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FRAGMENT HAZARD INVESTIGATION PROGRAM: Prediction of Quantity Distance Requirements for Mass-Detonating Ammunition Using a Monte Carlo Simulation Model

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INTRODUCTION

The Department of Defense Explosives Safety Board (DDESB) has funded a continuing study of the quantity distance (QD) requirements for Class 1, Division 1 ammunition (Mass-detonating) at the Naval Surface Weapons Center (NSWC). The main emphasis of the program has been methodology development using pallets of M107 155mm TNT loaded projectiles as a test vehicle. Previous reports have described the methodology developed to predict the far-field fragment hazards resulting from the detonation of stacks of projectiles.[1,2] The initial deterministic methodology was based on the fitting of empirical relations to single pallet fragmentation data (weight-number and presented area distributions). Large-scale multiple pallet detonation tests conducted at the White Sands Missile Range (WSMR) and subsequent analysis showed that the far-field fragment density was directly proportional to the number of interaction areas (N_{ia}, spaces between projectiles in the face of the stack directed toward the fragment recovery zone). The empirical relations accurately predicted the total number of fragments recovered in the large-scale multiple pallet tests. However, prediction of the proportion of recovered fragments which would be considered hazardous (KE=>58 ft-lbf) was found to be unacceptably cumbersome. Consequently, it was decided to begin the development of a stochastic model to replace the original deterministic model. This report presents the results of the test and analysis effort pursued to validate the stochastic model. The details of the model development are presented elsewhere.[3]

BACKGROUND

The deterministic methodology assumed that all fragments were ejected from the stack at optimum ejection angles (5 to 45 degrees) and that the kinetic energy of far-field fragments could be related to the calculation of terminal velocity in free-fall. Comparison of small-scale fragmentation characterization test data and the large-scale multiple pallet detonation test data from the WSMR indicated that a great number of fragments collected in the far-field were being ejected at other than optimum angles. These non-optimum ejection angle fragments possessed greater kinetic energy than the optimum ejection angle fragments and thus violated one of the basic assumptions used to develop the deterministic methodology. It was recognized that the event being simulated was actually a random event and that these problems could be reduced using a fragment trajectory program modified to incorporate Monte Carlo simulation techniques. The development of this new approach (the stochastic model) encompassed approximately two years. The new model allows for the random behavior of the following parameters:

a. initial fragment velocity

b. fragment ejection angle

c. fragment drag coefficient

d. origin of fragments within the stack as a function of height

e. soil conditions for fragment ricochet

Input data for the model is the standard data (fragment mass, initial fragment velocity, recovery zone and fragment presented area) obtained from fragmentation characterization tests.[4] The user can specify the number of interaction areas in the stack (N_{ia}), the kinetic energy criterion and the hazardous fragment density criterion. The fragment trajectory calculation is a three-dimensional particle model that allows for a two-dimensional wind. Fragment ricochet effects are also included. Hit probability computations for striking a three-dimensional target (man, vehicle, building, etc.) are also incorporated in the model.

APPROACH

The Monte Carlo simulation model was validated by comparing the far-field fragment collection data from 155mm multiple pallet detonation tests and MK82 bomb single pallet detonation tests conducted at the WSMR to the far-field fragment densities predicted by the model. A series of small-scale fragmentation arenas was conducted to provide the input data for the model. The validated model was used to generate QD curves for stacks of 155mm projectiles and MK82 bomb pallets.

TEST AND ANALYSIS PROGRAM

155mm Projectile Pallets

Fragmentation Characterization

Two tests were conducted to determine the fragmentation characteristics of a two-pallet stack of 155mm projectiles configured identically to the detonation source used for the 36 pallet test at the WSMR (ie., two pallets positioned horizontally with the nose of one pallet beneath the bottom of the other pallet). Figure 1 presents the fragment velocity distribution measured as a function of polar zone. The maximum velocity for the fragments was recorded in the 50 and 60 degree zone. The velocity distribution was comparable to the distribution recorded for the single pallet characterization test.[2] All collected fragments weighing greater than 300 grains had their presented areas measured. The 300 grain limit was chosen because it was determined by analysis that no fragment weighing less than 300 grains would be hazardous in the far-field.

Model Validation

The arena fragmentation characterization data was used as input to the Monte Carlo model to determine the number of replications necessary to obtain stable far-field fragment density results and to determine if the random number seed chosen had a significant effect on the predicted far-field density. Figures 2 and 3 provide the results of varying the number of replications and the random number seed. Stable fragment densities were obtained using a minimum of 30 replications. The predictions varied approximately 5% using a variety of random number seeds. The subsequent validation runs were made using 30 replications.

In order to compare the results of the Monte Carlo model with the large scale multiple pallet tests, the actual test data must be considered as a single replication of the random event simulated by the model. Consequently, simply comparing the average predicted far-field density to the actual test data would not conclusively demonstrate the accuracy or inaccuracy of the model. The model was designed to maintain a record of the minimum and maximum number of fragments as a function of range for each replication. Figure 4 presents a comparison of the far-field fragment collection data for the WSMR 36 pallet detonation test[2] with the minimum and maximum number of fragments predicted by the Monte Carlo model for an identical stack. It can be seen that the minimum and maximum predictions neatly bracket the actual recovery data. This indicates that the model accurately predicts the far-field fragment density resulting from the detonation of stacks of 155mm projectiles.

MK82 Bomb Pallet

Fragmentation Characterization

It became apparent during the development of the model that it would be beneficial to validate the model for another weapon in order to demonstrate the general utitlity of the model. A series of fragmentation characterization tests and far-field fragment recovery tests were conducted at the NSWC and the WSMR using single pallets of bombs as a cooperative effort with the Naval Explosive Safety Improvement Program (NESIP). A series of large-scale single pallet detonations with far-field fragment pickup were conducted at the WSMR and a fragmentation characterization arena was conducted at the NSWC. The far-field collection tests were conducted with the pallet positioned horizontally. The center bomb in the bottom row was detonated. Fragments were collected in 36 ten degree wide collection zones 360 degrees around the pallet to a distance of 2700 feet. Six individual pallets were detonated and then the fragments were collected. The fragmentation characterization arena was conducted with the pallet positioned vertically. The center bomb in the row away from the celotex or steel plates was detonated. Figure 5 presents the fragment velocity distribution measured for the pallet of bombs as a function of polar zone. The maximum velocity (10900 ft/sec) was recorded between 20 and 40 and 60 and 80 degrees . The detailed fragmentation data and collection data are available.[5]

Model Validation

Figure 6 shows a comparison of the far-field collection data and the predictions of the Monte Carlo model for a single pallet of bombs. The model predicitions generally bracket the actual test data. This indicates that the model can be used to predict the far-field fragment hazard for mass-detonating ammunition.

Quantity Distance (QD) Requirements

155mm Projectiles

The test and analysis program conclusively demonstrated that the far-field fragment density is directly proportional to N_{ia} in the stack. For large stacks N_{ia} is approximately equal to the number of projectiles in the face of the stack. Figure 7 presents a comparison of the Monte Carlo predictions for the number of projectiles in the face of the stack (N_p) and the corresponding blast criterion ($40W^{1/3}$) for a stack of the same size. It can be seen that the blast criterion apparently underestimates the hazard. However, it must be realized that the DDESB has established a minimum QD distance of 1250 feet for stacks containing less than 30000 lbs of explosive. Furthermore, the model indicates that for ranges greater than 2500 feet the fragment hazard is zero (N_p=infinity). This range corresponds to stacks containing 245000 lbs of explosive based on the blast criterion.

The Monte Cario model was designed to be able to calcualate the QD requirements using different hazard criteria. The results of this analysis is presented in Figures 8 thru 11 and are discussed below:

a. Reducing the kinetic energy criterion from 58 to 10 ft-lbf increases the QD distance by approximately 200 feet (Figure 8).

b. Reducing the hazardous density criterion from 1/600 sq ft to 1/6000 sq ft increases the QD distance by approximately 600 feet (Figure 9).

c. Using the probability of hitting a standing man rather than the fragment density requirement does not significantly affect the QD criteria (Figure 10).

d. Reducing the probability of hitting a man from .01 to .001 increases the QD distance by 600 feet (Figure 11).

Figure 12 compares the effect of tail wind on the QD curve for 155mm projectiles. It can be seen that a 90 ft/sec tail wind increases the QD requirement by approximately 900 ft.

