program that would meet program objectives as well as provide agreement with existing data.

E. RESULTS:

The investigation resulted in the development of a computer code titled Quantity Distance Requirements for Earth Bermed Aircraft Shelters (QDRACS).

QDRACS currently allows the user to examine a third-generation aircraft shelter for hazardous debris throw distances. The shelter geometry is idealized as a collection of surfaces divided into rectangular elements. The user is allowed to place up to 20 separate explosive stacks at different locations with varying net explosive weights and TNT equivalence. QDRACS calculates the standoffs to all elements from each explosive stack and from other surfaces. Shock pressures and impulses are calculated using curves from Reference 14. QDRACS uses a ray-tracing technique to determine shock loads on each element. Loads on each element are lumped into a single, triangular pulse.

Two modes of structural failure are considered in QDRACS: (1) breakup of a slab into small pieces caused by intense shock loads and (2) breakup of a slab into large pieces caused by long duration (gas pressure) loads. Each element is analyzed to determine which type of failure mode occurs. Gas pressure buildup inside the aircraft shelter is predicted with the FRANG computer code. Debris velocity, mass, and ricochet and roll are predicted using the MUDEMIMP code. The TRAJ computer code was adopted to calculate debris trajectory.

F. CONCLUSIONS:

Comparisons were made with the DISTANT RUNNER test results for two different events. The DISTANT RUNNER tests used unbermed shelters. QDRACS was executed with identical explosives stacks as in the DISTANT RUNNER tests. Hazardous distances from debris throw off the arch section of the aircraft shelter were found to compare reasonably well for the unbermed cases. Q-D criteria based on the DISTANT RUNNER tests gave maximum hazardous distances of 820 and 1300 feet for Events 4 and 5, respectively. QDRACS calculated maximum hazardous debris distances of 680 feet for Event 4 and 1,230 feet for Event 5. QDRACS distances were reduced to 490 and 860 feet for Events 4 and 5, respectively, with earth cover ranging from 2 feet on the roof to 10 feet on the sides of the arch.

G. RECOMMENDATIONS:

Recommendations for Phase II were made for refinement of the prediction methods and software development. Recommendations for improved prediction methods include improvement in methods for calculating breakup patterns, structural response before failure and multiple vent areas; improvement in shock prediction methods; use of a finer grid mesh to allow for better local response effects; definition of breakup under various load conditions; hazards predictions in all directions; effects of berming and barricading; and various software improvements, including addition of more shelter types and geometries, better format for user input, and customized output routines.

PREFACE

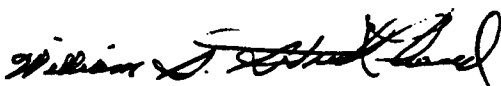
This work was performed during the period of 25 May 1991 to 15 February 1992. The work was performed by Wilfred Baker Engineering, Inc. (8700 Crownhill, Suite 310, San Antonio, Texas 78209-1128) under Contract No. FO8635-91-C-0189. The project was sponsored by Headquarters Air Force Civil Engineering Support Agency, Civil Engineering Laboratory, 139 Barnes Drive, Tyndall AFB, Florida 32403-6001. The technical project officer was Richard A. Reid, Capt, USAF, HQ AFCESA/RACS.

This report has been reviewed by the Public Affairs Officer (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for public release.



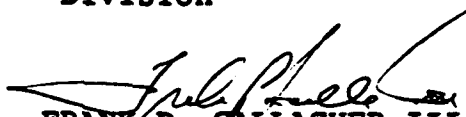
JON B. ANDERSON, GS-13
Chief, Air Base Survivability
Branch



WILLIAM S. STRICKLAND, GM-14
Chief, Engineering Research
Division



RICHARD A. REID, Capt, USAF
Project Officer



FRANK P. GALLAGHER III, Col, USAF
Director, Air Force Civil
Engineering Laboratory

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SECTION I

INTRODUCTION

A. OBJECTIVE

The project purpose (including work in future phases) is to develop a tool for the analysis and correction of hazards associated with accidental explosions inside Hardened Aircraft Shelters. This Phase I effort is directed toward a study of existing methods, software, and test data and the development of "first-generation" predictive software. This Phase I effort also identifies future needs to complete the project purpose.

A facilities planner must identify hazards for a given situation and be able to investigate changes to correct the problem. Thus, the final software should allow the user to accomplish the following:

1. Evaluate debris dispersion and associated hazard present with an existing or planned HAS at a given site.
2. Evaluate site specific changes to the HAS to reduce debris throw around an existing shelter. This will include placement of barricades or earth covering.
3. Analyze the effect of weapon placement or arrangement in the shelter.
4. Analyze the effect of changes in explosive quantities in the shelter.

As an example, a facilities planner should be able to evaluate an existing shelter with the software. If the current situation presents unacceptable hazards, then he would evaluate various options. The software will define what portions of the shelter are causing the hazard. If sidewall debris are being thrown the furthest, then the placement of barricades at some short distance is a viable option. Once location and height of the barricades are defined, the software will delete all debris impacting the barricade from updated hazard calculations. The barricade height and placement can be modified as necessary. A similar approach to the problem would be to earth mound the shelter side-walls. The software will account for reduced debris velocity and recalculate throw distance. Another option would be to rearrange weapons placement in the shelter. If the original placement, for instance, were directly against or close-in to the shelter wall, then reduction in hazard distance could be calculated for a change in munitions placement.

The final software shall be able to define debris impact energies and numbers of hits at acceptor areas surrounding the shelter. This will provide design criteria for either siting or hardening acceptor buildings.

If the software is to have the above features, it must be able to distinguish between debris originating for different portions of the shelter surface. The current goal is to define the concrete shell as a surface grid, perform separate analysis of each grid area (groups of elements), then add the results for a total hazardous debris distribution. This is a significant deviation from other methods which consider an entire wall or roof to behave uniformly as a source of debris hazards. The typical aircraft shelter is too large to justify the assumption that any surface will act uniformly under all circumstances.

This Phase I effort has achieved its goal of developing a first-generation, user-friendly software and has outlined the remaining effort to complete the work. Software has been programmed utilizing new and previously developed routines. This software, named QDRACS (Quantity-Distance Requirements for Aircraft Shelters) gives debris throw predictions using state-of-the-art methods.

QDRACS is a significant improvement over past methods which are labor intensive, requiring many hand calculations and the exercise of several different computer programs. QDRACS is a self contained program and, when completed at the end of Phase II, will allow the planner to make Q-D evaluations. In Phase II, development of new data and advancements in predictive methodology will be made and incorporated into QDRACS.

B. BACKGROUND

Explosions inside a structure can result in the throw of debris and fragments along with the venting of blast pressures. These hazards must be considered when siting these facilities and occupied areas nearby. Debris are pieces of the destroyed structure which are thrown by the force of the explosion. The quantity of debris and the distances individual pieces are thrown are dependant on the construction of the building and the quantity of explosives involved.

The Department of Defense provides general siting criteria in DOD 6055.9 (Ref 1) for debris throw from explosions in buildings. In certain situations, protection from hazardous fragments and debris is required, and the minimum distance is specified to be that at which the density does not exceed one fragment per 600 ft². A hazardous fragment or debris piece is defined as having an impact energy of 58 ft-lb or greater. If the distance at which this density occurs is not known, then DOD 6055.9 provides further guidance. For a Net Explosive Weight, NEW, of 100 pounds or less, a distance of 670 feet, and for a NEW above 100 pounds, a distance of 1,250 feet, are established as meeting the hazard criteria. The distance for a NEW of 100 pounds or less is for situations involving munitions which present no more high velocity fragment hazard than that from a single 500-pound MK82 bomb. DOD 6055.9 does not have a similar restriction for the condition where the NEW is greater than 100 pounds. Again, these criteria are not specific to any particular structure type.

The DOD sponsored testing under the "DISTANT RUNNER" program (2) and related analysis in an attempt to develop hazards criteria specifically for the third-generation Hardened Aircraft Shelter (HAS). This work established Quantity-Distance, Q-D, criteria in directions to the side, front and rear of a shelter. These criteria were adopted into DOD 6055.9, Chapter 10, "Theater of Operations Quantity-Distance," Section C, "Airfields Used Only By Military Aircraft." When the Net Explosive Quantity, NEQ, is greater than 50 kg and up to 5,000 kg, the safety distances are:

$$\text{Front: } D = 20Q^{1/3}$$

$$\text{Side: } D = 25Q^{1/3}$$

$$\text{Rear: } D = 16Q^{1/3}$$

where Q is in kg and D in meters. When the NEQ is 50 kg or less, there is a fragment hazard distance of 80 meters to the front and is "nil" to the side and rear. All of the above hazard distances are for exposure to unhardened sites.

DISTANT RUNNER was a successful program resulting in much valuable information concerning debris hazards from explosions in HAS's. Upper limit Q-D criteria were defined and adopted by the Defense Department Explosive Safety Board, DDESB, as mentioned. Others have performed related experimental and engineering studies. Of particular note is the Norwegian government which has funded several programs, the results are which were included in the developments of this study. The effort described in this report involves development of a prediction tool to define debris hazards for more specific circumstances than that available in the past. Specifically, this is the first step toward development of software which will allow prediction of debris throw for a given situation and engineering analysis of design alternatives to reduce debris throw.

