

AEDC-TR-87-32

(4)

DTIC FILE COPY

AD-A187 289



Glass Failure Prediction for Arnold Engineering Development Center

Prepared by
H. Scott Norville
Joseph E. Minor

Glass Research and Testing Laboratory
Texas Tech University
Lubbock, Texas 79409

Submitted to
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, California 94550

November 1987

DTIC
ELECTE
DEC 09 1987
S H D

Final Report for Period November 1, 1985 - August 31, 1987

Approved for public release; distribution is unlimited.

ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE BASE, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

87 11 30 103

NOTICES

When U. S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Technical Information Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.

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

APPROVAL STATEMENT

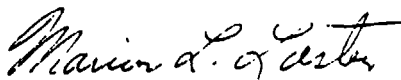
This report has been reviewed and approved.



CARLOS TIRRES
Facility Technology Division
Directorate of Technology
Deputy for Operations

Approved for publication:

FOR THE COMMANDER



MARION L. LASTER
Director of Technology
Deputy for Operations

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AD-A187289

REPORT DOCUMENTATION PAGE				Form Approved ON: 3 No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AEDC-TR-87-32			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Lawrence Livermore National Laboratory		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) P.O. Box 808 Livermore, CA 94550			7b. ADDRESS (City, State, and ZIP Code)		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Arnold Engineering Development Center		8b. OFFICE SYMBOL (If applicable) DO	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER MIPR FY 7483-83-0008		
8c. ADDRESS (City, State, and ZIP Code) Air Force Systems Command Arnold Air Force Base, TN 37389-5000			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
11. TITLE (Include Security Classification) Glass Failure Prediction for Arnold Engineering Development Center					
12. PERSONAL AUTHOR(S) Norville, H. Scott and Minor, Joseph E., Glass Research and Testing Laboratory (Cont)					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM 11/1/85 TO 8/31/87		14. DATE OF REPORT (Year, Month, Day) November 1987	
				15. PAGE COUNT 54	
16. SUPPLEMENTARY NOTATION Available in Defense Technical Information Center (DTIC).					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	blast effects dynamic failure prediction		
19	04		window glass personnel safety		
11	02		siting		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) An assessment of expected window breakage at the Arnold Engineering Development Center in the event of an accidental motor detonation at either the J-5 test site or the proposed J-6 test site has been conducted. Motor detonations equivalent to 30,000- and 20,000-lb TNT were considered at the J-5 test site, and a motor detonation equivalent to 100,000-lb TNT at the proposed J-6 test site was considered. A dynamic failure prediction model based upon a Weibull strength distribution was used to estimate probabilities of failure for window glass plates acted upon by anticipated blast waves that would occur in conjunction with such accidental motor detonations. In the event of an accidental motor detonation at either of the sites, considerable window glass breakage would result. Breakage that would result from an accidental motor detonation equivalent to 100,000-lb TNT at the proposed J-6 test site is expected to be less than breakage that would result from an accidental motor detonation equivalent to either 20,000- or 30,000-lb TNT at the J-5 test site. (Cont)					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL C. L. Garner			22b. TELEPHONE (Include Area Code) (615) 454-7813		22c. OFFICE SYMBOL DOCS

DD Form 1473, JUN 86

Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

108



Dist

Avail and/or
Special

A-1

UNCLASSIFIED

12. PERSONAL AUTHORS (Cond)

Texas Tech University, Lubbock, TX 79409

19. ABSTRACT (Cond)

CONT. ➤ This study concludes that the proposed J-6 test site is located adequately so that an accidental motor detonation would result in no more window glass breakage than would be expected from an accidental motor detonation at the J-5 test site.

UNCLASSIFIED

PREFACE

The research reported herein was conducted by the Glass Research and Testing Laboratory, Texas Tech University, under Contract MIPR FY 7483-83-0008, Subcontract 6549005, for Lawrence Livermore National Laboratory (LLNL), to the Director of Technology, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Base, Tennessee, during the period November 1, 1985 to August 31, 1987. The Project Manager was Mr. Carlos Tirres, AEDC/DOT. Ray Pierce was the Project Manager for LLNL, and Bob Murray was the LLNL Project Leader for this task. Dr. H. Scott Norville, P.E., and Dr. Joseph E. Minor, P.E., directed the project for Texas Tech University. Technical work was conducted by Dr. H. Scott Norville. The manuscript was submitted for publication November 16, 1987.

CONTENTS

	<u>Page</u>
I. INTRODUCTION	7
II. WINDOW GLASS STRENGTH	8
III. DYNAMIC FAILURE PREDICTION FOR WINDOW GLASS PLATES	10
IV. WINDOW GLASS SURVEY	15
V. BLAST LOADS AND ESTIMATED PROBABILITIES OF FAILURE	20
VI. UNCERTAINTIES AND LIMITATIONS	32
VII. CONCLUSIONS	34
REFERENCES	36
APPENDIX: Discussion of Glass Breakage Predictions for Arnold Engineering Development Center . .	39

ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1. Orientation of Surfaces Containing Windows with Respect to Direction of Blast Wave Travel	17
2. Plan View of Arnold Engineering Development Center	18
3. Ideal Blast Load Time-History	21
4. Typical Cumulative Probability of Failure Curve for a 16 x 48 x 0.12 in. Glass Plate	24
5. Probability of Glass Failure Contours for a 20,000 lb Equivalent TNT Detonation at the J-5 Test Facility	25
6. Probability of Glass Failure Contours for a 30,000 lb Equivalent TNT Detonation at the J-5 Test Facility	26
7. Probability of Glass Failure Contours for a 20,000 Equivalent TNT Detonation at the Proposed J-6 Test Facility	27
8. Probability of Glass Failure Contours for a 30,000 lb Equivalent TNT Detonation at the Proposed J-6 Test Facility	28
9. Probability of Glass Failure Contours for a 100,000 lb Equivalent TNT Detonation at the Proposed J-6 Test Facility	29

TABLES

<u>Table</u>	<u>Page</u>
1. Biaxial Stress Correction Factors, $c(x,y)$	13
2. Percentages of Window Glass Plates at Various Distances from the J-5 Test Facility.	15
3. Percentages of Window Glass Plates at Various Distances from the Proposed J-6 Test Facility	19
4. Blast Load Parameters for a 100,000 lb TNT Detonation	20
5. Blast Load Parameters for a 30,000 lb TNT Detonation	22
6. Blast Load Parameters for a 20,000 lb TNT Detonation	22
7. Expected Percentages of Window Glass Breakage in the Event of Accidental Detonations	31

I. INTRODUCTION

Arnold Engineering Development Center is a large test facility complex for the static testing of aircraft, space, and missile systems and/or subsystems. In any test of a rocket motor containing Class 1.1 propellant, the possibility of an accidental detonation of the unburned solid propellant exists. In the event of such an accidental detonation, structural damage could result. At a minimum, some window glass in the buildings at Arnold Engineering Development Center would be broken.

The purpose of the study described in this report is to provide estimates of window glass breakage which could be expected in the event of an accidental explosion occurring at one of two rocket motor test facilities at Arnold Engineering Development Center. The two facilities are the existing J-5 test facility and the proposed J-6 test facility. The yields of the accidental explosions used for this study are 20,000 lb and 30,000 lb equivalent TNT for the existing J-5 test facility and 20,000 lb, 30,000 lb, and 100,000 lb equivalent TNT for the proposed J-6 test facility.

The estimates provided by this study are very approximate. They are based on a crude survey of the window glass population of Arnold Engineering Development Center, ideal blast load time-histories anticipated for the expected yields of the detonations, assumed strength characteristics for the window glass population, a finite difference dynamic response model of the window glass plates excited by the blast loads, and a dynamic failure prediction model for window glass plates.

II. WINDOW GLASS STRENGTH

The strength of a window glass plate depends upon many factors including, but not restricted to, type and duration of loading, type (tensile or compressive) of load-induced stresses, method of manufacture of the window glass plate, geometry of the plate, and age of the plate. The strength of a window glass plate is controlled by the existence of microscopic cracks and flaws on its surfaces (1, 2, 3, 4, 5, 6, 7). The flaws concentrate tensile stresses in their immediate neighborhoods to high local values (3, 4, 5, 6). If one of these flaws is capable of concentrating tensile stresses above some critical value, fracture of the plate ensues (3, 4). A flaw at which fracture of the window glass plate initiates is termed the "critical" flaw. In destructive tests of window glass plates under uniform lateral load, a single fracture origin at the critical flaw can almost always be located.

Flaws exist on the surfaces of both new and in-service window glass plates (2, 7). In addition, the action of the environment produces new flaws and changes the geometry of existing flaws on the window glass plates undergoing in-service conditions (2). The action of the environment upon in-service window glass plates is termed "weathering." Weathering of window glass plates results in a significant loss of strength of the plates to resist the action of lateral loads (7).

Most of the published strength results for window glass plates were obtained from the destructive testing of new window glass plates (8, 9, 10). The only estimates of weathered or in-service glass strength were

published in conjunction with ongoing research at Texas Tech University (4, 5, 6, 7). The published data tend to indicate a degradation of window glass strength with time beginning at installation and continuing through approximately the first ten years of service. After the first ten years of in-service conditions the strength of the weathered window glass is believed to remain almost constant at about 40 percent of its pristine strength.

III. DYNAMIC FAILURE PREDICTION FOR WINDOW GLASS PLATES

The failure prediction model advanced by Beason (4) for window glass plates relates the probability of failure of a window glass plate to uniform lateral load acting upon the plate. The model is based upon a theory of strength for brittle materials advanced by Weibull (11) which considers the interaction of surface flaws with tensile stresses on the surface of the brittle material. The model characterizes window glass strength in terms of two parameters, m and k , which are termed surface strength parameters. The model accounts for all factors known to affect the strength of a window glass plate: load, load duration, time variation of the load, stress magnitude, state of stress, geometry of the window glass plate, age of the glass plate, temperature, and relative humidity. In this study, temperature and relative humidity are assumed to remain constant during a detonation and are not addressed explicitly.