MK 82 Bomb Pallet

Figure 13 presents the QD curve for MK82 bombs generated using both the existing DDESB density criterion and a probability of hitting a standing man of 0.01. The curves asymptotically approach 3500 feet for stacks with more than 200 bombs in the face. The curves indicate that the current blast criterion will underestimate the fragment hazard for stacks containing less that 670000 lbs of explosive. Furthermore, the current hazard criteria (KE_{haz}=58 ft-lbf, Density =1/600 ft^2) accepts a greater risk than does the .01 probability of hit criterion.

Figure 14 presents the effect of a 90 ft/sec tail wind on the QD curve. The tail wind will increases the distance required from 3500 ft to 4500 ft.

CONCLUSIONS

The Monte Carlo model has been shown to be an effective and accurate tool in predicting both the near and far-field areal fragment density resulting from the accidental detonation of stacks of Class 1, Division 1 (Mass-Detonating) ammunition. The model allows the user to easily assess the effect on the far-field fragment hazard of changes made to the hazard criteria (i.e, density or kinetic energy). Furthermore, the model eliminates the necessity of large-scale, multiple pallet tests with far-field pickup. Properly designed small-scale fragmentation characterization arenas can be used to gather the necessary data.

The model has shown that the fragment hazard resulting from the detonation of Class 1, Division 1 ammunition exceeds the existing blast criterion (minimum 1250 feet) for relatively small stacks (less than 30,000 lbs of explosive). The fragment hazard asymptotically approaches a maximum (approximately 2500 feet for 155mm projectiles and 3500 feet for MK82 bombs) as the stack size grows larger. The blast criterion exceeds this distance for stacks containing more than 245,000 lbs of explosive for 155mm projectiles and 670,000 lbs for MK82 bombs. The fragment hazard for smaller stacks can be reduced by judicious stacking of the pallets to reduce the number of units in the face of the stack.

RECOMMENDATIONS

The explosive hazard classification procedures used by the DDESB[6] should be modified to incorporate the test and analysis procedures developed by this program.

The instructions used by ammunition depots to stack ammunition in magazines should be reviewed and modified to reduce the number of units in the face of the stack to a minimum. Circular stacking of pallets should be studied as a means to minimize fragment hazards.

It is recommended that small-scale fragmentation characterization of additional Class 1, Division 1 ammunition be conducted and the Monte Carlo model used to generate new QD curves.

The Monte Carlo model should be used to generate QD curves for other classes of ammunition such as Class 1, Division 2 (Non-mass detonating). Minor modification of the model will be required.

The effect of magazine structures on the fragmentation characteristics of the ammunition studied should be determined. Small-scale fragmentation arenas should be used to develop the data required by the model.

REFERENCES

1. Ramsey, R. T., et al, *Fragment Hazard Investigation Program*, NSWC TR-3664, October 19[illegible]8

2. Powell, J. G., et al, *Fragment Hazard Investigation Program: Natural Communication Detonation of 155mm Projectiles*, NSWC TR 81-54, July 1981

3. McCleskey, F., *Fragmentation Hazard Computer Model*, Minutes of the 21st DDESB Seminar, 1984

4. Ammerman, D. J., *Fragmentation Test Proc[illegible] Used at NSWC*, NSWC MP 81-16, June 1981

5. Smith, W. D., *Fragment Hazard Investigation Program: Validation of the Monte Carlo Simulation Model*, NSWC TR 86-187, Unpublished

6. Department of Defense Explosives Hazard Classification Procedure, Army TB700-2, Navy NAVSEAINST 8020.8, Air Force TO 11A-1-47, Defense Logistics Agency DLAR 8220.1, September 1982.

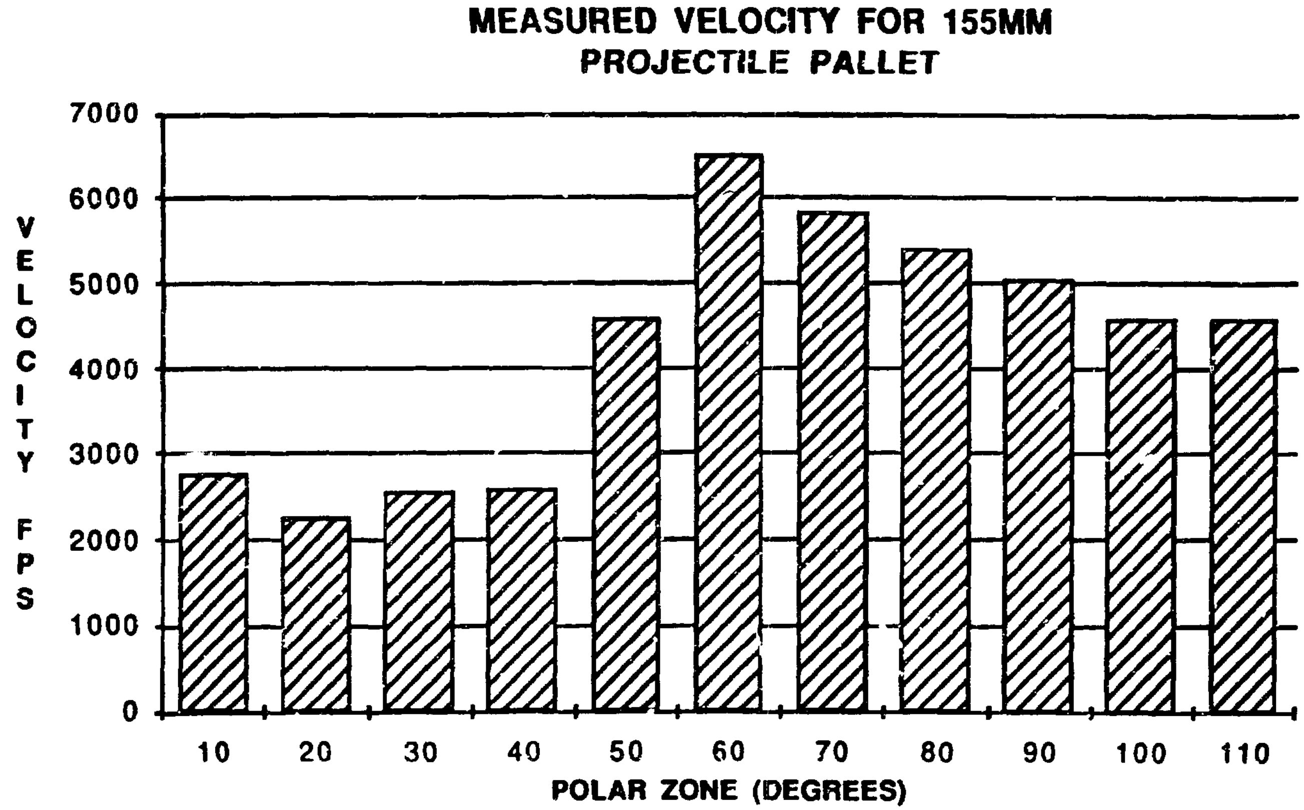

MEASURED VELOCITY FOR 155MM
PROJECTILE PALLET
VELOCITY FPS
7000
6000
5000
4000
3000
2000
1000
0
10
20
30
40
50
60
70
80
90
100
110
POLAR ZONE (DEGREES)