C. PROJECT SCOPE

The scope of work for the Phase I effort is in accordance with the Work Breakdown Structure in Table 1:

TABLE 1. PROJECT WORK BREAKDOWN STRUCTURE	
WBS Item	Topic
1	Literature Survey
2	Review of Technical Reports and Related Test Data
3	Review of Related Analysis and Computer Programs
4	Develop or Revise Analysis or Computer Codes
5	Compare Codes with Existing Test Data
6	Reporting and Presentation Material

1. Literature Survey

A computer-assisted literature survey was completed and pertinent reports added to those previously on hand. An extensive bibliography was prepared including all documents collected along with many on related issues.

2. Review of Technical Reports and Related Test Data

The most relevant documents identified in the attached bibliography have been reviewed. This includes work under the DISTANT RUNNER program and that funded by the Norwegian government (3 and 4). In addition, reports covering a recent test program conducted for the Department of Energy concerning characterization of debris hazards for reinforced concrete operating bays were studied.

3. Review of Related Analysis and Computer Programs

Several computer programs identified have been used in the prediction of confined explosion blast loading and prediction of debris throw. Previously existing software and debris hazard prediction methods were principally directed toward explosions inside box shaped cubicles and for explosives quantities less than 500 lb. Recently developed prediction methods, Reference 5, while providing a significant improvement in previous state-of-the-art methodology, involves miscellaneous hand calculation and the separate exercise of several computer codes. These methods, in their current format, are not suited to adequately fulfil the program objectives. Modifications of existing software and much new work were determined to be necessary.

4. Develop or Revise Analysis of Computer Codes

Substantial development of software was made with two goals in mind. First, the predictions methods must be directly applicable to aircraft shelters. Second, the software should be user friendly and self contained under one program.

As mentioned, previously existing software and methods are principally directed toward box-shaped cubicles such as weapons manufacturing operating bays. Because of the different geometry of an HAS, a new shock loads prediction scheme was developed and selected for use in QDRACS over existing software. Gas load predictions in QDRACS used existing software for this Phase I effort; however, substantial revisions of this element are recommended in Phase II. Slab breakup, debris size selection, and debris velocity calculation schemes and associated programming were all developed under this Phase I effort. Debris throw utilized existing software, with some programming required for arrangement and presentation of input and output.

The software developed is useable on an IBM-compatible DOS-based PC. The software is self contained. The user does not have to exercise several different programs, transferring input and output between them, nor make hand calculations at intermediate steps. QDRACS has easy to use menus, with input and output that are convenient to the user, with further improvements planned for Phase II.

5. Compare Codes with Existing Test Data

QDRACS results were compared with results of the DISTANT RUNNER test program. Reasonable comparisons were achieved in line with Phase I expectations. Improvements are planned for Phase II.

6. Reporting and Presentation Material

This report summarizes work accomplished under the Phase I project. Presentation material which provides an overview of the work and the software produced has been submitted separately.

SECTION II

LITERATURE SURVEY AND REVIEW OF TECHNICAL REPORTS

A survey of technical literature was completed to identify pertinent documents related to debris hazards in general, and debris hazards from explosions inside hardened aircraft shelters. The survey included review of in-house documents and document abstracts identified in a computer-aided search of the literature. The electronic service DIALOG was utilized, with key words input in the following groups.

TABLE 2. KEY WORD GROUPS			
Group 1	Group 2	Group 3	Group 4
Explosive(s)	Aircraft	Shelter	Safety
Detonation	Storage	Magazine	Quantity-Distance
Blast	Ammunition	Earth Berm(e)	Testing
Explosion	Weapons	Bunker	Model
		Arch	

A listing of reports identified which are specific to debris hazards due to explosions inside hardened aircraft shelters is provided, followed by a complete bibliography of pertinent reports identified in the literature survey.

Review of these and other documents reveal that the prediction of debris hazards must include a definition of the internal blast load history, a prediction of the response of the structure to that load, and the subsequent throw of debris. Recent debris prediction methods tend to rely on a combination of analytical and empirical procedures rather than either one alone. Prediction procedures for debris hazards are typified by the elements defined in Table 3 below.

TABLE 3. ELEMENTS OF PREDICTION PROCEDURES	
1.	Shock loading on internal surfaces
2.	Gas pressure load
3.	Structural Breakup
4.	Debris velocity
5.	Debris throw to first impact
6.	Roll or ricochet after impact

A similar structure was adopted for this study and programmed into the QDRACS software.

Numerous reports were examined to identify test data, prediction methods, and software concerning debris formation and hazards. A summary is provided in Table 4 of debris test data and accident surveys which report debris throw data for a variety of building types. This information provided vital insight into understanding the mechanics involved in debris formation and throw.

TABLE 4. SUMMARY OF EXISTING DATA*

Item No.	Ref. No.	Component or Building Description	Accident or Test	Number of Tests	Scaled Stand-off, z (ft/lb ^{1/3})	Energy/Bldg. Vol.	Failure Modes Observed	Debris Mass Measured	Debris Velocity Measured	Missile Map	General Notes
1	(a)	Scaled, unlaced R/C panels, representing 9'x9'x1' or 1.5' dividing walls w/no. 4 bars EUEF 4, 7, 6 or 12" o.c. Full scale. Tested panels were 1 or 3 sides clamped.	1/6 scale component test	36	$0.3 < z < 0.88$	N/A	local breaching and flexural	largest and avg. mass and no. of pieces	largest and average	yes	Acceptor side color coded; no. of pieces, mass and vel. recorded for each color, acceptor, and interior; also data for 2 shapes
2	(a)	Masonry dividing walls, 5' wide x 5' high x 8" thick, made w/full scale blocks, rebar #6 @ 48" o.c. (2 bars). Report indicates fixed base-questionable (other 3 sides free).	full scale component test	4	$0.87 < z < 1.25$	N/A	wall cracking, partial wall fall over	no debris thrown	no debris thrown	no debris thrown	Charge range 1-3 lbs standoff = 1.25 ft
3	(b)	Steel frame w/masonry end walls, frangible sidewalls, concrete floors, bricks: inner 2 1/2 x 3 7/16 x 7 3/4 in, outer 2 1/2 x 3 5/8 x 8 in. Four story rect. bldg--36' x 72' x 33' high. 12" R/C south wall 24" R/C east wall earth backed 12" cinder brick west wall (40'x14'x36' ft bldg)	accident	N/A	not available	0.011 lb/cu ft	not available	some pieces	N/A	yes	Explosive on 2nd floor in feeder to centrifuge Bldg 3045 Radford AAP, 11/2/78, approx. 11 lbs Nitrocellulose
4	(b)	3 side, 12" R/C & earth mounded; one side wood, wood floors, shingle roof, no firewalls, sandfilled bullet shield in front. Bldg dimensions not given	accident	N/A	not available	350 lbs, volume unknown	not available	some pieces	N/A	yes	Becchus Plant, Mercules Powder Co., Magna, Utah, 10/5/61

*This table is adapted from material in Fragment and Debris Hazard Evaluation. Scale Test Requirements and Test Plan, Final Test Plan under SRI Project 06-2362; prepared by Charles J. Oswald, et al., Southwest Research Institute, San Antonio, TX, March 7, 1989. References for the data are . . . the end of the table.

TABLE 4. SUMMARY OF EXISTING DATA
(Continued)

Item No.	Ref. No.	Component or Building Description	Accident or Test	Number of Tests	Scaled Stand-offs, ² (ft/lb ^{1/3})	Energy/Bldg. Vol.	Failure Modes Observed	Debris Mass Measured	Debris Velocity Measured	Missile Map	General Notes
5	(b)	Wood frame on concrete foundation, asbestos shingle roof. 16' x 16', height unknown, long porch in front	accident	N/A	estimated at 1.0	570 lbs, volume unknown	not available	some pieces	N/A	yes	Explosion centered, 570 lbs Nitrocellulose total. Bldg 3560, Hercules Powder Co., VA
6	(b)	Bldg with 4 HE bays, 3 walls R/C with exterior CMU walls, frangible roof (steel purlins with light insulated panels)	accident	N/A	not available	0.0134 lb/cu ft	block wall and frangible roof destroyed; flexural and shear damage in R/C walls	some pieces	N/A	yes	Explosive in bay 8 (estimated as 25' x 25' x 18') of Bldg 11-14A of Pentex Plant, 3/30/77, sympathetic detonation of 2 charges, 76 & 75 lbs
7	(b)	Concrete block and wood frame building	accident	N/A	not available	0.029 lb/cu ft		yes	N/A	yes	Estimated 5000 lb TNT equiv. from Polaris motors and other materials at Allegheny Ballistics Lab, 4/27/63
8	(b)	R/C walls, earth backed	accident	N/A	not available	0.14 lb/cu ft		yes		yes	4200 lbs NG-- Nitration House, Redford AAP, Bldg 9463, 62' x 30' x 15', estimated
9	(b)	18" R/C walls, endwalls with earth berm (23' width), 18" R/C slab roof	accident	N/A	not available	6000 lb TNT, volume unknown	N/A	yes	N/A	yes	6891 lbs of Petrin Arylate in loaded (total wt. 10,645 lbs) Mike Zeble motor, Redstone Arsenal, Alabama, Bldg 7857, 8/19/59
10	(c)	Metal frame bldg with light metal siding, lower 1/4 of bldg is CMU, 60' x 64' x 44'	accident	N/A	not available	0.0083 lb/cu ft	metal siding stripped from frame, CMU debris, test cell, pieces & hatch thrown	yes	N/A	yes	Probable deflagration of 1100 lbs propellant motor being tested in cylindrical steel cell with top hatches

TABLE 4. SUMMARY OF EXISTING DATA
(Continued)