In the failure prediction model, the probability of failure for a window glass plate under the action of a uniform lateral loading is described by:

$$P_f = 1 - \exp [-B] \quad (1)$$

where B is a risk function. If only one surface of the plate is in tension, the risk function for the window glass plate is:

$$B(t) = k \int_0^b \int_0^a \left[c(x,y) \tilde{\sigma}_{\max}(x,y,t) \right]^m dx dy \quad (2)$$

in which a and b are the rectangular dimensions of the plate, m and k are the surface strength parameters, $c(x,y)$ is a biaxial stress correction factor, and $\tilde{\sigma}_{\max}(x,y,t)$ is the maximum 60-second equivalent principal tensile stress. The surface strength parameters, m and k , describe the distribution and severity of flaws upon the glass plate surfaces. Surface strength parameters cannot be measured directly but may be estimated only through carefully controlled destructive testing of samples consisting of a large number of window glass plate specimens. The 60-second equivalent principal tensile stress is the magnitude of the constant tensile stress which would cause the same amount of damage to a flaw if applied for 60 seconds as the actual time varying stress. Under dynamic loadings tensile stresses can initiate fracture on either surface of the plate; hence Equation 2 must be evaluated over both surfaces of the plate to provide a risk function for the entire plate for use in Equation 1.

Failure of a window glass plate is independent of the actual stress level, but depends upon a combination of stress magnitude, time duration of the stress, and severity of a flaw (4, 5, 12). This combination leads to the following expression for the 60-second maximum equivalent principal stress at a point on the plate surface:

$$\tilde{\sigma}_{\max} = \left[\frac{\int_0^{t_d} \sigma_{\max}^n(t) dt}{60} \right]^{1/n} \quad (3)$$

for constant temperature and relative humidity. In the above expression $\sigma_{\max}(t)$ denotes the time-dependent maximum principal stress at a point on the plate surface, t_d denotes the duration of the loading, and n is the static fatigue constant, usually taken to be 16. The static fatigue

constant, n , is a material constant for ceramics which measures crack growth velocity. As noted in Equation 2, the maximum equivalent principal stress is a function of location on the plate surface and the time-history of the stress at that location. The application of this model depends upon the values of the surface strength parameters, m and k , used to characterize the surface condition of the glass as well as determination of the time-dependent stresses on the plate under the action of a uniform, time-varying loading.

The biaxial stress correction factor $c(x,y)$ accounts for the fact that the flaws on the window glass plate surface have a random orientation with respect to the orientation of the principal stresses. The failure potential of a particular flaw is affected by this orientation. The biaxial stress correction factor is given by:

$$c(x,y) = \left[\frac{2}{\pi} \int_0^\alpha (\cos^2 \theta + N \sin^2 \theta)^m d\theta \right]^{1/m} \quad (4)$$

in which

N = ratio of the minimum to maximum principal stresses

$$\alpha = \begin{cases} \frac{\pi}{2}, & \text{if both principal stresses are tensile} \\ \tan^{-1} \left| \frac{\sigma_{\max}}{\sigma_{\min}} \right|^{1/2}, & \text{if the minimum principal stress is compressive} \end{cases}$$

Table 1 presents selected values of the stress correction factor as a function of m and the ratio of minimum to maximum equivalent principal stresses.

Using appropriate estimates of the surface strength parameters, m and k , the risk function for a window glass plate can be calculated as a function of time in the following manner. For a given blast load

Table 1. Biaxial Stress Correction Factors, $c(x,y)$

N	m											
	4	5	6	7	8	9	10	11	12	13	14	15
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.80	0.91	0.91	0.91	0.92	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.93
0.60	0.84	0.85	0.86	0.86	0.87	0.88	0.89	0.89	0.90	0.90	0.90	0.91
0.40	0.78	0.80	0.82	0.83	0.85	0.86	0.86	0.87	0.88	0.89	0.89	0.90
0.20	0.75	0.78	0.80	0.81	0.83	0.84	0.85	0.86	0.87	0.87	0.88	0.89
0.00	0.72	0.76	0.78	0.80	0.82	0.83	0.84	0.85	0.86	0.87	0.87	0.88
-.20	0.71	0.74	0.77	0.79	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.87
-.40	0.69	0.73	0.76	0.78	0.80	0.81	0.83	0.84	0.85	0.86	0.86	0.87
-.60	0.68	0.72	0.75	0.77	0.79	0.81	0.82	0.83	0.84	0.85	0.86	0.87
-.80	0.67	0.71	0.74	0.77	0.79	0.80	0.82	0.83	0.84	0.85	0.85	0.86
-1.00	0.66	0.70	0.73	0.76	0.78	0.80	0.81	0.82	0.83	0.84	0.85	0.86

time-history the stresses at discrete points on the plate surface and discrete times can be calculated using a finite difference stress analysis technique advanced by Vallabhan and Selvam (13). At each discrete time point, the 60-second equivalent maximum stresses for each discrete point on the window glass plate are calculated for the stress-time histories from the inception of loading by numerical integration of Equation 2.

At each time point, the 60-second equivalent stresses are assumed to act over the small area, ΔA , of the window glass plate around the discrete point on the glass surface. For the discrete area, the risk function becomes:

$$\Delta B(t) = k \left[c(x,y) \bar{\sigma}_{\max}(x,y,t) \right]^m \Delta A \quad (5)$$

Evaluation of the integral represented by Equation 2 is then reduced to the summation of the $\Delta B(t)$ terms over all the discrete points at which stresses are calculated. Substitution of the risk function into Equation 1 gives the probability of failure of the window glass plate as a function of time as:

$$P_f(t) = 1 - \exp [-B(t)] \quad (6)$$

IV. WINDOW GLASS SURVEY

A coarse survey of the window glass population at risk at Arnold Engineering Development Center was performed. The purpose of this survey was to determine the size and approximate number of window glass plates at risk in the event of an accidental explosion occurring at either of the test facilities (J-5 and J-6).

Various sizes of annealed, weathered window glass plates were found. The most common size of window glass plate encountered was 16 x 48 x 0.12 in. The ages of the window glass plates noted in the survey were not available. Window glass plates of other sizes usually were of smaller rectangular dimensions than 16 x 48 in., with the notable exceptions of the insulating glass units in some buildings distant from the existing J-5 and proposed J-6 test facilities and a small number of window glass plates which were thought to be tempered glass used in and near doorways.

Approximately 13,500 windows were counted at Arnold Engineering Development Center. The exact number of the windows was not obtained. The results of the survey are divided into percentages of windows contained at varying distances from the existing J-5 and proposed J-6 test facilities. In addition, the percentages are divided into "percentages of windows facing" and "percentages of windows not facing" the facility. A window was designated as facing the facility if the angle, θ , between the direction of travel of a blast wave originating at the facility and the building surface containing the window lies between 45°

and 135° (Ref. Fig. 1). The estimated percentages are shown in Tables 2 and 3. The estimates are very tentative as the distances and orientations of the buildings with respect to the existing J-5 and proposed J-6 test facilities were estimated from the drawing shown in Figure 2 and a similar drawing.

Table 2. Percentages of Window Glass Plates at Various Distances from the J-5 Test Facility

<u>Distance from Facility R (ft)</u>	<u>Percentage of Windows</u>	<u>Percentage of Windows Facing Facility</u>	<u>Percentage of Windows Not Facing Facility</u>
$R \leq 1200$	7.0	2.0	5.0
$1200 < R \leq 1300$	4.0	1.0	3.0
$1300 < R \leq 1350$	2.5	0.5	2.0
$1350 < R \leq 1400$	1.5	0.5	1.0
$1400 < R \leq 1500$	2.0	1.0	1.0
$1500 < R \leq 1550$	2.0	1.0	1.0
$1550 < R \leq 1700$	8.0	2.0	6.0
$1700 < R \leq 1900$	8.0	2.0	6.0
$1900 < R \leq 2000$	6.0	1.0	5.0
$2000 < R \leq 2200$	16.0	3.0	13.0
$2200 < R \leq 2400$	4.0	1.0	3.0
$2400 < R \leq 2700$	9.0	2.0	7.0
$2700 < R \leq 2900$	1.5	0.5	1.0
$2900 < R \leq 3400$	2.5	0.5	2.0
$3400 < R \leq 4300$	2.5	0.5	2.0
$4300 < R \leq 4900$	20.5	3.5	17.0
$4900 < R \leq 7500$	<u>3.0</u>	<u>0.5</u>	<u>2.5</u>
TOTAL	100.0	22.5	77.5

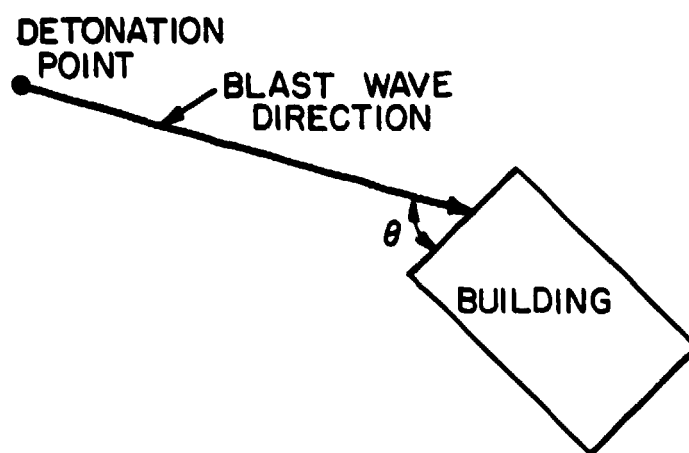


Figure 1. Orientation of Surfaces Containing Windows with Respect to Direction of Blast Wave Travel