FIGURE 1

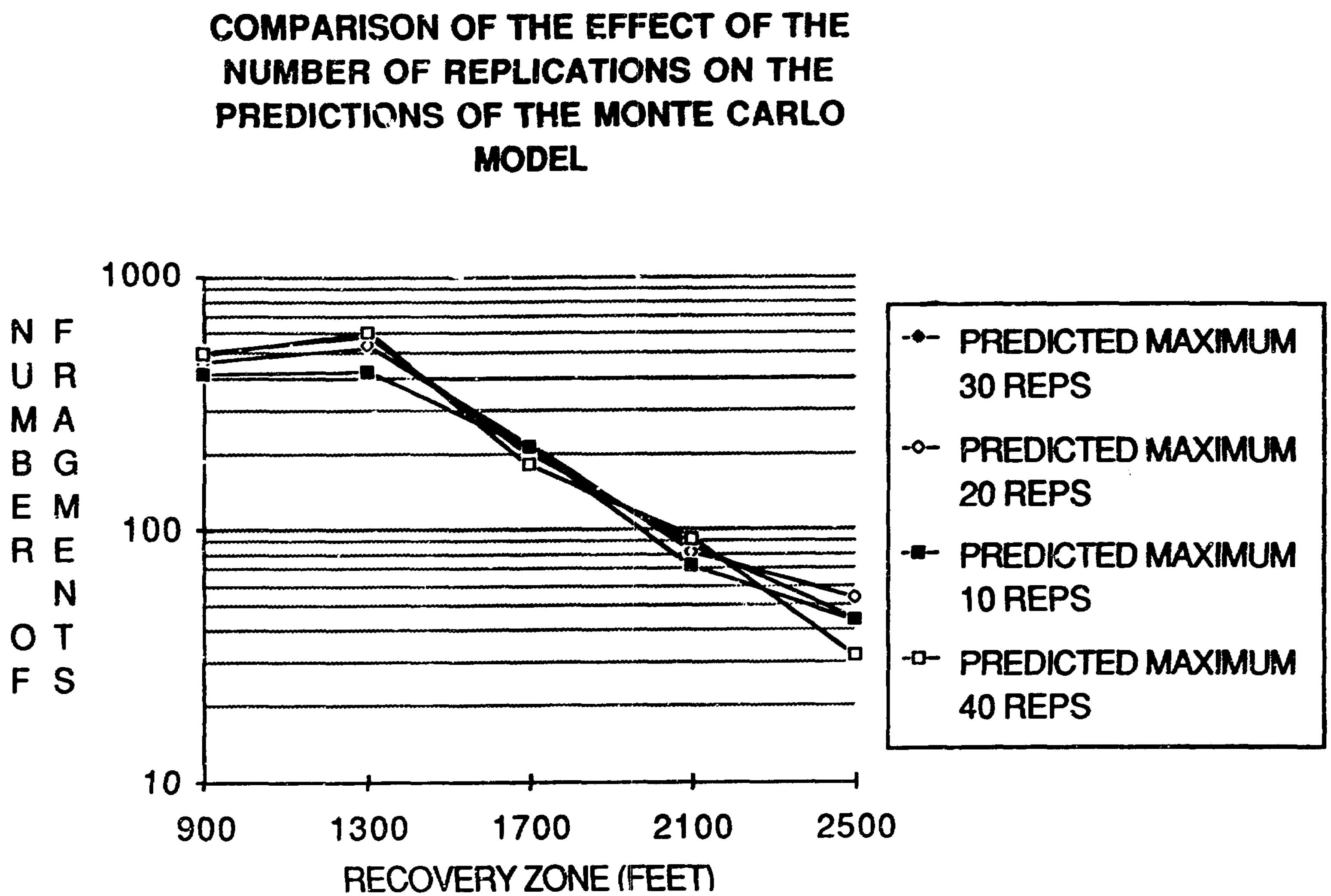

COMPARISON OF THE EFFECT OF THE NUMBER OF REPLICATIONS ON THE PREDICTIONS OF THE MONTE CARLO MODEL
NUMBER OF FRAGMENTS
1000
100
10
900
1300
1700
2100
2500
RECOVERY ZONE (FEET)
PREDICTED MAXIMUM 30 REPS
PREDICTED MAXIMUM 20 REPS
PREDICTED MAXIMUM 10 REPS
PREDICTED MAXIMUM 40 REPS

FIGURE 2

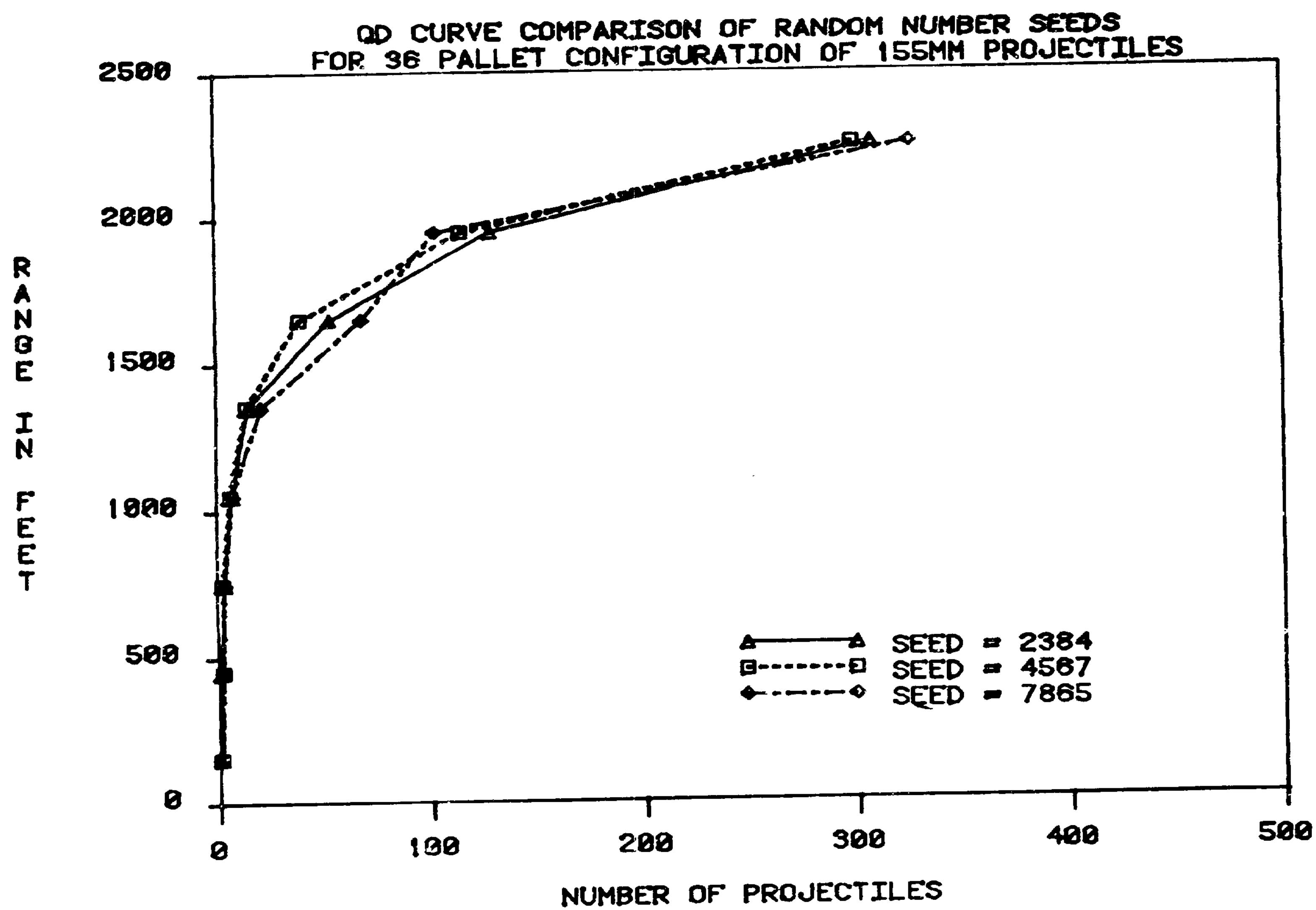

QD CURVE COMPARISON OF RANDOM NUMBER SEEDS
FOR 36 PALLET CONFIGURATION OF 155MM PROJECTILES
2500
2000
1500
1000
500
0
RANGE IN FEET
0
100
200
300
400
500
NUMBER OF PROJECTILES
SEED = 2384
SEED = 4567
SEED = 7865