Item No.	Ref. No.	Component or Building Description	Accident or Test	Number of Tests	Scaled Stand-offs, z (ft/lb ^{1/3})	Energy/Bldg. Vol.	Failure Modes Observed	Debris Mass Measured	Debris Velocity Measured	Missile Map	General Notes
11	(d)	Buried R/C, assembly bays with hinged R/C roof under 2' of soil (Pantex 12-64 bay). Ramp (1/2 scale only) is Cemento with aluminum cover on light metal frame	test	1 full, 1 half scale	roof = 2.7 ramp = 7.5 walls: 0.6 < z < 4.0	0.025 lb/cu ft	roof panels, ramp, doors thrown; cell walls pushed into soil	yes	some	yes	Velocity, size distribution of debris; airblast in donor & vented blast; external loads on acceptor, acceptor bay response; tests done at MES
12	(e)	3rd generation Norwegian A/C shelter, arch shaped R/C 21m x 35m x 7.5m, earth mounding up to 2.75m on sidewall, top of arch unburied in test, HE storage in off-centered, underground chamber	test	3 @ 1:20 4 @ 1:100	walls: 0.35 < z < 0.64 roof: z = 0.88	0.16 lb/cu ft	slabs close to charge broke into many pieces; other parts of shelter break into whole slabs	yes	yes	yes	10000 kg full scale; airblast measurements in 2 directions out to z = 130 ft/lb ^{1/3}
13	(f)	3rd generation U.S. A/C shelter, R/C arch structure with interior steel liner, 71' x 120' x 28'. Door is a steel/R/C composite plate supported by an external steel frame	test	2-full scale	simultaneous detonation of several mini-tions distributed throughout the shelter	0.020 lb/cu ft and 0.082 lb/cu ft	R/C arch fragmented into many small pieces	yes	yes	yes	2292 and 9168 lbs Tritonal in 2 tests (TNT equiv. 1.64) called DISTANT RUNNER Events 4 and 5 respectively; bldg volume = 186,400 cu ft
14	(g)	Model scale tests of item 13-R/C arch with steel liner, door steel plate and R/C composite with external steel frame, 7' x 12' x 2.8' high	test	5-1/10 scale	simultaneous detonation of several mini-tions in shelter	0.082 lb/cu ft	fragmented into many small pieces	yes	yes	yes	Model tests replicate Event 5 of DISTANT RUNNER only. G-D for debris hazard reproduced by model but model debris is measured larger than full scale debris
15	(h)	R/C box magazines--4 types, all flat slabs, single layer rebar centered in slabs, one or more door openings in each model	test	18 models 1/10 scale	generally, explosives centered	0.49-30 lb/cu ft	depending on loading, some had flexural cracking, others fragmented	yes	yes	yes	Report is in German

TABLE 4. SUMMARY OF EXISTING DATA
(Continued)

Item No.	Ref. No.	Component or Building Description	Accident or Test	Number of Tests	Scaled Stand-off, z (ft/(lb ^{1/3} /s))	Energy/ Bldg. Vol.	Failure Modes Observed	Debris Mass Measured	Debris Velocity Measured	Missile Map	General Notes
16	(i)	Sheetrock walls with metal and timber studs	test	12	UNS Shock Tunnel	1.7-3.8 psi peak incident pressure	punch out of entire wall from frame	entire wall only	yes	no	Walls were "nailed" to support frame; some separation of sheetrock from studs during flight
17	(i)	Concrete block walls (unreinforced), cantilevered	test	6	UNS Shock Tunnel	3.6-4.0 psi peak incident pressure	several flexural cracking & fragments according to cracks	no	yes	no	Walls seemed to form several flexure cracks at about 1/3 height and had large fragments determined according to these cracks
18	(i)	Clay tile walls (unreinforced), cantilevered	test	2	UNS Shock Tunnel	1.6-3.9 psi peak incident pressure	cracked below center, 2 fragments & wall broke up upon landing	no	yes	no	
19	(j)	8" unreinforced brick with simple supports	test	9	UNS Shock Tunnel	1.6 psi peak incident pressure	2-3 large pieces along yield lines	no	no	all fragments within 20'	
20	(j)	8" unreinforced brick with simple supports	test	1	UNS Shock Tunnel	5 psi peak incident pressure	2-3 large pieces along yield lines	no	no	all fragments within 70'	Scattering occurred after 2-3 large fragments hit the ground
21	(j)	8" unreinforced brick with plate supports	test	6	UNS Shock Tunnel	2-8 psi peak incident pressure	wall breaks into several large fragments along yield (crack) lines	no	no	limited info.	Main fragment in center section
22	(k)	Metal beams falling in flexure	test	60 sub-scale	Impulsive loading:	0.5 < t < 5 psi sec	beam breakup at points of maximum moment	yes	yes	N/A	Relationship established between beam structural parameters, applied impulses, and initial fragment velocity

TABLE 4. SUMMARY OF EXISTING DATA
(Continued)

Item No.	Ref. No.	Component or Building Description	Accident or Test	Number of Tests	Scaled Stand-offs, ² (ft/lb ^{1/3})	Energy/Bldg. Vol.	Failure Modes Observed	Debris Mass Measured	Debris Velocity Measured	Missile Map	General Notes
23	(l)	3 wall cubical with roof (hardened) in pre-engineered type building.	accident	N/A	18 lbs centered in cubical	fully vented	cubical did not fail. Exterior metal wall and cement asbestos roof failed		N/A		Case history assessment by Huntsville CDE. Accident at Milan AAP
24	(m)	Frangible "mini-wall" built adjacent to magazine	test	1	4.4 kg PETN prima cord divided into 20 strings hanging from roof	N/A	yes		yes		Test conducted for MDCS
25	(n)	36" R/C north wall 12" R/C south wall 24" R/C east wall earth backed 12" cinder brick west wall (40x16x36 ft bldg)	accident	N/A	4200 lbs of TNT	0.21 lb/ft ³	Debris thrown in all directions	yes	N/A	yes	Accident investigation by NSAC. Bldg owned by Air Force, Explosives Processing building
26	(o)	Concrete building above ground, no earth cover	accident	N/A	15 tons TNT stored at time of accident		Bldg totally destroyed with large crater	yes	N/A	yes	Further most debris thrown was a 5 kg piece at 720m. Explosion in Swedish munitions storage bldg
27	(p)	Full scale 1/10 scale and 1/5 scale models of earth covered bldg with reinforced concrete walls and roof	test	10	100 kg to 1200 kg TNT in full scale	1 to 32 kg/m ³	roof debris thrown		yes		Good agreement in roof velocity between 1/10 and 1/5 scales over entire load realm
28	(q,r,s)	Various brick and concrete walled and roofed buildings, some with earth mounding	test	13	charge quantities varied from 1800 kg to 45,000 kg		debris thrown	yes	yes	yes	UK/Australian explosive storage buildings

TABLE 4. SUMMARY OF EXISTING DATA
(Concluded)

Item No.	Ref. No.	Component or Building Description	Accident or Test	Number of Tests	Scaled Stand-offs, ² (ft/lb ^{1/3})	Energy/Bldg. Vol. (lb/ft ³)	Failure Modes Observed	Debris Mass Measured	Debris Velocity Measured	Missile Map	General Notes
29	t	Full, half and quarter scale component tests of reinforced concrete, masonry and metal walls; venting conditions included fully vented, partially vented, and closed	test	31	$0.5 < z \leq 7.9$ ft/lb ^{1/3}	0.001 to 0.02 lb/ft ³	local breach and flexural; debris thrown	yes	yes	yes	Tests were used to refine and validate a debris prediction model
30	u	Three different reinforced concrete aircraft shelters; tests conducted in 1/15 scale; all three shelter types tested with and without rock rubble berm	test	22	centered charges: 0.2 lb, 0.6 lb, 1.8 lb in 1/15 scale	0.004-0.04 lb/ft ³	three failure modes observed: 1) 3 major debris 2) 2 major debris 3) basal separation (one piece)	no	yes	no	Test objective was to determine effect of rock rubble berm on debris velocity and angle
31	v	Modular concrete and steel beam, earth covered igloos	test	1	centered charge 500,000 lbs		structure destroyed and debris thrown large distances	partial	no	partial	Object of test was to determine if propagation could occur. Debris measurements were secondary
32	w	Full scale and 1/4 scale reinforced concrete residential buildings subject to large internal loading for cased and uncased charges	test	6	primarily, quasi-static loading	1 kg/m ³	walls sheared at supports for uncased charges; walls broken up by shrapnel for cased charges	yes	yes	debris very directional; all fragments within 300' full scale	Measured debris velocities from 1/4 scale and full scale were almost equal

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SECTION III

REVIEW OF RELATED ANALYSIS AND COMPUTER PROGRAMS

Computer programs and analysis procedures currently used for predicting debris hazards can be separated according to the elements identified under Table 3 above. These are identified in Table 5.

TABLE 5. EXISTING SOFTWARE			
Item	Topic	Computer Programs	Predictive Procedure
1.	Shock Loading	SHOCK, BLASTINW	Computer Prediction
2.	Gas Pressure Load	FRANG	Computer Prediction
3.	Structural Breakup	SDOF programs	Computer Prediction
4.	Debris Velocity	None identified	Impulse/Momentum Calculation or Empirical
5.	Debris Throw	MUDEMIMP, TRAJ	Computer Prediction
6.	Roll or Ricochet	None identified	Empirical

All of the above software was exercised and compared for compatibility with explosions in aircraft shelters. A brief description of each is provided as follows.