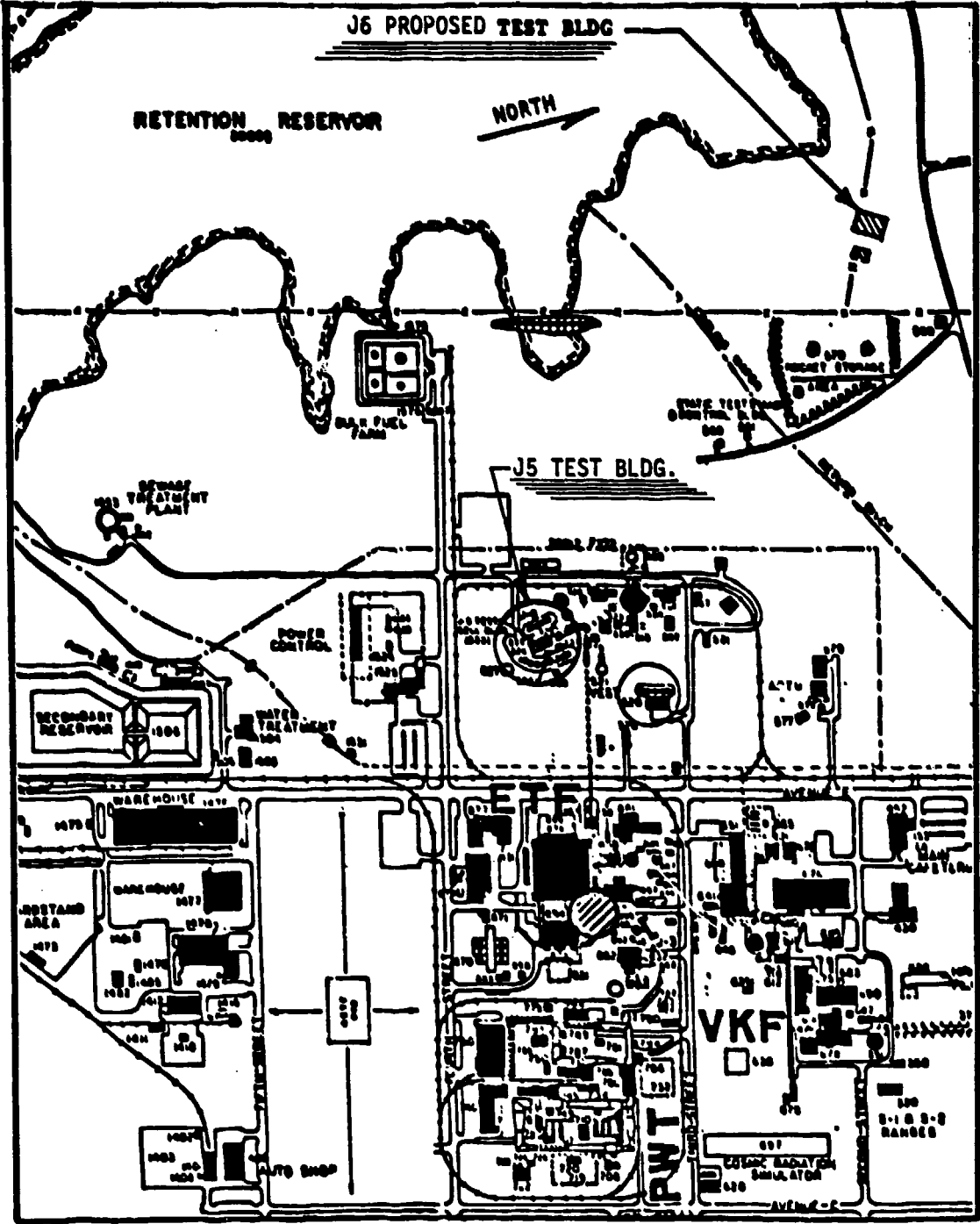


Figure 2. Plan View of Arnold Engineering Development Center

Table 3. Percentages of Window Glass Plates at Various Distances from the Proposed J-6 Test Facility

<u>Distance from Facility R (ft)</u>	<u>Percentage of Windows</u>	<u>Percentage of Windows Facing Facility</u>	<u>Percentage of Windows Not Facing Facility</u>
R < 2900	0	0	0
2900 < R ≤ 3300	16.0	4.0	12.0
3300 < R ≤ 3400	9.5	1.0	8.5
3400 < R ≤ 4000	32.5	7.0	25.5
4000 < R ≤ 4300	4.0	1.0	3.0
4300 < R ≤ 4900	14.0	3.5	10.5
4900 < R ≤ 5000	2.0	0.5	1.5
5000 < R ≤ 7300	<u>22.0</u>	<u>8.0</u>	<u>14.0</u>
TOTAL	100.0	25.0	75.0

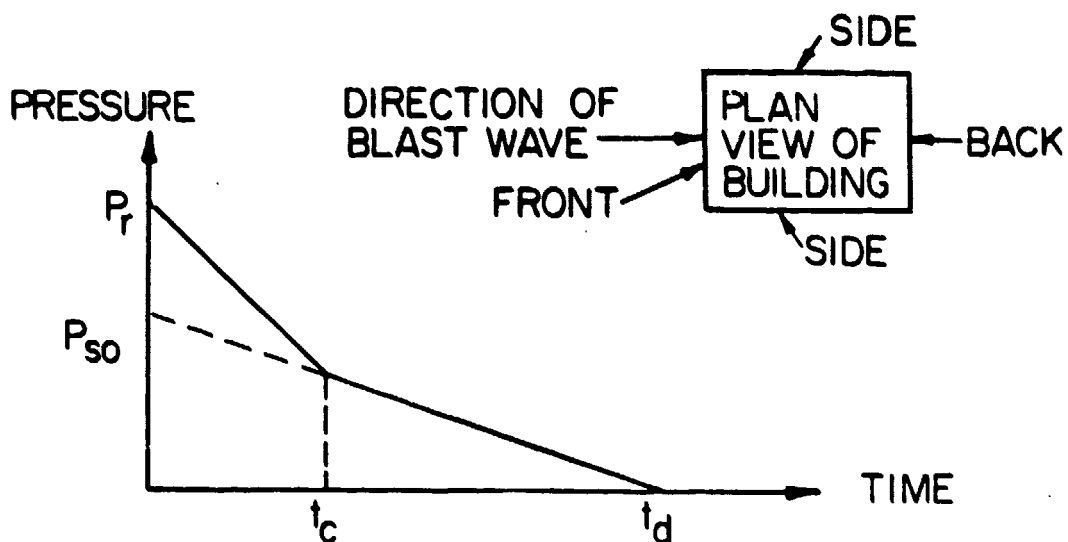
The window glass population at risk at Arnold Engineering Development Center consists of plates of varying ages. No samples were taken to determine strength characteristics of the window glass population. With no definite information pertaining to the surface condition of the window glass population at risk, the correct surface strength parameters which would represent the window glass population at Arnold Engineering Development Center are unknown. In lieu of surface strength parameters which would be representative of the window glass population at risk, the parameters estimated for the Anton sample of weathered glass (7) were used. The Anton sample consisted of 132 glass plates removed from a public school building in Anton, Texas. These plates had been exposed to in-service conditions for approximately 25 years when tested. The surface strength parameters are $m = 5.00$ and $k = 9.67 \times 10^{-22}$.

V. BLAST LOADS AND ESTIMATED PROBABILITIES OF FAILURE

The general shape of the expected blast load time-history is shown in Figure 3. The parameters used in this study for detonations equivalent to 100,000 lb, 30,000 lb, and 20,000 lb TNT are shown in Tables 4, 5, and 6, respectively. The blast load time-histories and the parameters for the various yield explosions were provided by Stephen A. Short of NTS Engineering, Long Beach, California.

Table 4. Blast Load Parameters for a 100,000 lb TNT Detonation

Distance from Detonation R (ft)	Peak Incident Overpressure P_{so} (psi)	Incident Pressure Duration t_d (ms)	Peak Reflected Overpressure P_r (psi)
2900	0.6	230	1.2
3300	0.5	234	1.0
4000	0.4	240	0.8
5000	0.3	253	0.6
7300	0.2	272	0.4
12900	0.1	292	0.2



P_{so} = PEAK INCIDENT OVERPRESSURE

P_r = PEAK REFLECTED OVERPRESSURE

t_d = INCIDENT PRESSURE DURATION

t_c = CLEARING TIME

Figure 3. Ideal Blast Load Time-History

Table 5. Blast Load Parameters for a 30,000 lb TNT Detonation

Distance from Detonation R (ft)	Peak Incident Overpressure P_{so} (psi)	Incident Pressure Duration t_d (ms)	Peak Reflected Overpressure P_r (psi)
1300	1.0	135	2.1
1400	0.9	139	1.8
1550	0.8	143	1.6
1700	0.7	148	1.4
1900	0.6	152	1.2
2200	0.5	156	1.0
2700	0.4	161	0.8
3400	0.3	170	0.6
4900	0.2	182	0.4
8600	0.1	196	0.2

Table 6. Blast Load Parameters for a 20,000 lb TNT Detonation

Distance from Detonation R (ft)	Peak Incident Overpressure P_{so} (psi)	Incident Pressure Duration t_d (ms)	Peak Reflected Overpressure P_r (psi)
1200	0.9	116	1.8
1350	0.8	119	1.6
1500	0.7	122	1.4
1700	0.6	125	1.2
2000	0.5	130	1.0
2400	0.4	140	0.8
2900	0.3	148	0.6
4300	0.2	160	0.4
7500	0.1	171	0.2

Since distances of the buildings from the existing J-5 and proposed J-6 test facilities and orientations of the buildings with respect to the direction of travel for the blast waves could only be roughly estimated from Figure 1, some simplifying assumptions were made concerning the blast wave parameters. If a surface was designated as facing the blast, then P_r , the peak reflected pressure, was used. For surfaces designated as not facing the detonation, the peak incident overpressure, P_{so} , was used. A further assumption made for windows facing the blast was that the clearing time for the blast load, t_c , was 50 ms. This assumption was made since no precise dimensions were available for the buildings. The probability of failure for a window glass plate is much less sensitive to t_c than to P_{so} . If t_c is doubled from the assumed 50 ms used in this study, probabilities of failure will increase by less than 0.02 for each case where P_r is less than 1.0.