FIGURE 3

PREDICTED VERSUS ACTUAL RECOVERY DATA FOR 36 PALLETS OF 155MM PROJECTILES

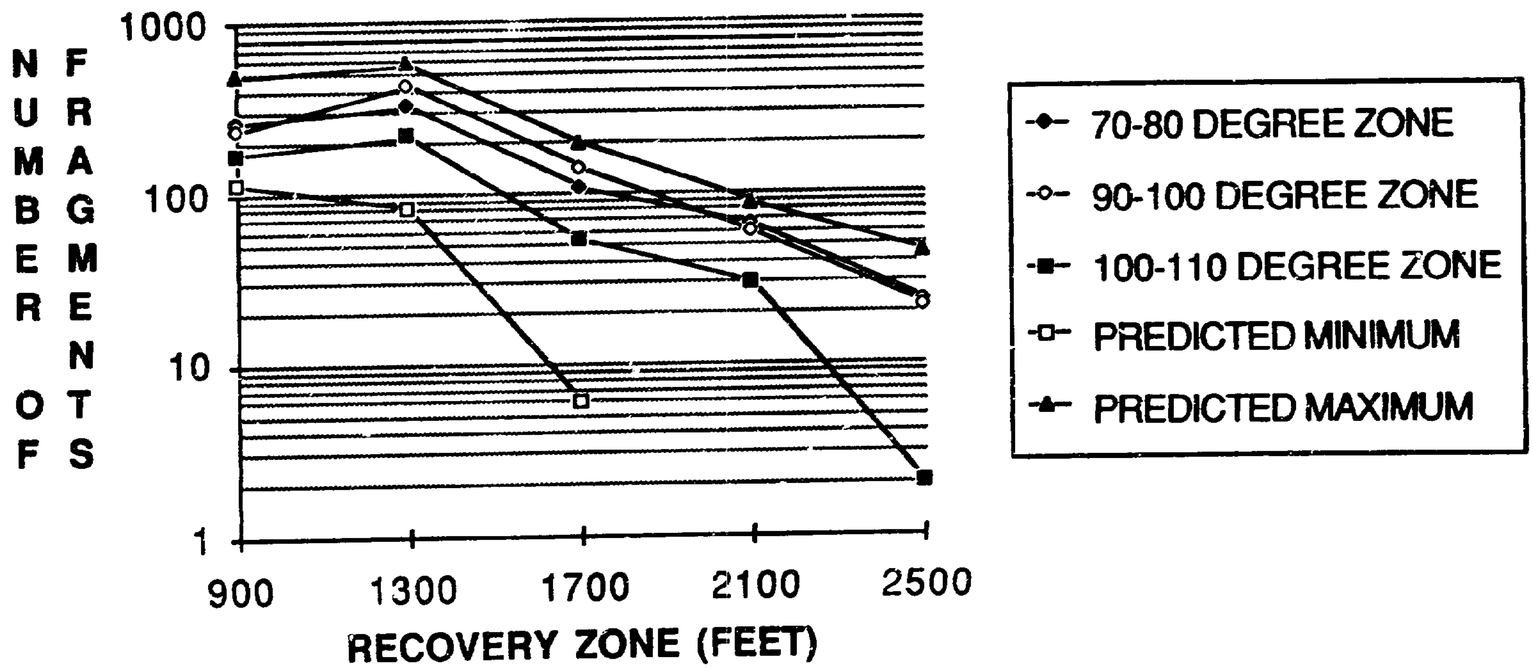


FIGURE 4

MEASURED VELOCITY FOR MK82 BOMB PALLET

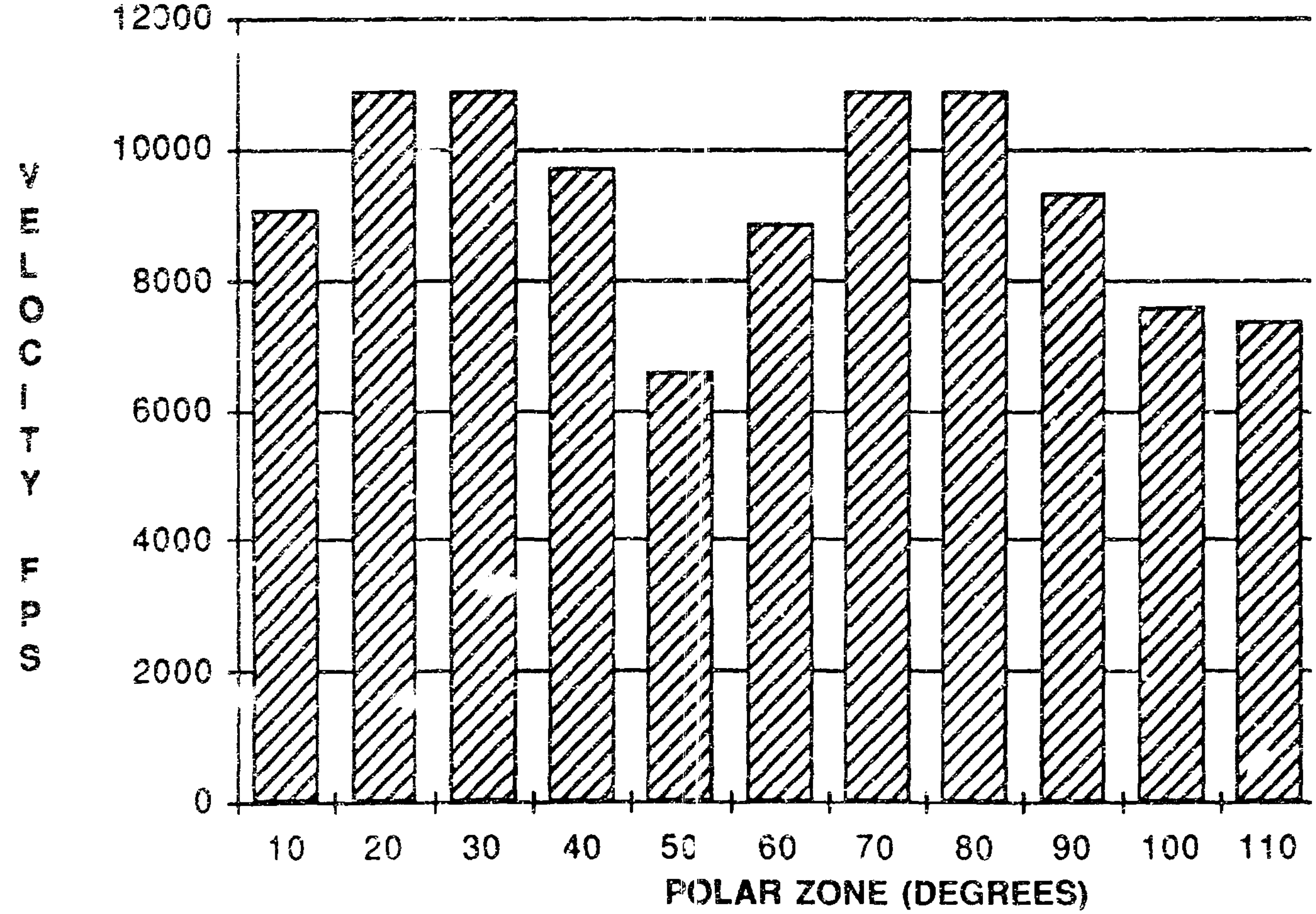


FIGURE 5

PREDICTED VERSUS ACTUAL RECOVERY DATA FCR MK82 BOMB PALLET

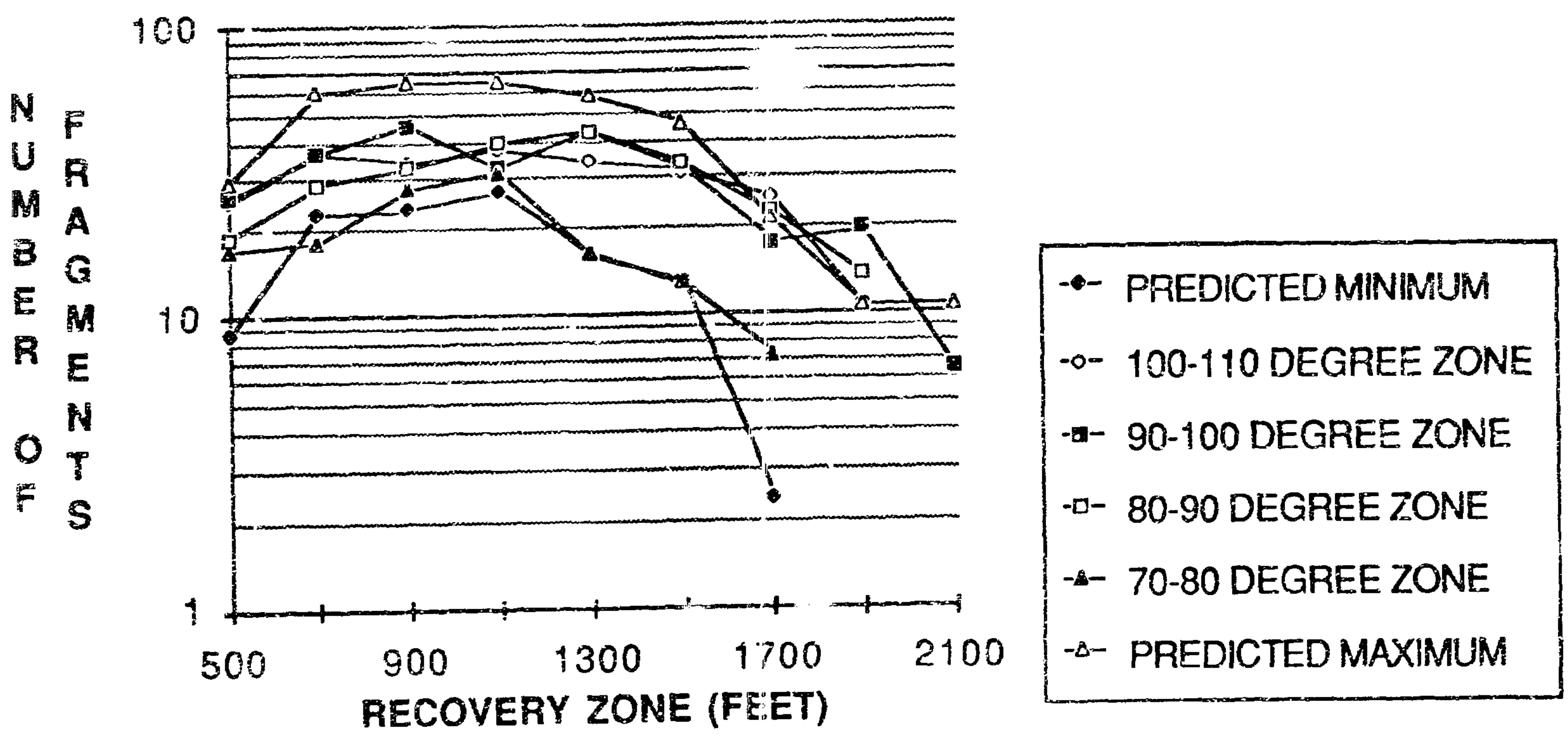
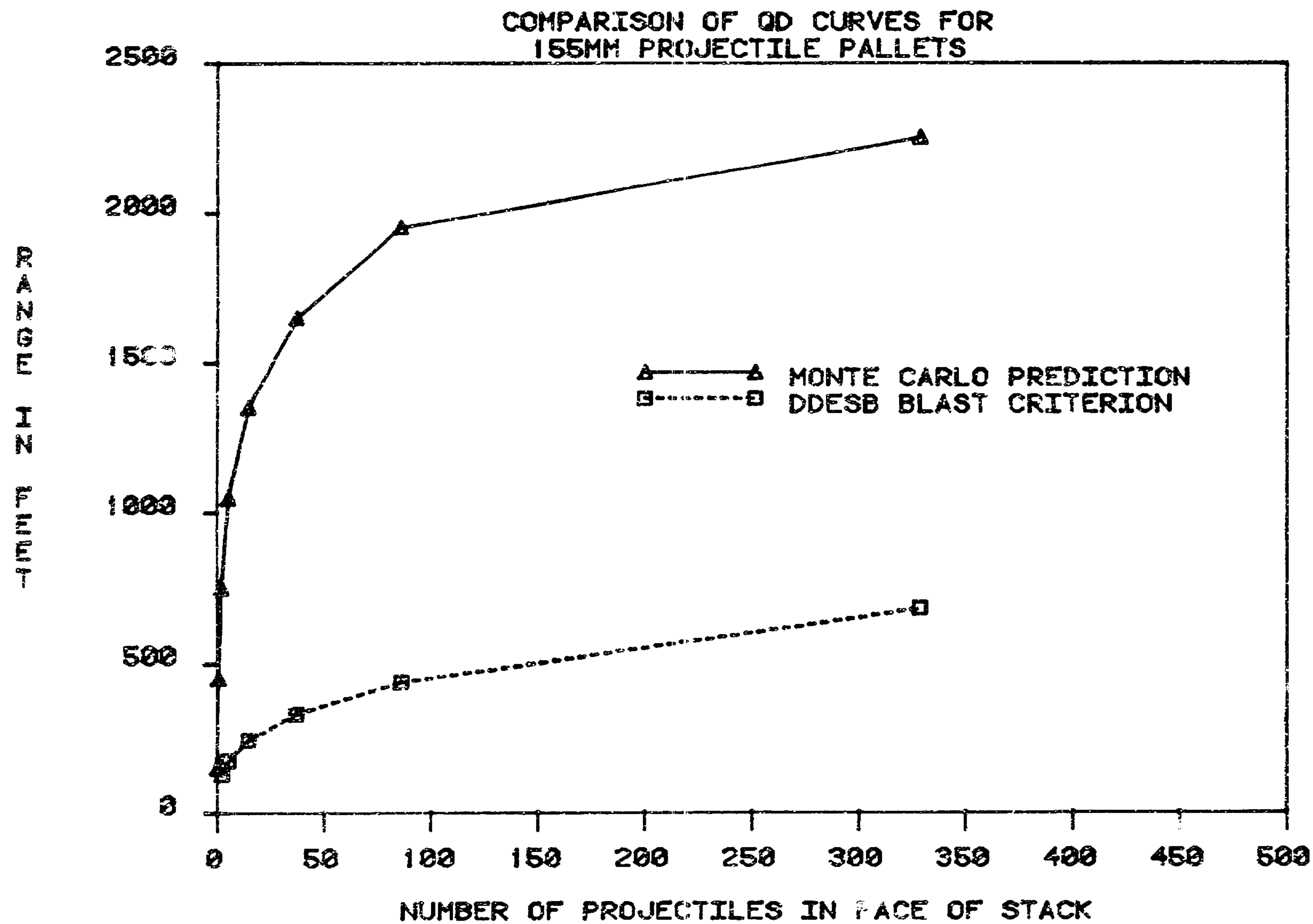


FIGURE 6



COMPARISON OF QD CURVES FOR
155MM PROJECTILE PALLETS