A. SHOCK

The SHOCK computer code (6) provides one computerized method for estimating internal shock loads. This code calculates the blast impulse and pressure on all or part of a cubicle surface which is bounded by one to four non-responding reflecting surfaces. The code calculates these loads from the incident blast wave and from the waves reflecting off of each adjacent surface. It uses these results to determine the maximum average pressure on the blast surface from each incident and reflected wave and the total average impulse from the sum of all the waves. The duration of this impulse is also calculated.

SHOCK includes a reduced area option which allows determination of average shock impulse over a portion of a surface or at a single point on the surface. Loads over an entire component, over a local area, or at a point directly across from a charge can be determined using the SHOCK code.

Results of the SHOCK code have been compared to measured shock loading phase pressures and impulses in a rectangular box structure (5). The measured peak pressures did not agree well with the SHOCK predictions, but the predicted impulses correlated reasonably well. One drawback of the code is that it does not account for the effect of reflections off the wall opposite the loaded wall, nor does it account for gas pressure load contributions. If the room is large and the explosives charge is close to the surface being analyzed compared to the distance to the opposite surface, the opposite surface will have little influence and SHOCK results are reasonable. This is not true when the charge is centered in the building.

B. BLASTINW

The BLASTINW code, described by Britt, et al. (7), treats the combined shock wave (including multiple reflections off walls) and explosive gas pressure produced by conventional high explosive detonations in a closed, nonresponding, rectangular, box-shaped room. The shock wave effects can only be calculated for bare, spherical TNT explosive charges; however, the gas pressure model can treat an arbitrary mixture of several explosive components. The code has the capability to treat multiple non-simultaneous explosions in a room, modifications of shock arrival times and peak pressures to account for Mach stem effects, and the option to obtain pressure and impulse waveforms averaged over a number of target points on a wall. It does not account for movement of any of the walls or the roof.

The theoretical background for the BLASTINW code is described in Reference 7. Initial shock loads are predicted using free-field curve fits to blast data in Reference 8 and are converted to wall shock loads using results from hydrocode calculations (9). This shock wave reflection model is in good agreement with the standard TNT pressure and impulse peak values for reflection at normal incidence over the pressure range from 1 to 90,000 psi. The code has been validated for selected cases for pressure up to about 1,000 psi at oblique reflection angles. Effects of wall reflections are accounted for by postulating the detonation of image charges behind each wall, with proper timing. Waveforms for the loads are obtained by fits to modified exponential decays for positive phases, and exponential times sine functions for negative phases. The code purports to properly handle Mach reflections, and it does account for loads from multiple shock reflections for all walls in the assumed closed room. The gas pressure model has been validated up to high pressure levels for TNT and PETN and to lower levels for other explosives (10).

Options exist for running the code to compute only shock loads, only gas loads, or the two combined. If gas phase loads are desired, these loads are calculated separately and are then added numerically to the shock loads. The gas phase of loading is based on Reference 11, but has been modified to make it more efficient. Gas pressure arrival time is based on fits to test data. BLASTINW will handle multiple detonations of up to 20 explosive charges, of any desired mass and detonation delay, and at any locations within a box-shaped room. Loads can be calculated at up to 20 target locations. An option can also be exercised to obtain pressure and impulse averages over a number of points on a wall. The code runs on an IBM-PC or compatible computer. The biggest drawback of BLASTINW is that it will not allow an open wall or venting of any kind. As stated earlier, the room is assumed to be nonresponding.

C. FRANG

The FRANG analysis program, described by Wager and Connett (12), calculates a time history of gas pressure and impulse which result from an explosion inside a rectangular room. The code considers the effect of the escape of gas from the room through vents, both uncovered and covered by a frangible panel (an exterior surface designed to break loose and vent quickly enough to limit internal explosion effects). The vent area is a function of the panel displacement with time. Uncovered vents have a constant vent area. In addition to the time history of the gas pressure and impulse, FRANG calculates the change in displacement, velocity, acceleration, and vent area of the panel with time. The gas pressure decays with time, and the calculation continues until the gas pressure drops below 0.1 percent of the peak gas pressure. Required input for the code includes charge weight and type, room volume, covered and uncovered vent areas, covered vent perimeter, unit surface weight of frangible panel, initial recessed depth of the panel, the shock impulse on the panel, and the analysis time step.

As currently structured, this program will only allow input of one uncovered and one covered area. There must be at least one uncovered or one covered vent area, or the program fails; the code must be able to calculate a decay in the gas pressure. Other limits to the code are defined by the data on which the code is based. The ratio of charge weight to room volume, W/V , must lie between 0.001 and 2.0 lb/ft³. The scaled specific impulse cannot exceed 2,000 psi-msec/lb^{1/3}. The scaled unit surface weight must be less than 300 lb^{2/3}/ft². If these ratios are not within the stated limits, the calculated gas impulse may be underestimated.

FRANG modifies the input reflected shock impulse acting on the frangible panel, I , to a reduced reflected shock impulse. The input shock impulse would be equal to the reflected shock impulse if the reflecting surface were of infinite mass. Since the mass of the panel is finite, the panel will not cause full reflection of the shock waves which strike it. Thus, the code modifies the input impulse to account for panel movement.

The FRANG code has an option to print a history of gas pressure and impulse, frangible panel acceleration, velocity, displacement, and effective vent area at 1 msec intervals. Also, the printout will indicate the initial conditions immediately after the explosion, the conditions at the point when the vent area reaches its maximum size (time of critical venting), and the conditions when the gas pressure reaches 0.1 percent of its peak value and the calculation stops.

The FRANG code provides reasonable estimates of the gas pressure history for a detonation in a rectangular bay with one frangible, venting wall or roof. The only way to use this code with more than one venting surface is to modify the input, e.g., use the total vent area and perimeter of all vent surfaces with an area weighted average unit weight. Results obtained using this input modification are questionable though, mainly due to differences in the actual unit surface weight of each panel.

D. MUDIMEMP

The MUDEMIMP code, for Multiple-Debris Missile Impact Simulation, is used to determine the hazardous debris arcs for each structure analyzed. This code, written at Naval Civil Engineering Laboratory (NCEL), uses a probabilistic approach to cover variations and uncertainties of launch/flight characteristics of each individual debris missile from an explosion. It starts by using the Monte Carlo random sampling technique to select a set of launch/flight parameters for a single debris piece. It will then calculate the trajectory, impact range, and terminal kinetic energy of that piece. The Monte Carlo process and trajectory calculations are then repeated for all the debris missiles from an explosion. The code outputs a histogram of the accumulated number of critical (kinetic energy greater than 58 ft-lb) debris as a function of impact range. Hazardous debris arcs can be established using these histograms. A detailed description of the input and output information for the MUDEMIMP code is contained in Reference 13. The five main launch/flight parameters required to run the code are listed below:

- o debris mass,
- o initial velocity,
- o initial trajectory angle,
- o drag coefficient,
- o drag area factor.

The code input is in the form of probability distributions which describe the possible range of values for each major parameter. As discussed earlier, parameters are chosen by the code for each individual debris piece by randomly selecting from these distributions. The distributions available to describe the five launch/flight parameters are:

- o exponential,
- o normal,
- o uniform,
- o Weibull,
- o constant,
- o beta, or
- o log normal.

Significant changes to MUDEMIMP were made during the effort described in Reference 3. The principal changes are listed below:

- Addition of missile roll or ricochet after initial impact.
- Acceptance of trajectory angles greater than 90 degrees.
- Selection of debris initial conditions has been changed to not be completely randomly selected. Excluded are combinations of velocity, trajectory, and mass, which are all extremes. Such combinations will not occur.
- The maximum allowed velocity is the average plus three standard deviations.
- Debris densities for any grid include missiles landing in the grid and those passing over the grid.
- Downrange, the grid areas expand by a constant 5-degree angle on each side.

E. COMPARISON OF PROGRAMS

The two programs which allow prediction of shock phase loading were specifically developed for box-shaped cubicles. All input and output is for this geometry, and does not allow calculations for any other geometry. The shape of HAS is sufficiently different from that of a cubical to warrant development of new shock calculation software. This was accomplished under this Phase I effort for the third generation HAS geometry.

Another deficiency noted in existing software is that the above programs work independently to predict loads and response. It is clear, especially for an accurate prediction of the gas pressure history, that response of all structural elements must be linked to load prediction. This is partially completed in the FRANG program, which tracks venting as a single movable panel is pushed away from a vent area by the internal load. FRANG was adopted for use with QDRACS with input specified as described in Section IV; however, it is recommended that improvements be made for Phase II to account for improved coupling between response and venting.

The program MUDEMIMP, which uses TRAJ as a subroutine, has been recently updated by Bowles et al. One improvement is the addition of the prediction of debris roll and fragment ricochet after first impact. This software is widely accepted, including the DDESB, in the prediction of debris throw prediction. This software was utilized in the QDRACS program.

SECTION IV

DEVELOPMENT OR REVISION TO ANALYSIS METHODS AND COMPUTER CODES

An analysis procedure which includes the steps indicated in Table 2 has been developed and programmed into software named QDRACS. The following paragraphs describe the elements of the QDRACS program, which are illustrated by the flow chart in Figure 1.

A. USER INPUT

Upon starting the software, the user is asked to choose the type of shelter to be analyzed. At this time, only the U.S. third-generation HAS is available, others can be added during Phase II. The menu is presented as an example of the user-friendly software format of the program. This selection will allow use of stored shelter geometry data specific to the selected shelter type. The true geometry of a third generation HAS is that of an arch cross-section, which is currently idealized as the collection of five flat surfaces, with the front and end representing two additional surfaces, as shown in Figure 2.