The blast load time-histories were used to calculate probabilities of failure as a function of time using the dynamic stress analysis in combination with the dynamic failure prediction model, described above. Figure 4 shows a plot of cumulative probability of failure versus time for a blast load time-history. The following assumptions were employed in calculating probabilities of failure: (1) the plate size used was 16 x 48 x 0.125 in. and (2) the probability of failure of the glass plate at the end of the blast load time-history was taken as the probability of failure for the plate. Since blast load parameters are known only at discrete distances from the J-5 and proposed J-6 test facilities (shown in Tables 4, 5, and 6) probabilities of failure for window glass plates can be determined only at these discrete distances. Figures 5, 6, 7, 8, and 9 show the contours associated with each probability of failure at selected discrete distances.

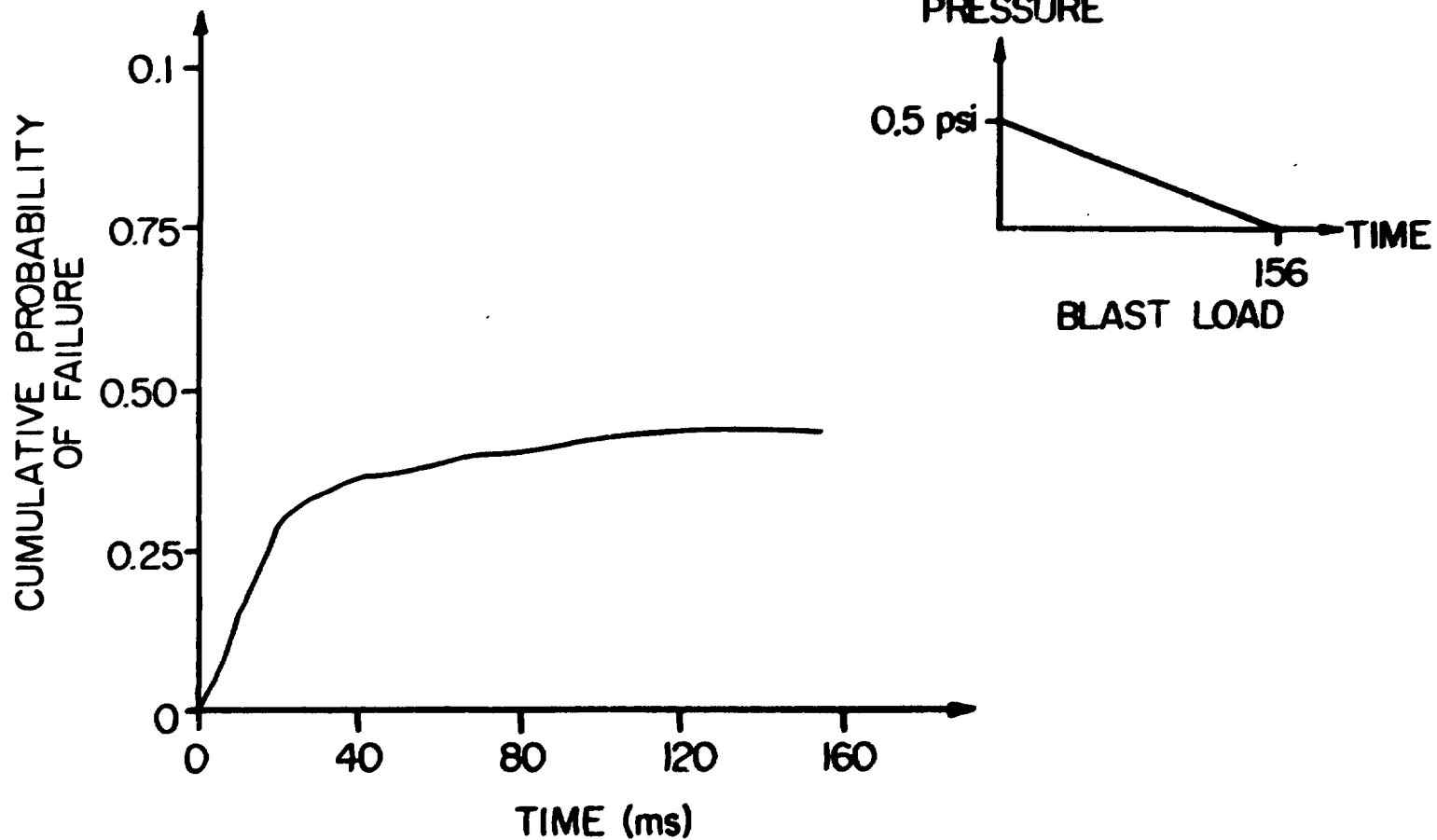


Figure 4. Typical Cumulative Probability of Failure Curve for a 16 x 48 x 0.12 in. Glass Plate

Contour	Range (ft)	P_f for Glass Plate Facing Detonation	P_f for Glass Plate Not Facing Detonation
A	1200	1.0000	1.0000
B	1350	1.0000	0.9996
C	1500	1.0000	0.8923
D	1700	1.0000	0.7077
E	2000	0.9932	0.4164
F	2400	0.9528	0.1868
G	2900	0.6088	0.0551

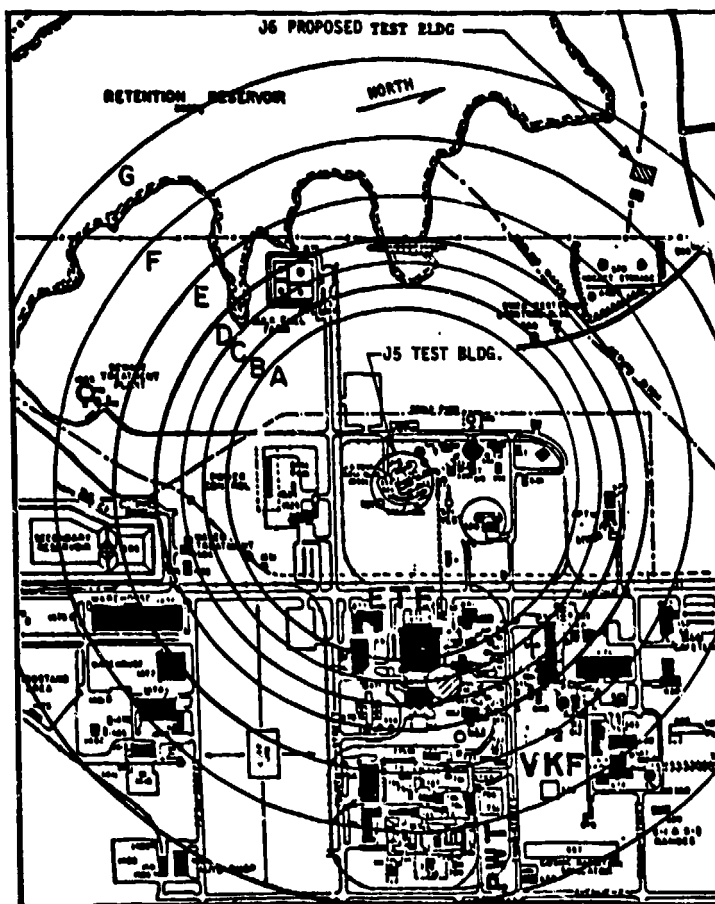


Figure 5. Probability of Glass Failure Contours for a 20,000 lb Equivalent TNT Detonation at the J-5 Test Facility

Contour	Range (ft)	P_f for Glass Plate Facing Detonation	P_f for Glass Plate Not Facing Detonation
A	1300	1.0000	1.0000
B	1400	1.0000	0.9900
C	1550	1.0000	0.9888
D	1700	1.0000	0.9473
E	1900	1.0000	0.7905
F	2200	0.9994	0.5115
G	3400	0.6414	0.0697
H	4900	0.1660	0.0100

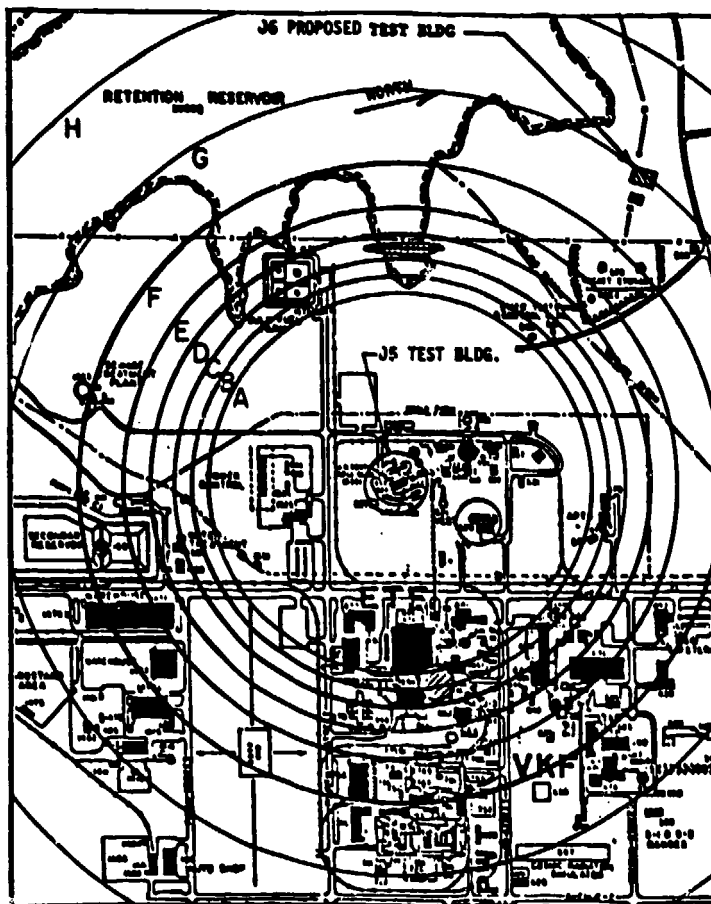


Figure 6. Probability of Glass Failure Contours for a 30,000 lb Equivalent TNT Detonation at the J-5 Test Facility

Contour	Range (ft)	P_f for Glass Plate Facing Detonation	P_f for Glass Plate Not Facing Detonation
E	2000	0.9932	0.4164
F	2400	0.9528	0.1868
G	2900	0.6088	0.0551
H	4300	0.1474	0.0084