MONTE CARLO PREDICTION
DDESB BLAST CRITERION
RANGE IN FEET
2500
2000
1500
1000
500
0
0
50
100
150
200
250
300
350
400
450
500
NUMBER OF PROJECTILES IN FACE OF STACK

FIGURE 7

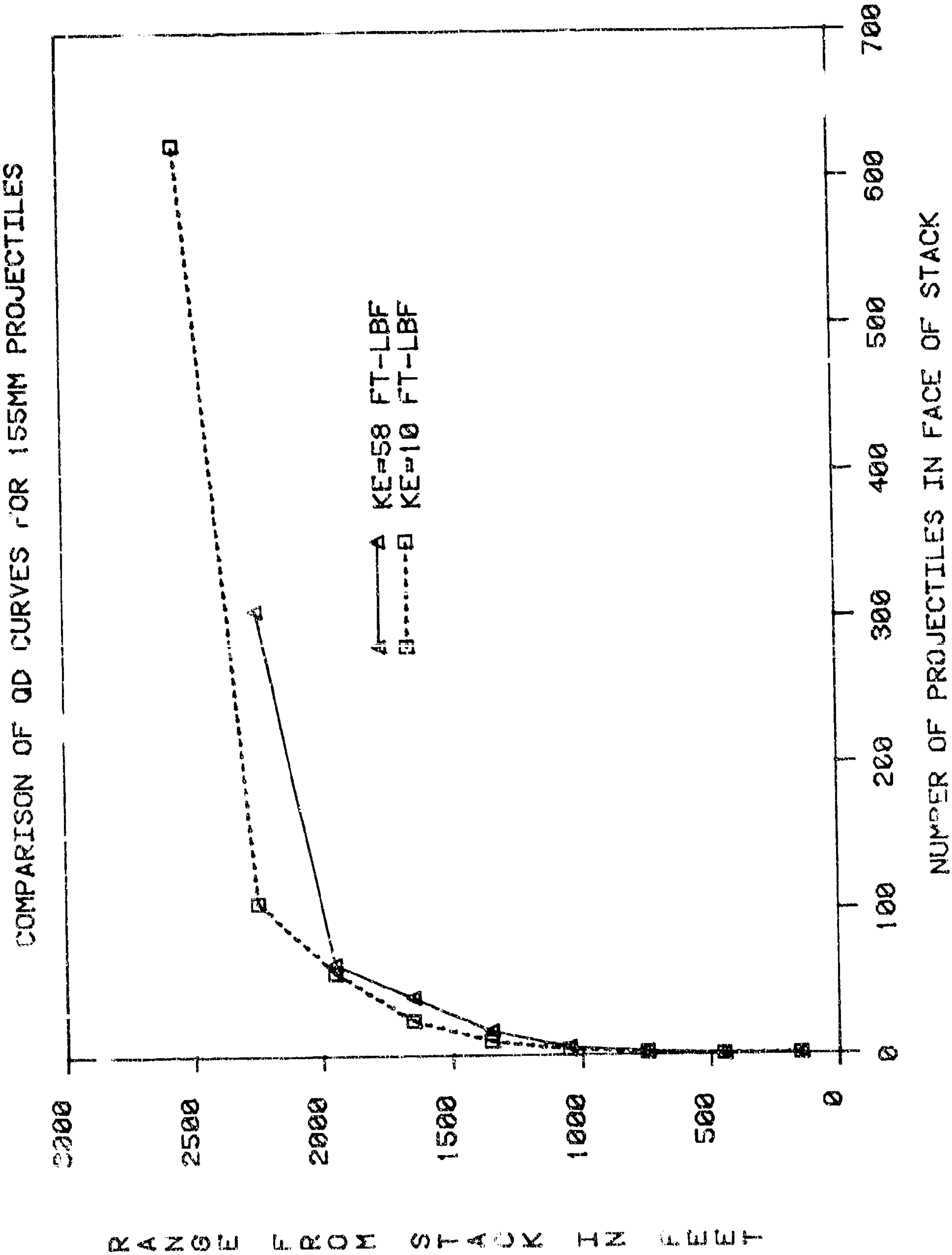

COMPARISON OF QD CURVES FOR 155MM PROJECTILES
KE=58 FT-LBF
KE=10 FT-LBF
RANGE FROM STACK IN FEET
3000
2500
2000
1500
1000
500
0
NUMBER OF PROJECTILES IN FACE OF STACK
0
100
200
300
400
500
600
700