Each surface is then divided into rectangular elements, interconnected at corners by nodes. In Figure 3, the shelter is "flattened" to better show all elements. The shelter geometry is defined under an x,y,z orthogonal coordinate system (the same used to define positions of weapons stacks) with the origin located in the front left corner of the structure. The floor is not considered a source of debris for the purpose of this study, but it is a reflecting surface thereby increasing shock loads on other surfaces. The program has stored x,y,z coordinates of all nodes and hence the location of all element and surface corners. The program will calculate all element and surface midpoint coordinates. The program includes stored data on the concrete thickness and the depth of soil cover (if any). This information is not utilized in calculating the shock loading; however, it is used later in the calculation of shelter response to load and debris formation and throw. Variations on these parameters can be examined by changing the data file.

Possible improvements to this geometry representation should be considered in Phase II. A finer grid mesh could be used, however connectivity of elements would be necessary to represent debris pieces that are larger than a single element. Also, a different scheme will be necessary to account for shocks which arrive at an element due to surface reflections.

B. SHOCK LOAD PREDICTION ON INTERNAL SURFACES

The adoption or modification of existing programs was felt to be inappropriate since they do not model a structure with the geometry of typical aircraft shelters. A shock load prediction program specific to HAS was developed using a methodology similar to that in the BLASTINW program where direct shocks and shock reflections off adjoining surfaces are accounted for through ray tracing from image charges. Also similar to BLASTINW, the method used will analyze multiple charge locations. At this time, however, QDRACS does not distinguish times of arrival of shocks from different munitions stacks or from reflections. Impulses of separate shocks are calculated then added together and treated as a single triangular pulse and the peak pressure is taken as the largest of any one shock. It is recommended that time phasing of shocks be considered in Phase II. The scheme used to calculate shock loading includes the following steps which are described further in subsequent paragraphs:

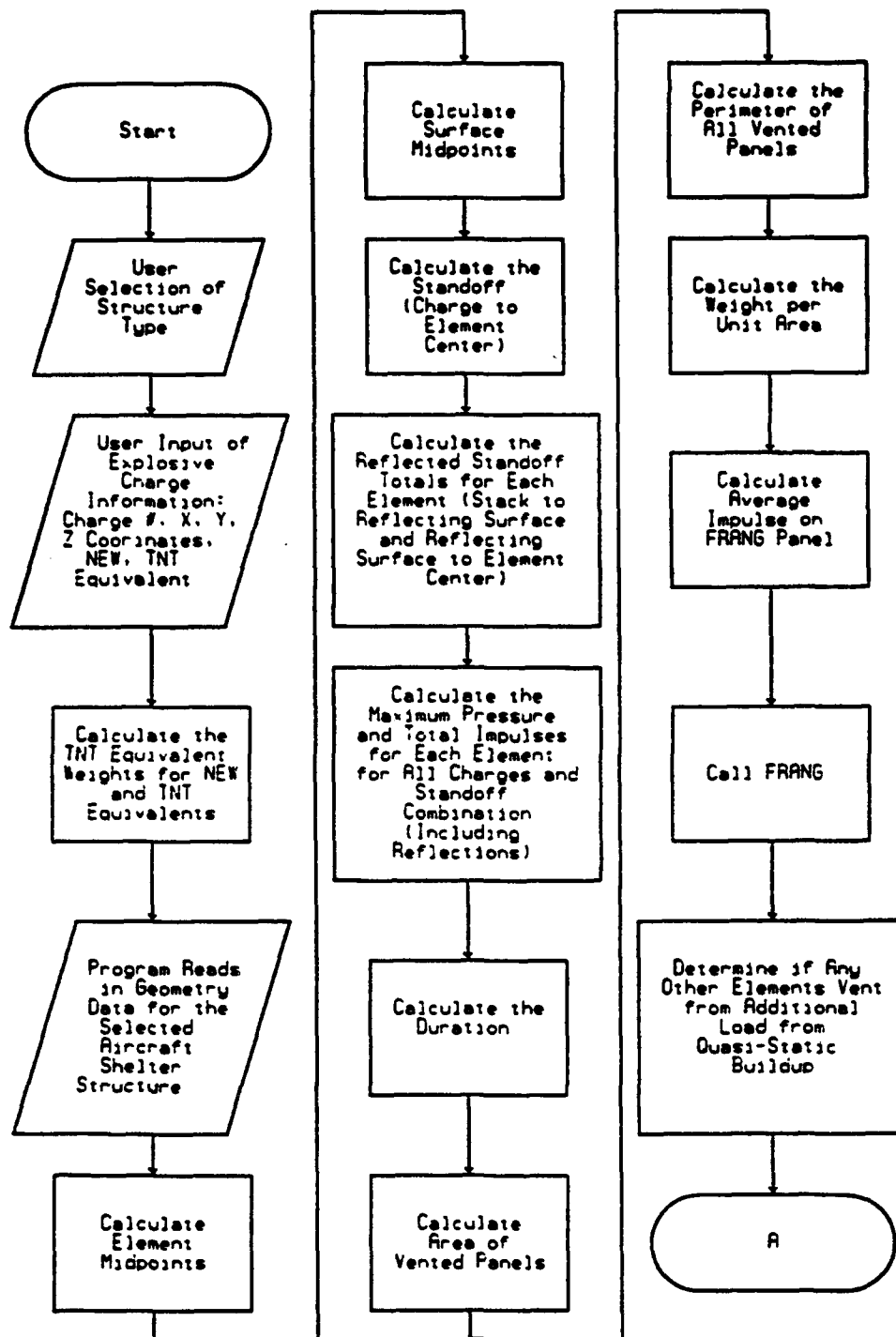


Figure 1. QDRACS Flow Diagram

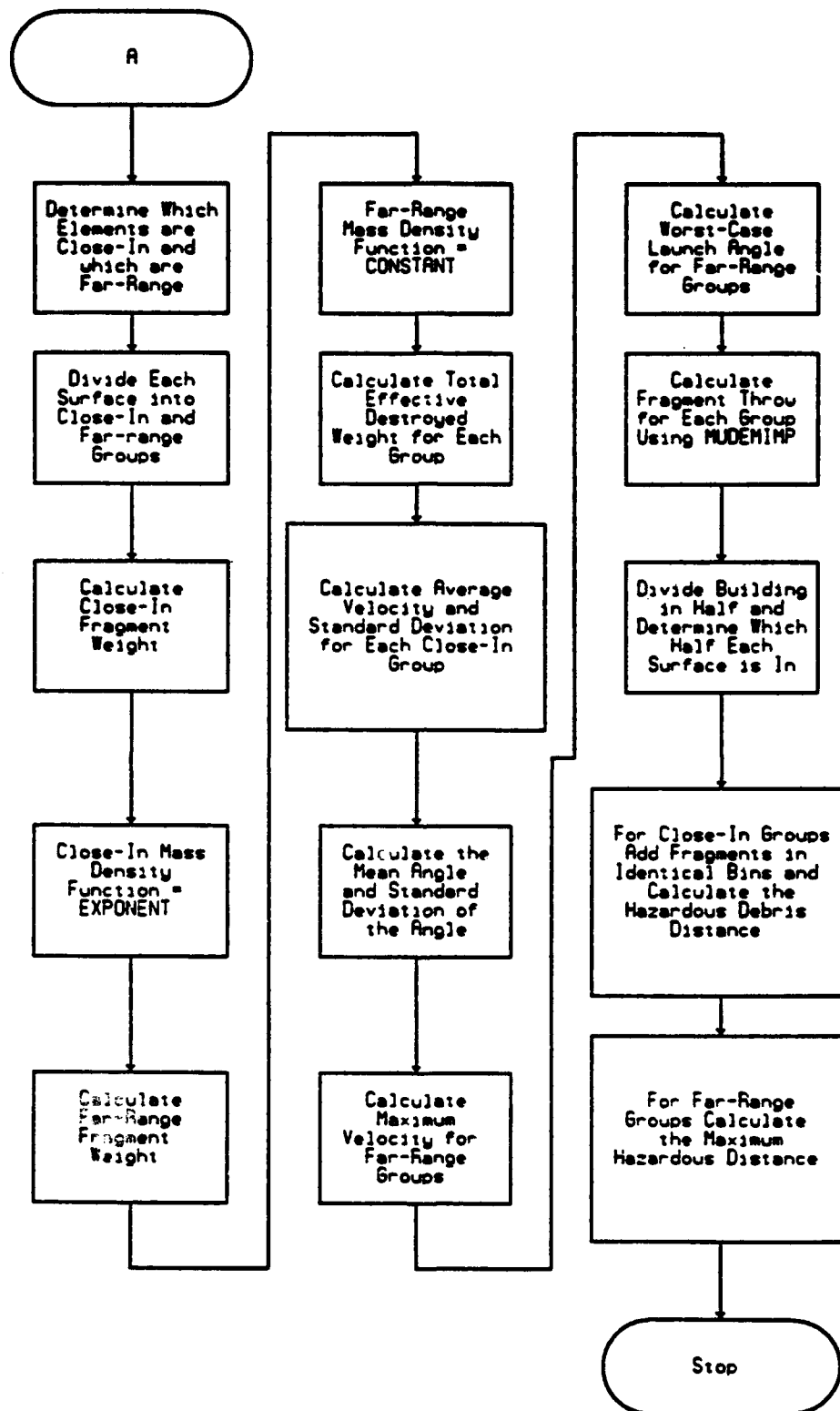


Figure 1. QDRACS Flow Diagram (Concluded)