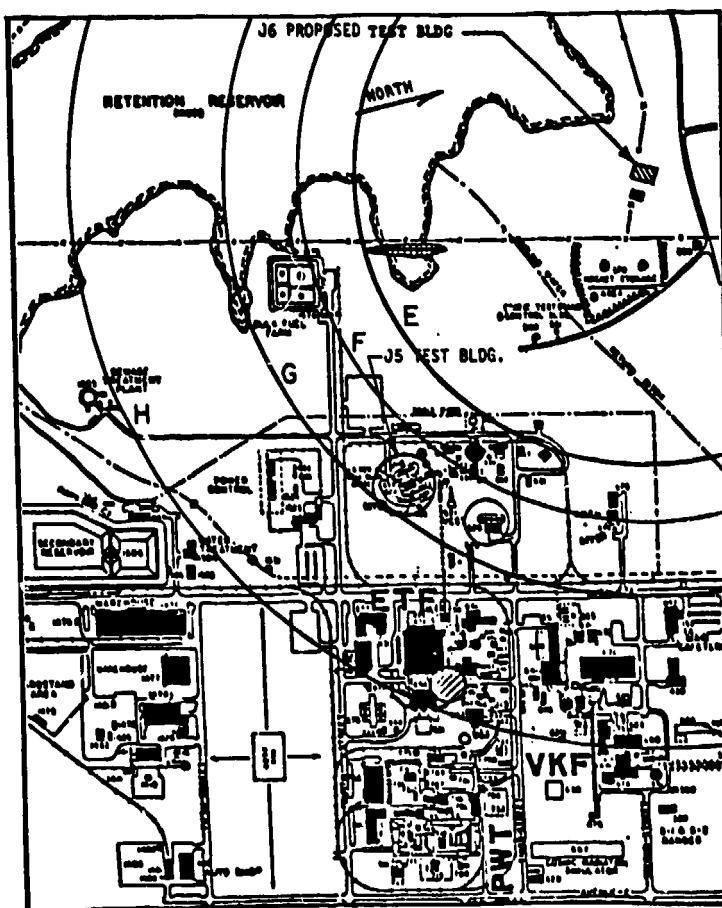


Figure 7. Probability of Glass Failure Contours for a 20,000 lb Equivalent TNT Detonation at the J-6 Test Facility

Contour	Range (ft)	P_f for Glass Plate Facing Detonation	P_f for Glass Plate Not Facing Detonation
E	1900	1.0000	0.7905
F	2200	0.9994	0.5115
G	2700	0.9564	0.2592
H	3400	0.6414	0.0697
I	4900	0.1660	0.0100

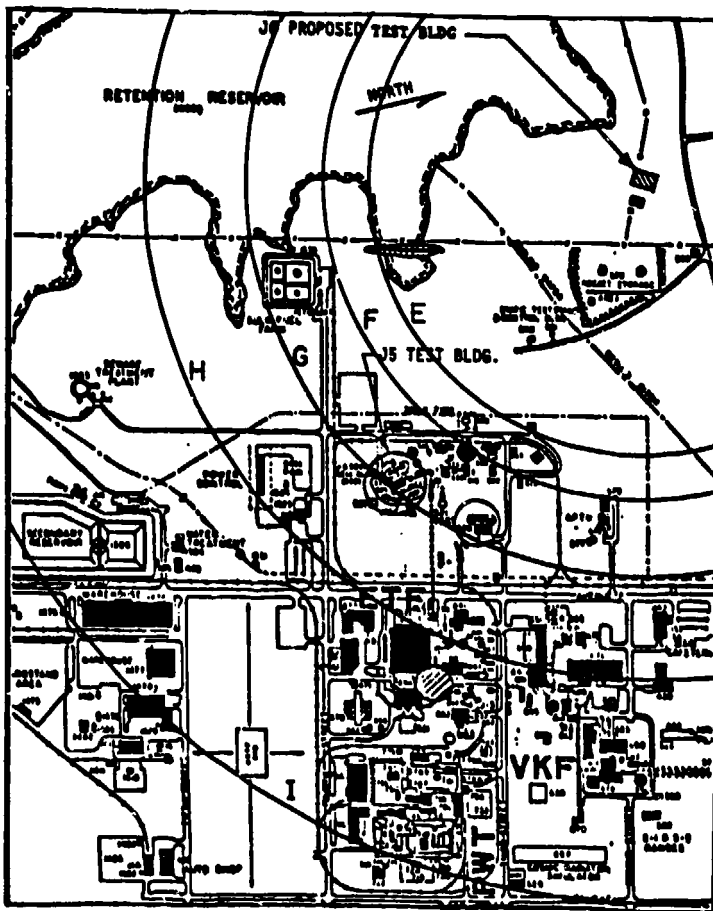


Figure 8. Probability of Glass Failure Contours for a 30,000 lb Equivalent TNT Detonation at the J-6 Test Facility

Contour	Range (ft)	P_f for Glass Plate Facing Detonation	P_f for Glass Plate Not Facing Detonation
A	2900	1.0000	0.7900
B	3300	0.9997	0.5110
C	4000	0.9714	0.2490
D	5000	0.6858	0.0700
-	7300	---	---
-	12900	---	---

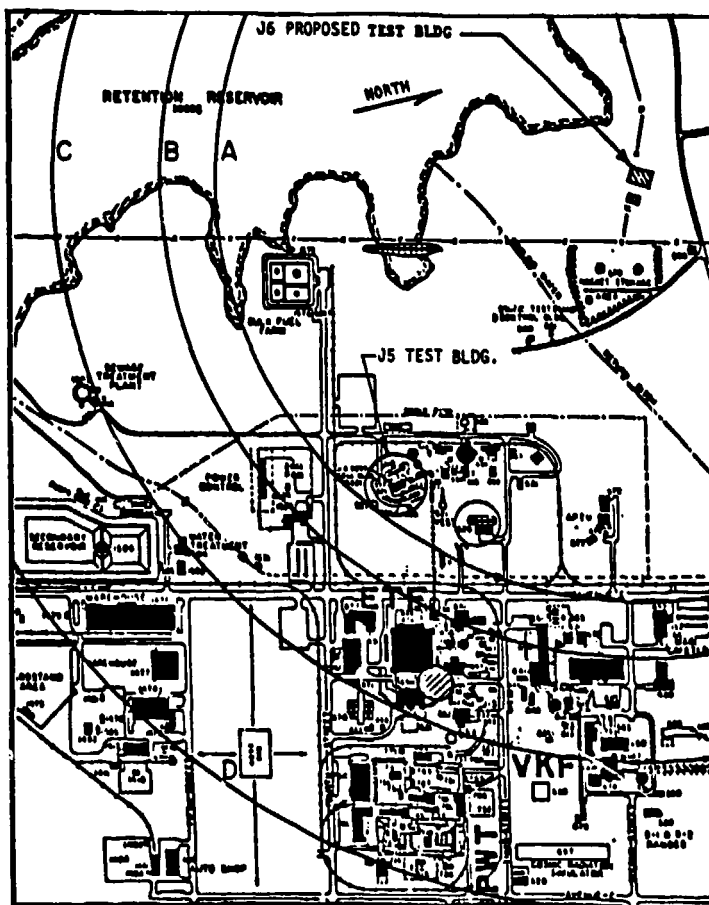


Figure 9. Probability of Glass Failure Contours for a 100,000 lb Equivalent TNT Detonation at the J-6 Test Facility

Finally, the expected percentage of windows which will be broken in the event of a detonation is calculated. For a given detonation, the expected percentage of windows broken can be expressed as the summation of the products of the percentage of windows at each orientation between two contours (Ref. Figs. 5-9) and the appropriate probability of breakage for that percentage of windows between the contours. The expected percentages of windows broken for the five cases considered are shown in Table 7.

Table 7 gives the expected percentages of windows broken as a range of values. The lower bound of the range is obtained by using the probabilities of breakage at the farther contours from the detonation point for each product in the summation. For example, with respect to Figure 5, the percentage of windows at an orientation, either facing or not facing the detonation, contained between contours A and B would be multiplied by the appropriate probability of breakage at contour B in the summation. Similarly, the upper bound is obtained by using the probabilities of breakage at the contours nearer to the detonation point.

**Table 7. Expected Percentages of Window Glass Breakage
in the Event of Accidental Detonations**

<u>Yield and Location</u>	<u>Percentage of Breakage</u>
Equivalent 100,000 lb TNT Detonation at Proposed J-6 Test Facility	32-54
Equivalent 30,000 lb TNT Detonation at Proposed J-6 Test Facility	7-14
Equivalent 20,000 lb TNT Detonation at Proposed J-6 Test Facility	2-13
Equivalent 30,000 lb TNT Detonation at Existing J-5 Test Facility	54-67
Equivalent 20,000 lb TNT Detonation at Existing J-5 Test Facility	42-54

VI. UNCERTAINTIES AND LIMITATIONS

The expected percentages of window glass broken in the event of accidental detonation have been estimated. Due to the relatively high overpressures which would result from an equivalent 100,000 lb TNT detonation at the proposed J-6 test facility, the expected percentage of windows broken for this case is high. The expected breakage could be reduced by placing the J-6 test facility even farther than is now proposed from the other buildings, but this is not a recommendation of this study due to the uncertainties contained within this study. Some of these uncertainties are discussed below.

Foremost among the uncertainties is the strength of the population of window glass plates at risk at Arnold Engineering Development Center. The strength of the population at risk could be much higher than assumed, which would tend to reduce the expected percentages of window glass breakage considerably. Of course, the strength could be lower. An estimate of the strength of the window glass population at Arnold Engineering Development Center should be made before any consideration is given to moving the site of the proposed J-6 test facility.

Another major uncertainty lies in the fact that the blast load time-histories considered in this study do not contain a "negative phase" which would amount to outward acting pressure, similar to suction, on the windows. A negative phase of the blast load time-histories would tend to increase the expected percentage of window glass breakage.