FIGURE 8

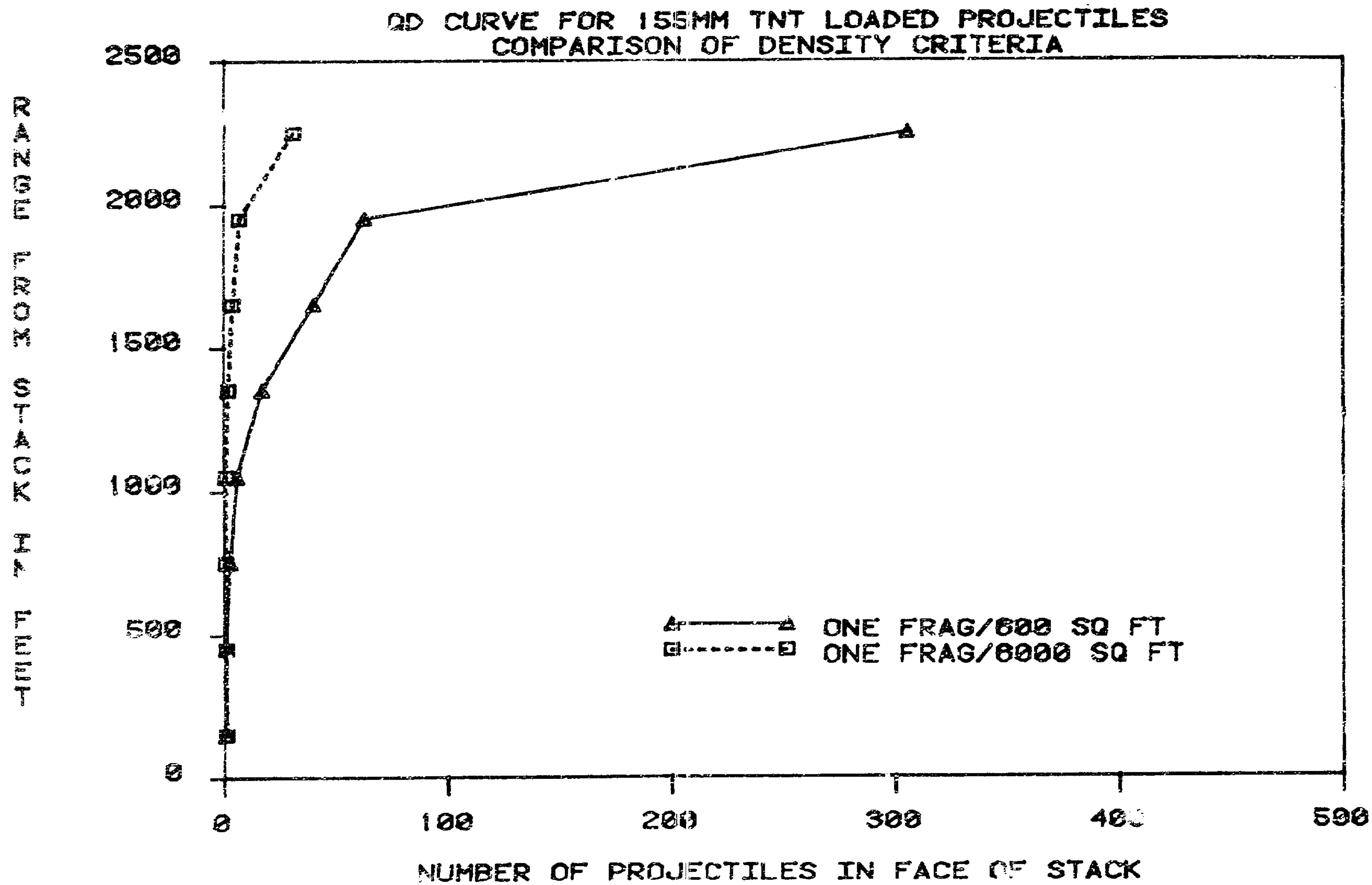

QD CURVE FOR 155MM TNT LOADED PROJECTILES
COMPARISON OF DENSITY CRITERIA
RANGE FROM STACK IN FEET
2500
2000
1500
1000
500
0
100
200
300
500
NUMBER OF PROJECTILES IN FACE OF STACK
ONE FRAG/600 SQ FT
ONE FRAG/6000 SQ FT

FIGURE 9

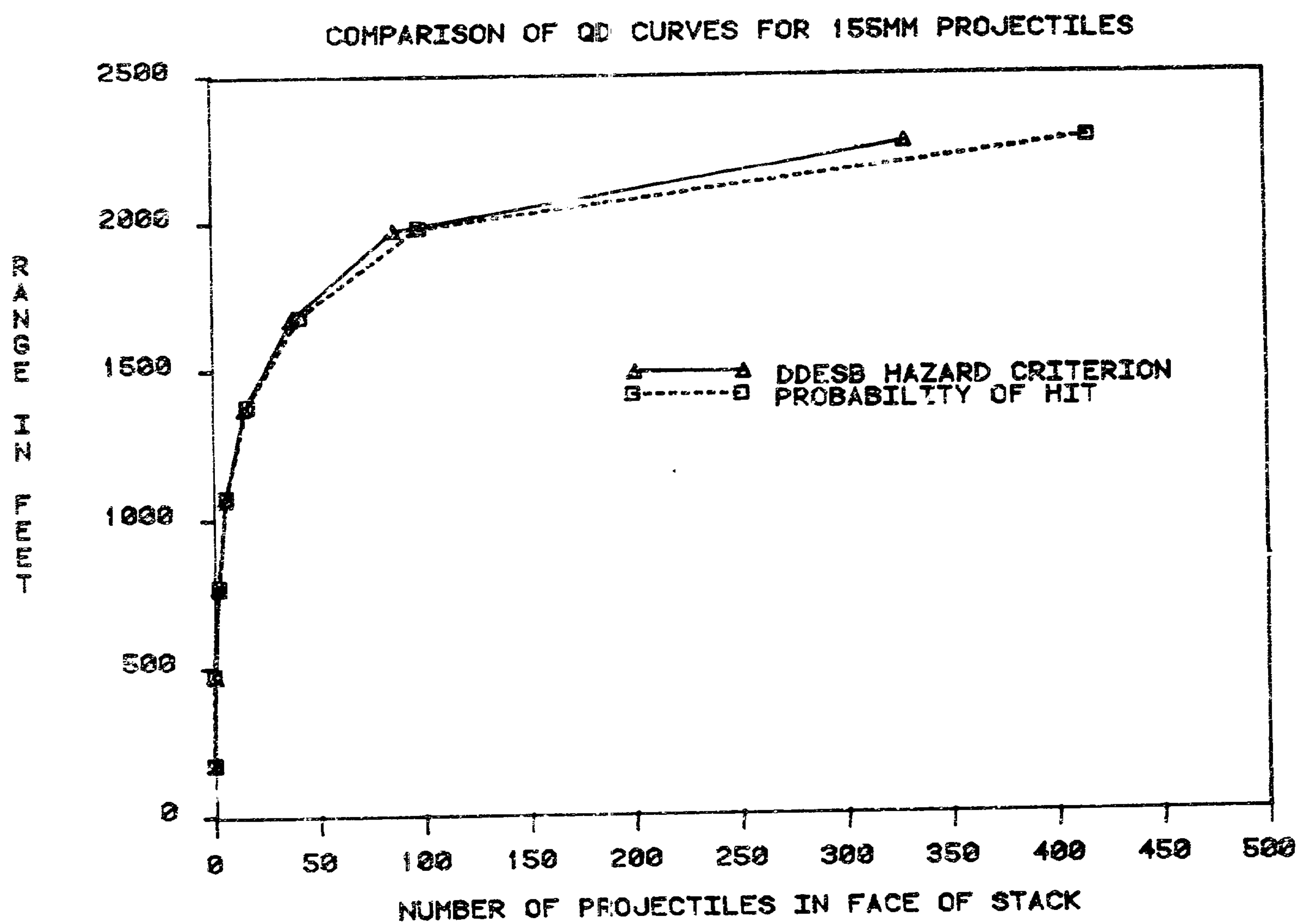

COMPARISON OF QD CURVES FOR 155MM PROJECTILES
2500
2000
1500
1000
500
0
RANGE IN FEET
DDESB HAZARD CRITERION
PROBABILITY OF HIT
0
50
100
150
200
250
300
350
400
450
500
NUMBER OF PROJECTILES IN FACE OF STACK