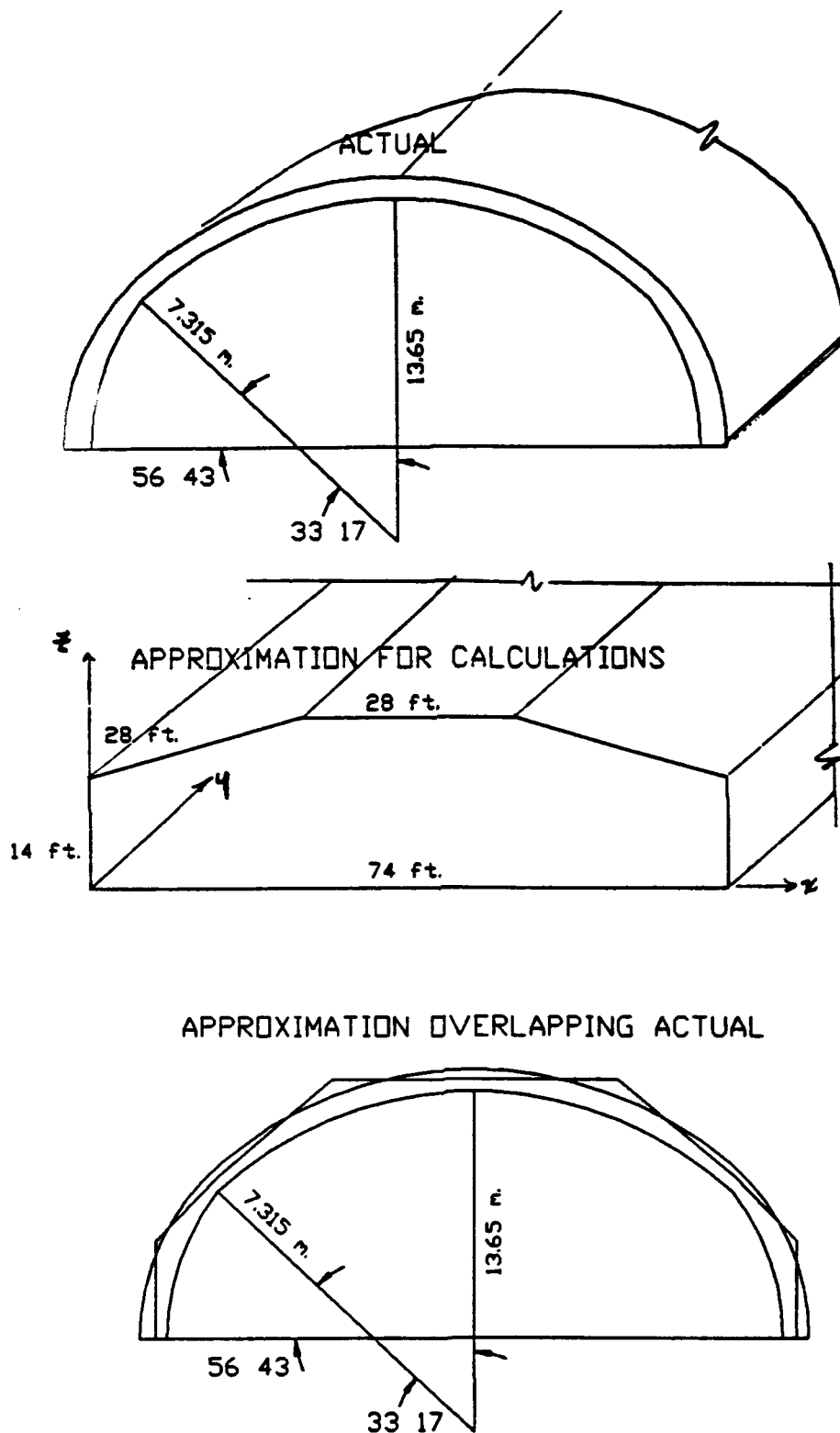


Figure 2. Approximate Shelter Geometry for QDRACS

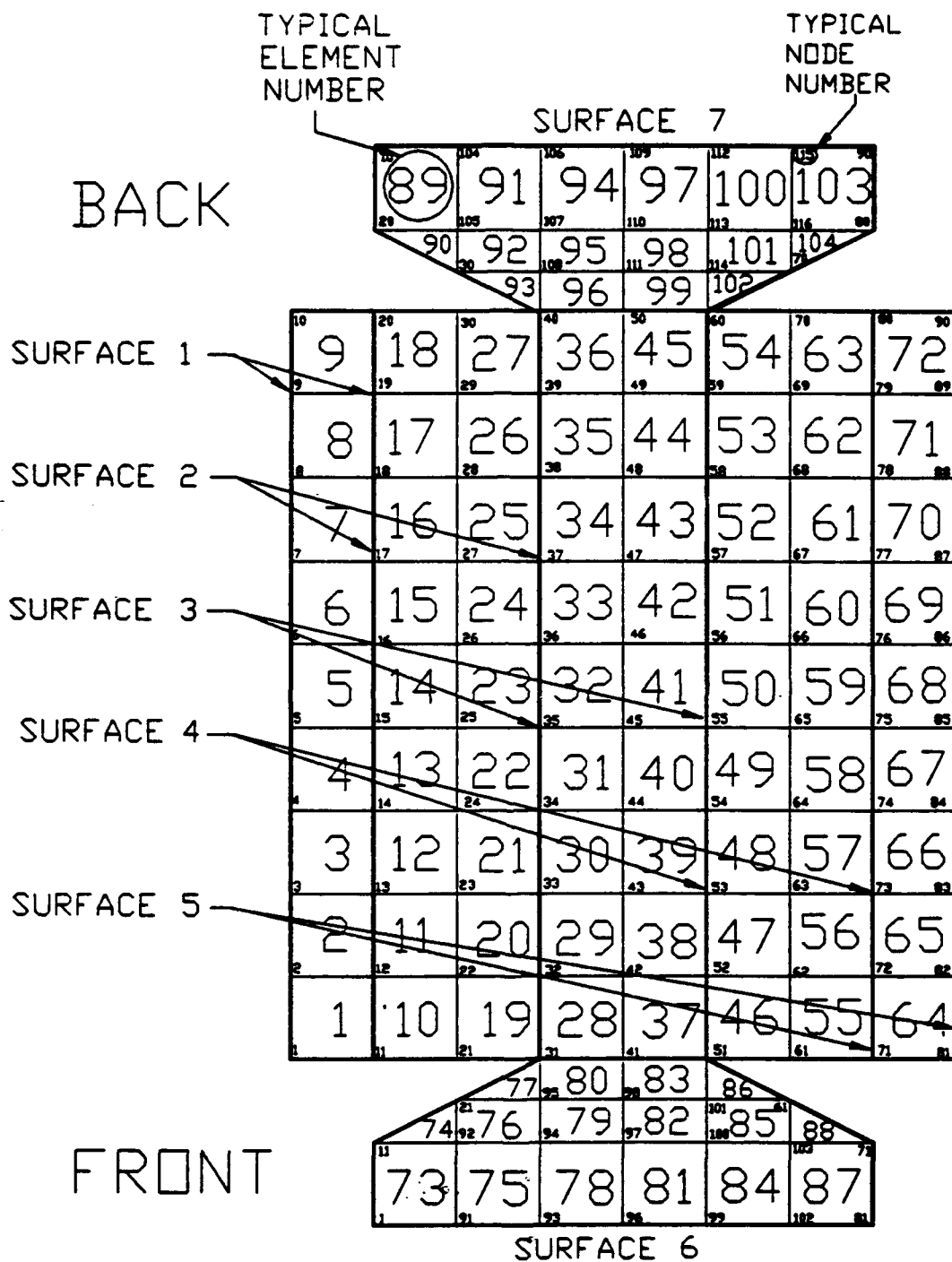


Figure 3. Grid, Surface, and Node Definition for Shelter

1. Determine standoff from each charge to each element center.
2. Determine distance from each reflecting surface to each element.
3. Determine distance from each charge to each reflecting surface.
4. Sum 2 and 3 for surface reflection standoff.
5. Calculate pressure and impulse from each charge and standoff combination (including reflections).
6. Sum impulses.
7. Select maximum pressure.
8. Use single triangular pulse shape to calculate duration.

1. Calculate Standoffs

Standoffs will be calculated in a series of steps. First, distances from each charge location to the center of each element are calculated. This will give us the standoff for all direct or "line of sight" shock wave reflections on each element from the various charges.

The second step is to account for secondary reflections off the various shelter surfaces. This must be accomplished for each element. Secondary reflections will be treated by the same means as a "line of sight" shock, except that the standoff will include the total distance from the charge to the nearest point on the reflecting surface then to the center of the element under consideration. This is accomplished for all reflecting surfaces except the one on which the element is located. For example, when considering an element on Surface 3, then all reflecting surfaces but 3 should be included. The total standoff is in two parts, first from the charge to the reflecting surface, then from the reflecting surface to the element.

2. Calculate Shock Loading on Elements

Once standoffs are defined, then shock loads can be calculated. The multi-pulse shock loading phase, which includes the initial and all reflected shocks, is approximated as a single triangular pulse. The shock load profile will have a peak pressure equal to the largest peak of any of the individual pulses and will have an impulse of the sum of the impulses in all pulses. A non-responding or rigid structure is assumed when calculating the shock load phase, hence all surfaces are considered to remain intact and act to reflect the shock as if they were rigid. Later in the analysis of structural motion, individual elements are allowed to move under the shock load.