Finally, no consideration is given to the possibility of focusing of the blast waves, resulting from either reflection from adjacent buildings or atmospheric conditions. Focusing could affect significantly the amount of window glass broken in the event of a detonation. Under proper atmospheric conditions, a possibility of breaking windows in neighboring communities exists.

VII. CONCLUSIONS

This study has produced the estimates of probabilities of breakage of window glass which may be expected in the event of accidental detonations of 20,000 lb, 30,000 lb or 100,000 lb equivalent TNT occurring at the proposed J-6 test facility and accidental detonations of 20,000 lb or 30,000 lb equivalent TNT at the J-5 test facility. The ranges of expected breakage are given below.

Expected Percentages of Window Glass Breakage in the Event of Accidental Detonations

<u>Yield and Location</u>	<u>Percentage of Breakage</u>
Equivalent 100,000 lb TNT Detonation at Proposed J-6 Test Facility	32-54
Equivalent 30,000 lb TNT Detonation at Proposed J-6 Test Facility	7-14
Equivalent 20,000 lb TNT Detonation at Proposed J-6 Test Facility	2-13
Equivalent 30,000 lb TNT Detonation at Existing J-5 Test Facility	54-67
Equivalent 20,000 lb TNT Detonation at Existing J-5 Test Facility	42-54

Most noticeable is the fact that the expected window glass breakage in the event of a 100,000 lb equivalent TNT detonation at the proposed J-6 test facility is not significantly higher than expected window glass

breakage from a 20,000 lb equivalent TNT detonation at the existing J-5 test facility. The location of the proposed J-6 test facility presents no greater risk of glass breakage in the event of a detonation than currently exists in the event of a detonation at the existing J-5 test facility. There appears to be no reason to change the location of the proposed J-6 test facility on the basis of expected glass breakage.

Finally, a determination of the strength of the window glass population of Arnold Engineering Development Center based upon a large sample of window glass plates would give a much better estimate of the expected window glass breakage in the event of a detonation. Such a determination would require the careful removal, transportation, and testing of approximately 150 panes of glass. Such an effort would require about one year to complete. While the expected breakages based upon a strength determination of this type would be more precise, the risk of breakage due to a 20,000 lb equivalent TNT detonation at the J-5 test facility should remain about the same or slightly higher than the risk of breakage due to a 100,000 lb equivalent TNT detonation at the proposed J-6 test facility.

REFERENCES

1. Griffith, A. A., 1920: "The Phenomena of Rupture and Flow in Solids," Philosophical Transactions of the Royal Society of London, Vol. CCXXI-A587, October, pp. 163-179.
2. Levengood, W. C., 1959: "Experimental Method for Developing Minute Flaw Patterns in Glass," Journal of Applied Physics, Vol. 30, No. 3, pp. 378-386.
3. Shand, E. B., 1961: "Correlation of Strength of Glass with Fracture Flaws of Measured Size," Journal of the American Ceramic Society, Vol. 44, No. 9, pp. 451-455.
4. Beason, W. L., 1980: "A Failure Prediction Model for Window Glass," Institute for Disaster Research, Texas Tech University, Lubbock, TX (NTIS Accession No. PB81-148421), May.
5. Beason, W. L. and Morgan, J. R., 1984: "Glass Failure Prediction Model," Journal of Structural Engineering, ASCE, Vol. 110, No. 2, pp. 197-212.
6. Norville, H. S. and Minor, J. E., 1985: "The Strength of Weathered Window Glass," Bulletin of the American Ceramic Society, Vol. 64, No. 11, pp. 1467-1470, November.
7. Abiassi, J. J., 1981: "The Strength of Weathered Window Glass Using Surface Characteristics," Institute for Disaster Research, Texas Tech University, Lubbock, TX (NTIS Accession No. PB82-172735), June.
8. Orr, L., 1957: "Engineering Properties of Glass," Windows and Glass in the Exterior of Buildings, Building Research Institute, NAS-NRC, Publication 478, March.
9. Bowles, R. and Sugarman, B., 1962: "The Strength and Deflection Characteristics of Large Rectangular Glass Panels Under Uniform Pressure," Glass Technology, Vol. 3, No. 5, October.
10. Hershey, R. L. and Higgins, T. H., 1973: "Statistical Prediction Model for Glass Breakage from Nominal Sonic Boom Loads," Booz-Allen Applied Research, Inc., Report No. Faa-RD-73-79, Bethesda, Maryland, January.
11. Weibull, W., 1939: A Statistical Theory of the Strength of Materials, Ingeniorsvelenskapsakademiens, Handlingar NR151, Stockholm, Sweden.

12. Brown, W. G., 1974: "A Practicable Formulation for the Strength of Glass and Its Special Application to Large Plates," National Research Council of Canada, Division of Building Research, NRCC 14372, Ottawa, Ontario, Canada, November.
13. Vallabhan, C. V. G. and Selvam, R. P., 1986: "Nonlinear Dynamic Response of Window Glass Plates Using Finite Difference Method," Proceedings, Third Conference on Dynamic Response of Structures, EM Div./ASCE, University of California, March 31-April 2, 1986.

APPENDIX

DISCUSSION OF GLASS BREAKAGE PREDICTIONS FOR ARNOLD ENGINEERING DEVELOPMENT CENTER

A.1 GENERAL

An independent review of the glass breakage prediction report has been conducted by Stephen A. Short of NTS Engineering and Robert C. Murray of Lawrence Livermore National Laboratory. Review comments were presented orally to AEDC personnel. AEDC concluded that some of the review comments provided valuable supplemental information to the report such that it was directed by AEDC that these review comments be formally documented in this appendix. Material covered herein includes: 1) general comments on the conclusions and limitations of the glass breakage predictions; 2) consistency between the predictions and Air Force explosive safety regulations; 3) assessing the reasonableness of the predictions by an alternative simplified approach and; 4) the impact of relocating the J-6 test cell in terms of cost and potential amount of glass breakage.

A.2 CONCLUSIONS AND LIMITATIONS OF GLASS BREAKAGE PREDICTIONS

The glass breakage prediction report provides estimates of expected glass breakage in the event of a motor detonation at either the J-5 or J-6 test facility. From these estimates, it is concluded in the report that the location of the proposed J-6 test facility presents no greater risk of glass breakage in the event of a detonation than currently exists in the event of a detonation at the existing J-5 test facility. This is a significant and valuable conclusion.

A.3 CONSISTENCY OF GLASS BREAKAGE PREDICTIONS AND AFR 127-100 SITING REQUIREMENTS

The J-6 test cell is planned to be located about 2900 feet from the nearest buildings at AEDC. The minimum distance from a potential detonation source equivalent to 100,000 pounds of TNT, as specified in Air Force Regulation, Explosive Safety Standards (AFR 127-100), is about 1900 feet, based on the quantity-distance (Q-D) criteria for inhabited buildings. Even so, it is estimated that between 32 and 54 percent of the windows at AEDC would be broken in the event of a 100,000 pound equivalent TNT motor detonation at the J-6 test cell. It is demonstrated below that the glass breakage predictions are not inconsistent with the Air Force regulations.

According to AFR 127-100, blast may cause the following damage at the inhabited building distance:

- a) Unstrengthened buildings can be expected to sustain damage up to about 5 percent of the replacement cost.
- b) Personnel are provided a high degree of protection from death or serious injury.
- c) Injuries that do occur are caused principally by glass breakage and building debris.

Hence, at the inhabited building distance, some glass breakage would be expected.

Distances of 1900 and 2900 feet from a 100,000 pound TNT detonation correspond to peak side-on overpressures of about 1.0 and 0.6 psi, respectively. Table 5-17 from AFR 127-100 is presented herein as Table A-1. This table describes the expected effects of blast induced overpressure on various structural elements. At overpressures of 1.0 psi and below, the table

indicates that building walls would not be expected to be damaged. However, this table indicates that glass breakage can be expected at overpressure levels as low as 0.5 psi. Hence some glass breakage is expected even at a distance of 2900 feet, which is 1000 feet more distant than the inhabited building distance.

Windows facing the potential detonation are loaded by the peak reflected pressure which, at the pressure levels considered herein, is twice the peak side-on overpressure. Thus, at a distance of 2900 feet from a 100,000 pound TNT detonation, the peak reflected pressure is about 1.2 psi. The peak reflected pressure resulting from a 100,000 pound TNT detonation is above 0.5 psi out to a distance of about 6000 feet. About 25 percent of the total window population faces the J-6 test cell and many of these windows would be expected to be broken in the event of a 100,000 pound detonation. Windows not facing the potential detonation (i.e. on the sides or back of the building relative to the test cell location) are loaded by the peak side-on overpressure without reflection effects. The peak side-on overpressure resulting from a 100,000 pound TNT detonation is above 0.5 psi only out to a distance of about 3300 feet such that many of the windows not facing the test cell which are located between 2900 and 3300 feet from J-6 would also be expected to be broken in the event of a detonation.

Combining the information from Tables 4 and 8 of the main report gives the information presented in Table A-2. This table indicates that if either P_r or P_{so} is 1.0 psi or above, the probability of glass failure is unity. Also, if either P_r or P_{so} is about 0.5 psi, the probability of glass failure is about 0.5. At P_r or P_{so} below 0.5 psi, the probability of failure reduces rapidly from 0.5 to zero. These values for probability of glass breakage as computed in the manner described in this report are very reasonable when compared to information from AFR 127-100 and

repeated in Table A-1 which states that glass breakage can be expected at pressures of 0.5 to 1.0 psi.

The effect of duration is sufficiently small that the expected percentages of window glass breakage would not be very sensitive to the value of assumed clearing time. The data presented in Table A-2 provides an indication of the effect of duration of the pressure loading on the calculated probability of glass failure. The duration of the incident side-on overpressure for a 100,000 pound detonation is on the order of 250 milliseconds as shown in Table 4. The duration of the reflected pressure is the clearing time required to relieve the reflected wave. For the purpose of glass breakage predictions, the clearing time has been assumed to be 50 milliseconds. At the same peak pressure load, the probability of failure for glass not facing the detonation subjected to 250 millisecond loading is a small amount higher than the probability of failure for glass facing the detonation subjected to 50 millisecond loading. For example, at peak pressures of 0.6, 0.4, and 0.2 psi, the probabilities of failure are 0.79, 0.26 and 0.011, respectively, for longer duration load and 0.69, 0.16, and 0.009, respectively, for shorter duration load.