FIGURE 10

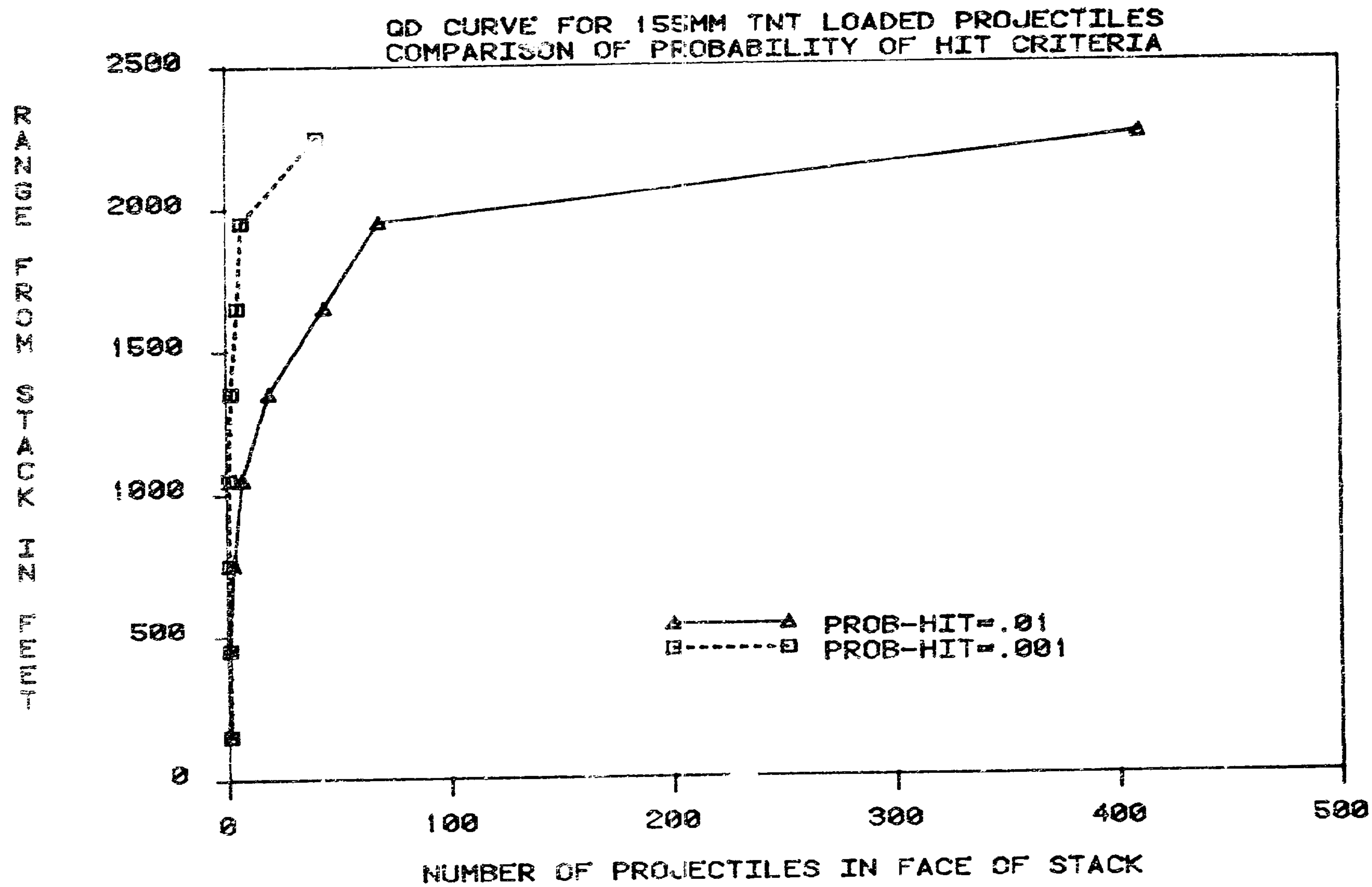
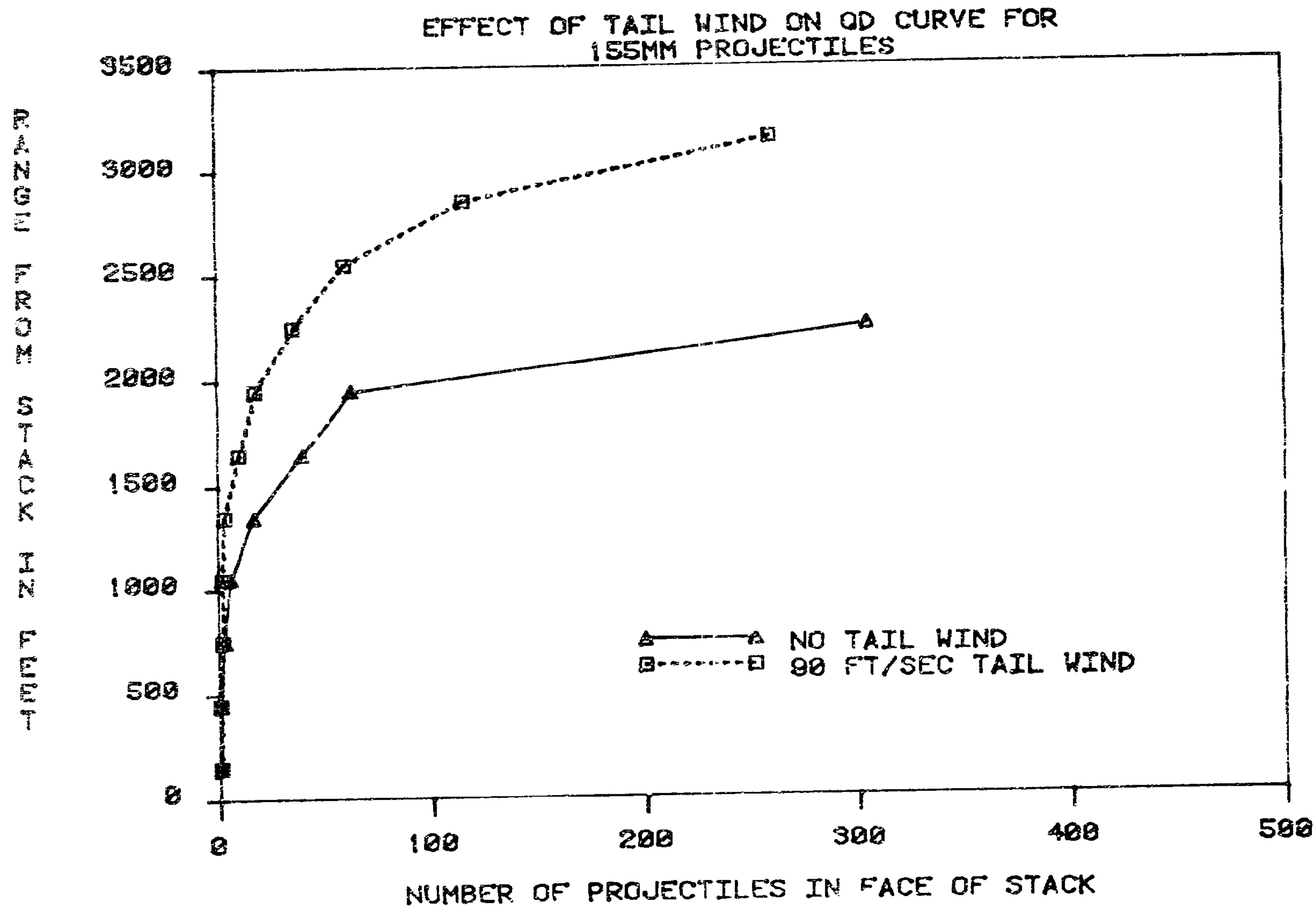