Shock pressures and impulses are calculated by a subroutine, SHOCK (not the program "SHOCK" referenced earlier), which uses a data file for reflected airblast curve given in Figure 4-7 of the newly revised AFM 88-22 (14). The data file, which includes 200 entries for both pressure and impulse each paired with a scaled standoff, was taken from the electronic version of that document which was developed by David Hyde of the U.S. Army Waterways Experiment Station. An interpolation scheme was programmed to determine values between points in the data file. The scheme is based on a spline curve fit to data points on each side of the value of interest.

The pressures and impulses calculated are for normal (90-degree) reflections. It is clear that not all arriving pulses strike normal to the surface, and oblique reflections occur. However, this is a very good approximation, at least to 39 degrees for strong shocks (the regular reflection angle limit) and at much greater angles for weak shocks. All strong shocks will be due to close standoffs, and thus relevant to elements near the charge, which means shallow angles. Elements at angles greater than 39 degrees will likely experience weak shocks. The use of normal reflected data for all predictions is reasonable and certainly conservative (will overpredict loads). Phase II studies may include angle of shock incidence and account for off-normal reflections.

3. Combine Shocks

Each element will have numerous shock reflections calculated. These are lumped as a single triangular pulse. For each element, the pressures are scanned and the largest value which is used as the peak shock pulse pressure. For each element, the impulses for all shocks are summed. Pulse durations are calculated by using the triangular shape, where duration equals twice the summed impulse divided by the peak pressure. An array is created that summarizes the shock load at the various elements. This provides the shock load distribution over the interior surface of the shelter.

C. GAS PRESSURE LOAD PREDICTION ON INTERNAL SURFACES

The steps involved in definition of the gas pressure load on individual elements is as follows.

1. Calculate area of shelter which fails due to shocks.
2. Add area of shelter front to (1) to determine total vent area and treat as a single vent panel.
3. Calculate vent panel perimeter.
4. Calculate area weighted average of vent panel weight/area.
5. Run FRANG.
6. Obtain i_{AMAX} and i_{TOTAL} .
7. Combine gas impulses with shock loads.
8. Check for additional structural failure.

As indicated above, the program FRANG was adopted for this phase I effort. This program was modified as a subroutine and incorporated into QDRACS. Before FRANG is called by QDRACS, the venting characteristics must be defined as input. These include vent area, vent perimeter (where leakage occurs), vent panel weight, and applied shock impulse. The following paragraphs expand upon the analysis steps involved.

1. Calculate Vent Area and Perimeter

The shelter surface area available for venting of gas pressures depends upon that which fails under load. Two modes of failure are examined. One where the slab is overwhelmed by intense shock load causing breakup into small pieces (similar to wall breach) and a second mode where slab failure occurs due to slab rotations and extensions, resulting in large missiles. Portions of the shelter surface may receive insufficient load to cause failure, which becomes important when considering a small NEW. A scan of the shock load on all elements is made to determine if the response will be breach failure, large slab failure, or no failure. A total failed area is calculated summing all failed elements. The front wall (doors) is considered to be unconstrained and free to move, whether structural failure of the panel occurs or not. The entire front wall area is always included in the vent area.

The vent area is considered to act as a single vent panel. This is a limitation of the FRANG program which cannot analyze multiple vent panels. To account for the breakup of the shelter into multiple panels, the perimeter length term used in FRANG was calculated by considering the total perimeter length of destroyed areas. Side-by-side elements which both failed were not considered to contribute to the vent perimeter along the edge connecting the two. All elements were summed for this condition, and the perimeter length summed only for edges between failed and non-failed elements. A minimum perimeter was maintained, however, including all edges joining all surfaces.

2. Vent Panel Weight and Applied Shock Impulse

FRANG requires input of the panel weight and applied shock impulse. The panel can include combinations from arch, front, and rear wall elements, which will have different thickness and receive different shock loads. Also, the user may want to investigate the effects of earth berming on the shelter, which can be accomplished with QDRACS. Berming will add mass to covered elements. To account for the distribution of weights and loads, an area weighted average was calculated for both. The area of each failed element was multiplied by the weight and all were summed then divided by the total destroyed area. The same type of averaging was made for shock impulse.

3. Run FRANG to Obtain Impulse, then Recheck for Failure

The QDRACS program then calls the FRANG subroutine to calculate gas load history. FRANG output includes the peak gas pressure, gas impulse to the time of critical venting (i_{AMAX}), and the total gas impulse (i_{TOTAL}). The maximum venting occurs when the vent panel has moved out to a distance where the perimeter area (perimeter length times distance) is equal to the panel area. At this point the venting is considered to be through an unobstructed area and continues until pressure drops to zero. The elements which make up the vent panel will gain additional velocity from the gas load. The i_{AMAX} is combined with individual shock impulses for all of these elements. Elements which did not fail due to the shock load did not contribute to the vent panel. To these, the i_{TOTAL} is combined with individual shock impulses. Once the appropriate gas impulse is added to shock impulse for each element, a second scan is made to determine if additional slab failures occur. This allows definition of all elements which will be considered for debris throw.

D. STRUCTURAL RESPONSE, BREAKUP, AND DEBRIS VELOCITY

As already mentioned, two modes of structural breakup have been considered in the QDRACS model. The first mode is where a slab is overwhelmed by intense shock load causing breakup into small pieces and the second mode where slab failure occurs due to slab rotations and extension, resulting in large missiles. Each element is checked to determine which type of response occurs, and the resulting debris velocity is calculated. More specifically, the following steps are taken:

1. Check all elements for mode of response.
2. Form debris groups.
3. Calculate debris mass and velocity in format for MUDEMIMP.

1. Wall Breach

The first mode is due to the combined effects of a stress wave transferred into the slab by the shock and the applied load overcoming the direct shear capacity of the slab. The stress wave is in compression until it reaches the outside free slab surface where it reflects as a tensile pulse. This causes spall if the tensile capacity of the slab is exceeded. The depth into the slab where spall fractures can be formed depends on the duration and peak pressure of the stress wave. At the same time, the concrete is responding to direct shears produced by the applied load. Failure of the concrete results in a breach in the slab. Such a "breach" is characterized by small fragmentation of the concrete, which disengages and is thrown separately from the rebar.

Criteria were selected for the project to define when this mode of response occurs. This was difficult due to the possibility of numerous separate stacks of weapons and reverberation of the shock within the structure. It was felt that breach would result only from shocks which occur relatively close in time. Gas load is not expected to be important to slab breach.

In developing criteria for breach, several references were studied. This includes guidance provided by Ross (14), who has developed an expression for the critical impulse to result in slab breach as follows:

$$i_{cr} = (2\sqrt{2}/3) h \{[(1-q)\rho_c + q\rho_r][(1-q)\sigma_{cd} + q\sigma_{rd}]\}^{1/2} \quad (1)$$

where h = slab thickness
 q = steel ratio
 ρ_c = density of concrete
 ρ_r = density of steel
 σ_{cd} = dynamic tensile strength of concrete
 σ_{rd} = dynamic ultimate strength of rebar

Also, Bowles, et al., specify criteria for what is called "close-in" failure based on test observations. This reference identified that for scaled standoffs of less than 1 ft/lb^{1/3}, concrete panels tested were "rubblized" by the blast. These criteria are a function of standoff and charge quantity alone and do not include slab thickness. Their tests were for a limited range of slab thicknesses of interest to their study.

Hader (15) provides a comprehensive summary of published data relating to wall breach for both cased and uncased munitions. His work includes the effect of slab thickness. He plots data for scaled slab thickness, $T/W^{1/3}$, versus scaled standoff, $R/W^{1/3}$. The plots are very comprehensive, including 96 data points for bare charges, 31 of which were conducted by the author. Another plot of cased weapons data is given including 37 data points, 15 of which were conducted by the author. In his plots are division lines representing the onset of spall and perforation or breach. The author points out the difference in cased and uncased weapons effects, the cased resulting in much more severe damage.

The information presented by Hader was chosen to establish breach criteria for QDRACS because his work accounts for slab thickness and the effects of cased munitions, which are representative of munitions inside HAS. The Ross method has the potential to account for these effects and should be studied further in Phase II. The curves by Hader are log linear and can be represented by the following equations:

	Cased Charges	Uncased Charges
Spall Limit:	$T/Q^{1/3} = 0.12(R/Q^{1/3})^{-0.4}$	$T/Q^{1/3} = 0.06(R/Q^{1/3})^{-0.565}$
Breach Limit:	$T/Q^{1/3} = 0.094(R/Q^{1/3})^{-0.4}$	$T/Q^{1/3} = 0.03(R/Q^{1/3})^{-0.565}$

For: T and R in meters and Q in Kg

These fits can be unscaled for the wall thickness of interest and converted to English units. This provides the following criteria for the arch portion of the structure which has an average thickness of 28 inches.

	Cased Charges	Uncased Charges
Spall Limit:	$5.34 = W^{0.467} R^{-0.4}$	$0.91 = W^{0.522} R^{-0.545}$
Breach Limit:	$6.8 = W^{0.467} R^{-0.4}$	$1.8 = W^{0.522} R^{-0.545}$

For: R in feet and W in lbs

It was decided that choice of the spall limit would be too conservative, but that the perforation criteria were unconservative, the latter especially in the light that individual stacks and not the entire NEW are used with the criteria. The final choice is to use the average of these two limits. Thus, the following criteria were established for determining if breach occurs.

$$6.1 = W^{0.467} R^{-0.4} \quad (2)$$

Note that these criteria do not include the gas phase loading. Phase II studies should investigate to determine it is a correct assumption that gas loading does not contribute to breach.