A.4 SIMPLIFIED APPROACH FOR ASSESSMENT OF GLASS BREAKAGE AT AEDC

Potential glass breakage due to a detonation may be assessed from a simplified approach by assuming that all windows subjected to pressure load of 0.5 psi or greater break and all windows subjected to pressure load of less than 0.5 psi survive. These assumptions are consistent with Table A-1 which states that glass breakage can be expected at pressures of 0.5 to 1.0 psi and greater. This simplified approach has been used to estimate glass breakage due to an equivalent 100,000 pound TNT detonation at the J-6 test cell and the results are compared to the glass breakage predictions presented in the main body of this report.

The distribution of windows with distance from the J-6 test cell is presented in Table 3. This data is illustrated in Figure A-1 along with pressure contours of 0.5 psi (both P_r and P_{so}). Figure A-1a indicates that out of the 25 percent of the windows facing J-6, about 21 percent of the windows will be subjected to reflected pressure in excess of 0.5 psi. In addition, Figure A-1b indicates that out of the 75 percent of the windows not facing J-6, about 12 percent will be subjected to side-on pressure in excess of 0.5 psi. Hence, by this simplified approach, it is estimated that about 33 percent of the windows at AEDC would be broken in the event of an equivalent 100,000 pound detonation at the J-6 test facility. This value is between the upper and lower bounds (although close to the lower bound) of the more rigorous glass breakage predictions presented in this report. Thus, this simple analysis supports that the glass breakage predictions presented herein are reasonable.

A.5 IMPACT OF RELOCATING THE J-6 TLST CELL ON AMOUNT OF GLASS BREAKAGE AND COST

The simplified approach described in the previous section can be used to readily evaluate the impact on glass breakage of changing the location of the proposed J-6 test facility relative to existing AEDC facilities. The associated cost impact has also been estimated. According to Carlos Tirres of AEDC, the cost of moving J-6 further out is approximately \$5600 per foot. It is assumed that cost savings of \$5600 per foot can be achieved by moving J-6 closer in to other AEDC facilities. Figures A-2 and A-3 provide similar information to Figure A-1, but for two different assumed locations of the J-6 test cell.

If J-6 is moved 400 feet further away from other AEDC facilities, it may be seen from Figure A-2b that none of the windows not facing the test cell would be broken due to a detonation. From Figure A-2a, it is estimated that about 19 percent of the windows would be broken due to a 100,000 pound TNT detonation due to reflected pressures acting on windows facing the detonation. The result of moving J-6 400 feet further out is that glass breakage is reduced by about 14 percent (from 33 percent as described in Section A.4 to about 19 percent as described above). However, to save 14 percent of the windows results in a cost increase of about 2.2 million dollars. It is obvious that J-6 should not be moved further out for reasons of glass breakage.

If J-6 was moved 1000 feet closer to the other AEDC facilities, the AFR 127-100 separation distance requirements would still be met such that lives would be protected from building failures which might result from a detonation. However, additional glass breakage would be expected to occur. From Figure A-3a, it may be seen that nearly all of the windows facing the detonation would be broken by a 100,000 pound TNT detonation. About 24 percent of the windows at AEDC would be broken due to the reflected pressure. In addition, Figure A-3b indicates that moving J-6 closer by 1000 feet would result in about 49 percent out of the 75 percent of the windows not facing the detonation being broken. Thus, if J-6 was moved closer by 1000 feet, it is estimated that about 73 percent of the windows would be broken in the event of a 100,000 pound TNT detonation. An additional 40 percent of the windows could be broken due to a detonation if J-6 is moved closer (i.e. 73 percent instead of 33 percent as described in Section A.4). On the other hand, AFR 127-100 siting requirements are met and cost savings on order of about 5.6 million dollars are possible if J-6 is moved 1000 feet closer and if simple cost assumptions are accurate.

Table A-1
General Overpressure Effects
 (Table 5-17 from AFR 127-100)

Structural Element	Type of Structural Failure	Overpressure (psi) Side-on
Aircraft	Damage to control surfaces and other minor repair	1.0-2.0
	Major repair	2.0-3.0
Glass Windows, large and small	Shattering, occasional frame failure	0.5-1.0
Corrugated asbestos siding	Shattering	1.0-2.0
Corrugated aluminum or steel paneling	Connection failure followed by buckling	1.0-2.0
Brick wall panel, 8 to 12 inches thick (not reinforced)	Shearing and flexure failure	7.0-8.0
Wood siding panels, standard housing construction	Usual failure at main connections allowing panel to be blown in	1.0-2.0
Concrete or cinderblock wall panel, 8 to 12 inches thick (not reinforced)	Shattering of the wall	2.0-3.0
Steel frame buildings	Sides blown in, distortion	8.6
Steel towers	Blown down	30.0

Table A-2
Probabilities of Failure and Pressure Loads for Glass Plate
(100,000 pound equivalent TNT detonation)

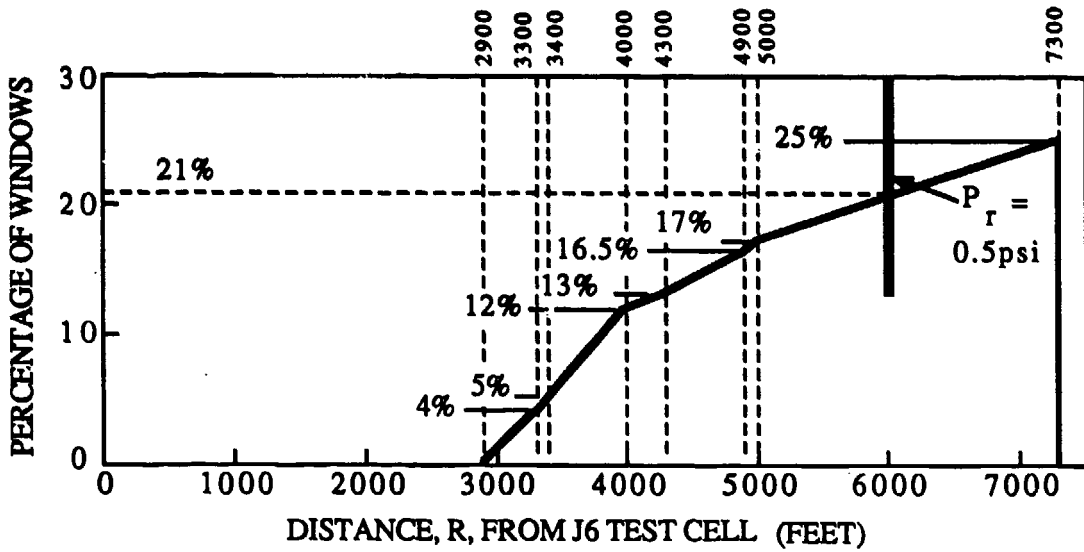
R (feet)	P _r (psi)	P _f for glass facing detonation	P _{so} (psi)	P _f for glass not facing detonation
2900	1.2	1.0	0.6	0.79
3300	1.0	1.0	0.5	0.51
4000	0.8	0.97	0.4	0.26
5000	0.6	0.69	0.3	0.07
7300	0.4	0.16	0.2	0.011
12900	0.2	0.009	0.1	0