QD CURVE FOR 155MM TNT LOADED PROJECTILES
COMPARISON OF PROBABILITY OF HIT CRITERIA
RANGE FROM STACK IN FEET
2500
2000
1500
1000
500
0
100
200
300
400
500
PROB-HIT=.01
PROB-HIT=.001
NUMBER OF PROJECTILES IN FACE OF STACK

FIGURE 11



EFFECT OF TAIL WIND ON QD CURVE FOR
155MM PROJECTILES
RANGE FROM STACK IN FEET
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
NUMBER OF PROJECTILES IN FACE OF STACK
NO TAIL WIND
90 FT/SEC TAIL WIND

FIGURE 12

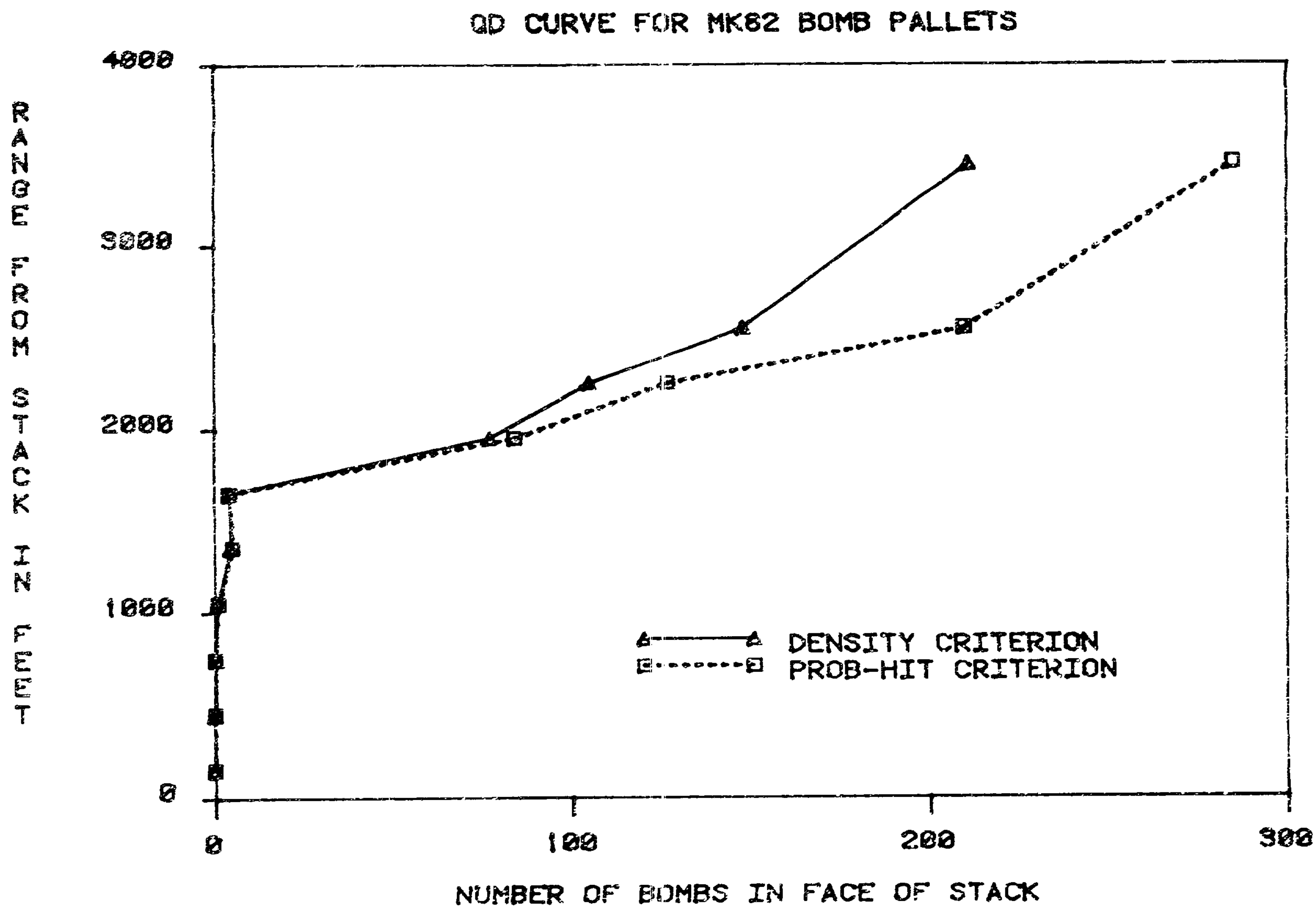

QD CURVE FOR MK82 BOMB PALLETS
RANGE FROM STACK IN FEET
4000
3000
2000
1000
0
100
200
300
NUMBER OF BOMBS IN FACE OF STACK
DENSITY CRITERION
PROB-HIT CRITERION

FIGURE 13

Effect of a Tail Wind on QD Curve for MK82 Bomb Pallet

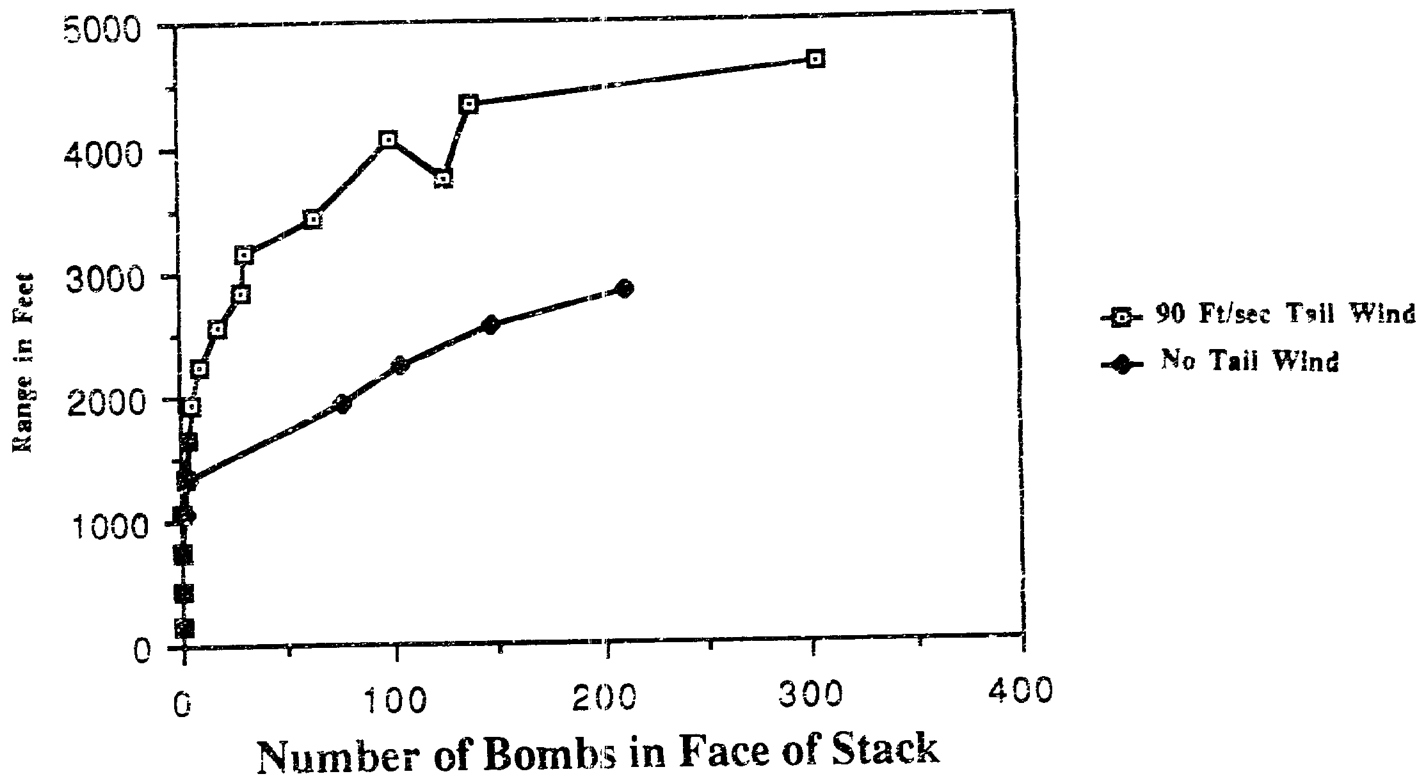


Figure 14

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