As stated, QDRACS will check each stack against each element to determine if breach will occur. If two stacks are close together relative to their distance from a particular element, then their effects should be combined when comparing for breach. For this reason it was necessary to define that all munitions close to one another would constitute a stack and not be defined separately. The distance of 10 feet was chosen, as this is a scaled distance of $1 \text{ ft/lb}^{1/3}$ unscaled for a 1,000-pound explosive weight. Thus, all munitions within a 10-foot radius shall be considered a single stack.

2. Rotation and Extension Failure

If the load is not severe enough to cause breach, then gross slab rotations and flexure response can result in breakup. This type of response is expected to develop large missiles with the exception of rubble formed at hinge locations. A criterion was chosen to specify when this type of failure would occur. The criterion is based on bending response of a single element. If the combined shock and gas impulse is greater than 2,000 psi msec, then this failure is determined to occur.

3. Form Debris Groups

After the response mode of each element is determined, QDRACS then forms debris groups. This is accomplished by scanning all elements on a single surface to determine how many fail as small debris (due to close-in loading), how many fail as large pieces (due to far-range loading), and how many do not fail. The process is repeated for each surface. Two debris groups for each surface are formed, one containing all small debris and the other containing all large debris. These groups are used in the debris throw analysis. The small and large debris are isolated in this manner to allow separate calculations for each debris type.

4. Debris Velocity and Mass

Debris velocity and mass must be defined in a format compatible with the MUDEMIMP program which was chosen for debris throw analysis. It is widely recognized that the conversion of applied impulse into debris momentum gives conservative estimates of velocity. Several references (5 and 6) offer less conservative methods for velocity calculation based on empirical observations. While improvements over simple momentum calculations, these methods are primarily based on test data for explosive weights less than 300 pounds and much, but not all, of the test data is for unconfined explosions where the shock load is the driving force. The situation for HAS is that the gas pressure load contributes to a significant portion of the debris velocity. In developing QDRACS, it was decided to use the impulse-momentum relationship, considering the combined shock and gas impulse, to calculate velocity. For these debris, the velocity calculated is taken as an average equal to 60 percent of this value. These selections are made based on recommendations in Reference 5. A normal distribution is used with a standard deviation of 14 percent of the maximum.

Debris mass is established by the two group types discussed earlier. The groups consisting of small debris from breached elements will have mass defined using criteria in Reference 5. This is corroborated by observations in the DiSTANT RUNNER tests where debris sizes on this order were collected. An exponential mass density function is assumed with an average mass, m_{avg} , calculated by the following equation:

$$m_{avg} = 0.10 [(\text{rebar spacing})^2 (\text{cover thickness}) (\text{density})]$$

The large debris resulting from slab rotations and extension was arbitrarily chosen to equal an entire element. Thus the mass for these groups is considered to be a constant with zero deviation. The velocity for such pieces is taken as a constant as well.

E. DEBRIS THROW AND ROLL AFTER IMPACT

The program MUDEMIMP described earlier has been incorporated as a subroutine to QDRACS. The subroutine will be called for calculations on each debris group. There may be two groups for each surface. Each group is analyzed separately and results summed as appropriate to account for debris thrown in the same direction.

MUDEMIMP requires definition of trajectory angle, drag area, and drag coefficient distributions. These are all made using recommendations from Reference 5. The MUDEMIMP output gives the number of hazardous fragments (those with impact energies greater than 58 ft-lb) per 600 ft² are found at various distances from the explosion. This format is complementary to debris hazards criteria established by the DDESB.

The MUDEMIMP program was improved by Bowles, et al., (5) to account for the distance traveled by debris after first impact due to roll or tumble. This feature is also used in the QDRACS calculations.

SECTION V

COMPARISON OF CODES WITH EXISTING TEST DATA

Comparisons have been made with the DISTANT RUNNER results for Events 4 and 5. Currently, QDRACS only predicts concrete missile throw to the sides of the shelter. The program evaluates response and debris throw from each side separately. The results for each side will be the same if the weapons are stacked symmetrically inside the shelter, resulting in the same loads on each side of the building. Otherwise, different results are expected.

The results of the comparison between QDRACS and DISTANT RUNNER are provided in Table 6. These calculations are for unbermed shelters, which were the type used in the Event 4 and 5 tests. These two cases were analyzed once again, but with an earth berm covering the shelter with the results included in Table 6 for comparison purposes. The earth berm used in the analysis included a 2-foot cover on the roof, a 4-foot cover on the slant, and a 10-foot cover on the side.

TABLE 6. MAXIMUM HAZARD DISTANCE IN FEET			
	DISTANT RUNNER	QDRACS (no earth cover)	QDRACS (with earth cover)
Event 4	820*	680	490
Event 5	1300*	1230	860
* Based on Q-D Criteria of 62 $W^{1/3}$			

These results are reasonable, especially in light of the fact that the 62 $W^{1/3}$ criteria are based on an extrapolation of the DISTANT RUNNER test data. The researchers did not measure a debris density of 1/600 ft² at the distances above. The QDRACS code does predict greater throw distances, but at lower debris densities.

A listing of loading and operating steps for QDRACS can be found in the appendix. The code can be executed with or without earth cover using existing data files. The user also has a choice of executing and viewing results from either Event 4 or Event 5.

SECTION VI

RECOMMENDATIONS FOR PHASE II

Throughout this report, recommendations have been made for the improvement of the prediction methods and software development. A summary of these and other recommendations is provided below. No particular priority has been given to these recommendations, as they are all considered important for improvement of the prediction model.

- o An effort should be made to account for breakup, the structural response before failure of multiple structural elements, and the formation of multiple venting paths and vent panels in calculation of gas pressure loads. Venting through breached areas may require use of a vent area ratio to account for the many leakage paths. This is an ambitious goal, but would be a great benefit to improving the accuracy of this model, in particular, and a great benefit to many different applications.
- o Improvement of the shock prediction methods should be made. Inclusion of angle of shock reflection and the phasing of shock arrival times and durations is important. Consideration should be given to sequential detonations based on primary fragment time of arrival.
- o Use of a finer grid mesh (smaller elements) would improve loads prediction and allow for better segregation of local response effects. Connectivity between elements is required to treat side-by-side elements, which respond the same, together in the analysis.
- o Improved definition of breakup under various load conditions is necessary. Criteria for onset of breach and slab failure should be studied, along with improved classification of debris size distributions.
- o Correlation between debris size and velocity calculation is necessary. Currently all sizes are treated the same; then a standard deviation is applied over an assumed normal distribution.
- o Velocity determination for breached areas should include drag load effects on small pieces as the gas load vents through the rubble. This is a different approach than that used currently in FRANG. The current method, developed for vent panels in operating bays, is applicable to large missiles whose motion is dominated by the applied gas pressure. Smaller pieces in a rubble area will have gas flow around the pieces to vent to the outside. This is a drag type loading.
- o Software improvements include
 - Addition of geometry data bases for additional shelter types such as the joint-US/NATO or the Norwegian shelter.
 - Improved format for user input, allowing specification of earth cover, placement of exterior barricades, and specification of weapon types. For the latter, a data base of weapons types can be included in the software which has all NEW and TNT equivalence information. Thus, the user can call out weapons by their name, such as MK82, rather than requiring input of NEW and TNT equivalences.

- Output can be customized to meet user needs.
- o Currently, the program only accounts for DOD Hazard Class/Division 1.1 mass detonating weapons. Class/Division 1.2 items are not mass detonating. Also, many have 1.3 components which, while not affecting the shock load phase, are important in calculation of the gas loading phase. The program can be modified to account for differences in hazard classification of warheads and rocket motors.
- o The model needs to include hazards predictions in all directions (front, side, rear) and all possible fragment types. This includes primaries, metal ring, door frame, and others.
- o The effects of earth berming on structural breakup must be studied. All current data are for air-backed slabs. Soil-backed slabs will most likely have differences in spall formation and also change breach conditions.

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APPENDIX
QDRACS OPERATING INSTRUCTIONS

1. Create Directory QDRACS:
Type *MD QDRACS*
2. Change to QDRACS Directory:
Type *CD QDRACS*
3. While in the QDRACS Directory, create Data Subdirectory:
Type *MD DATA*
4. Copy all Files to Directory QDRACS. Use the appropriate floppy and hard drive. A and C are assumed here:
Type *COPY A:.* C:\QDRACS*
5. After completion of copying, type QDRACCFG, while in the QDRACS Directory, and:
 - a. Select your monitor type.
 - b. Select mouse if present.
6. Copy the session file to the data directory to run a test case:
Type *COPY QDRACS.SES C:\QDRACS\DATA*
7. If the user decides not to set up a subdirectory DATA, then user must edit the Q.BAT program and set the %dpath% environment variable to the appropriate path for the data directory.
8. To analyze a case involving a preset earth cover depth:
Type *COPY EARTH.DAT QDRACS.INP*

-OR-
9. To analyze a case involving no earth cover:
Type *COPY NOEARTH.DAT QADRACS.INP*
10. To analyze Event 4, initialize the session file as indicated below and when executing QDRACS, select *using a previous session file* on the displayed menu. Use Item 9 or 10 above as desired before running QDRACS:
Type *COPY EVENT 4.DAT C:\QDRACS\DATA\QDRACS.SES*

-OR-
11. To analyze Event 5, initialize the session file as indicated below and when executing QDRACS, select *using a previous session file* on the displayed menu. Use Item 9 or 10 above as desired before running QDRACS:
Type *COPY EVENT5.DAT C:\QDRACS\DATA\QDRACS.SES*
12. Run the QDRACS program by executing the Q.BAT file as indicated below:
Type *Q*