R = distance to the detonation

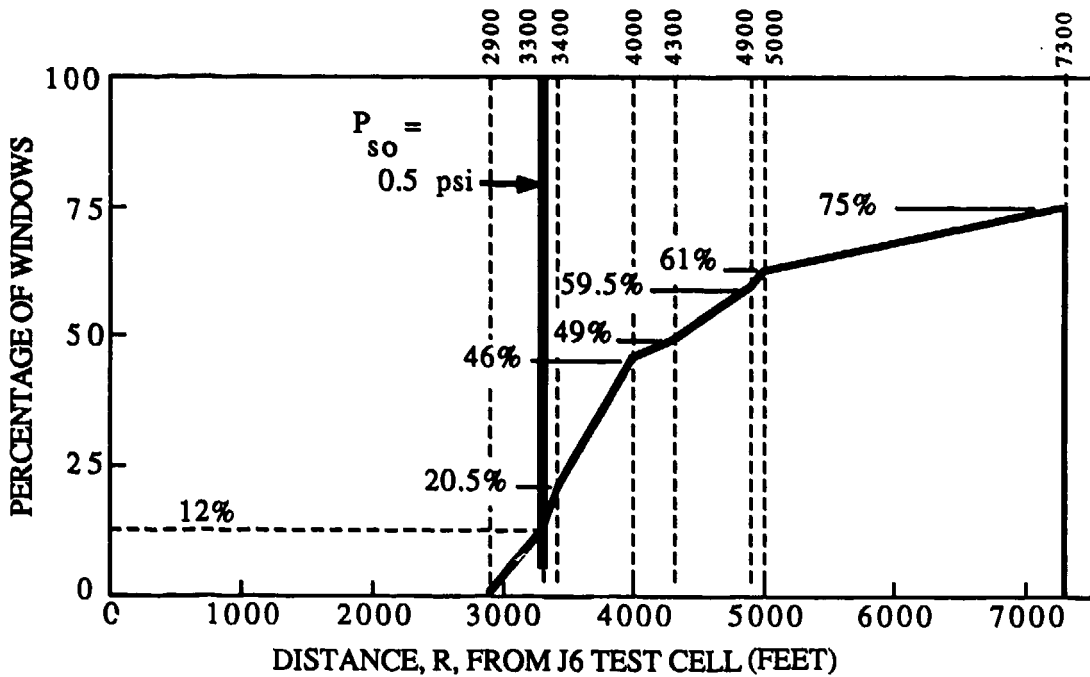
P_f = probability of failure

P_r = peak reflected pressure

P_{so} = peak side-on overpressure

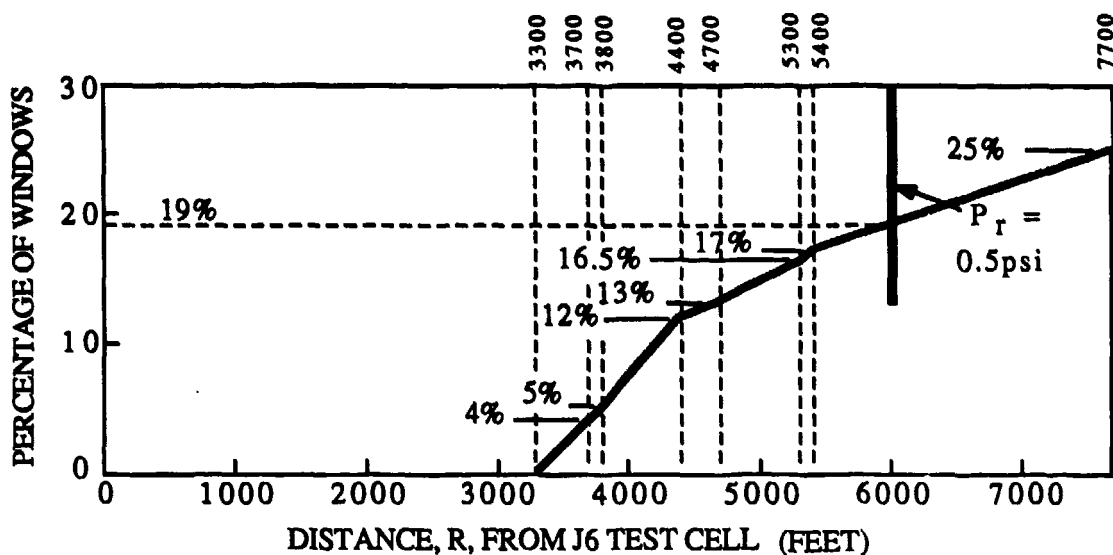


A. PERCENTAGES OF WINDOWS FACING J6 TEST CELL WITHIN DISTANCE, R

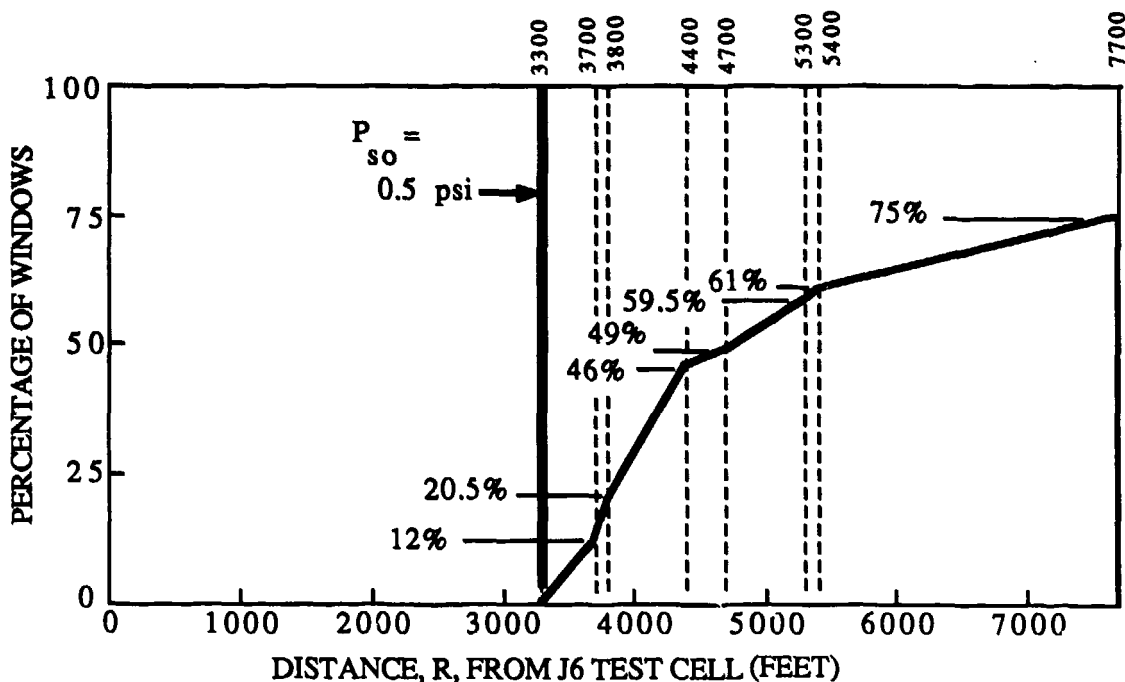


B. PERCENTAGES OF WINDOWS NOT FACING J6 TEST CELL WITHIN DISTANCE, R

FIGURE A-1 WINDOW DISTRIBUTION FROM J6 TEST CELL
(CURRENTLY PLANNED LOCATION OF TEST CELL)

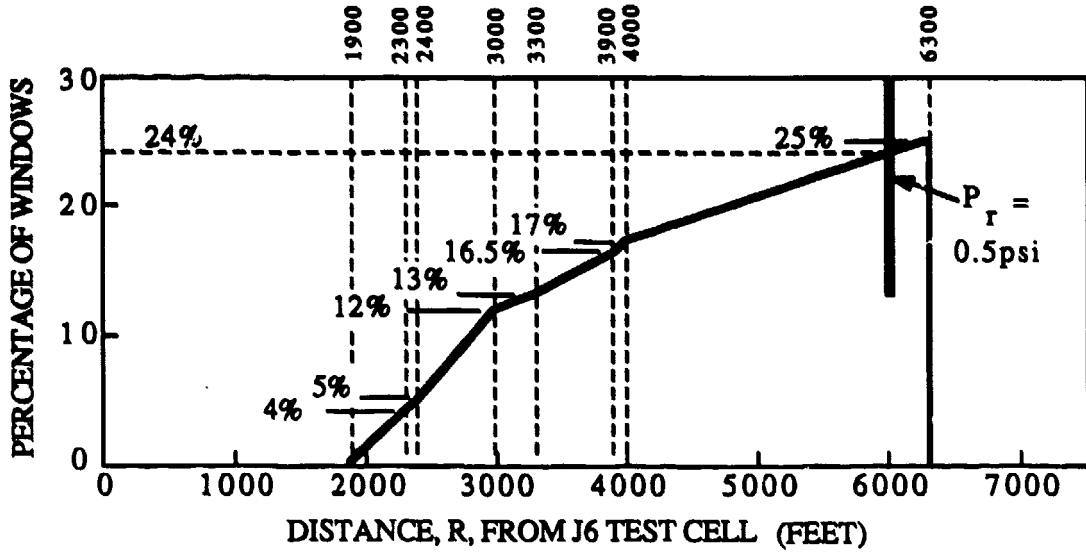


A. PERCENTAGES OF WINDOWS FACING J6 TEST CELL WITHIN DISTANCE, R

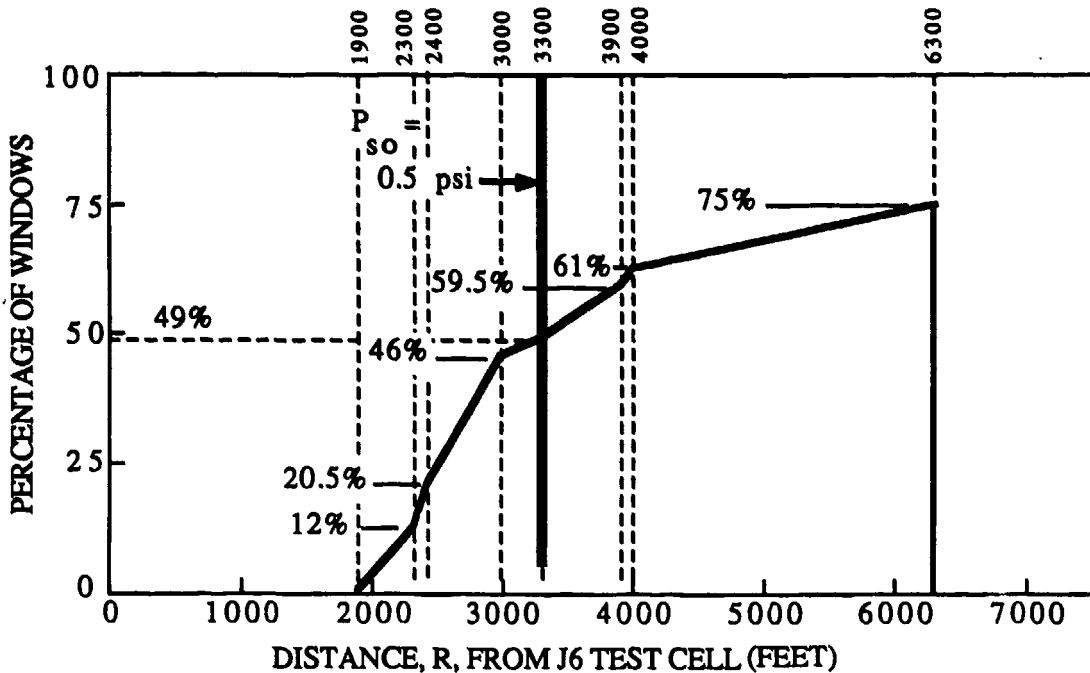


B. PERCENTAGES OF WINDOWS NOT FACING J6 TEST CELL WITHIN DISTANCE, R

FIGURE A-2 WINDOW DISTRIBUTION FROM J6 TEST CELL
(TEST CELL 400 FEET FURTHER OUT THAN CURRENT LOCATION)



A. PERCENTAGES OF WINDOWS FACING J6 TEST CELL WITHIN DISTANCE, R



B. PERCENTAGES OF WINDOWS NOT FACING J6 TEST CELL WITHIN DISTANCE, P.

FIGURE A-3 WINDOW DISTRIBUTION FROM J6 TEST CELL
(TEST CELL 1000 FEET CLOSER THAN CURRENT LOCATION)