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## DEGRADED STATES VULNERABILITY ANALYSIS: PHASE II

JOHN M. ABELL  
MARK D. BURDESHAW  
BRUCE A. RICKTER

OCTOBER 1990

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13. ABSTRACT (Maximum 200 words)  <p>In 1988, the Ballistic Research Laboratory (BRL) and the Army Materiel Systems Analysis Activity (AMSAA) began a joint program to develop improved metrics for use in vulnerability assessments, especially of ground combat vehicles. Traditional tank vulnerability metrics have made use of a mapping procedure called damage assessment lists (DALs). A DAL maps killed components and sets of components into degradation of combat utility (DCU). It has been known for a number of years that the use of DALs in the process of developing vulnerability measures of effectiveness is conceptually and mathematically problematic. Recent DAL work led to renewed focus on the problems associated with DALs, and to a proposal for their wholesale elimination from the process of vulnerability analysis, in favor of a methodology which yields the probabilities that a tank is in one or more degraded states.</p> <p>The primary purpose of this paper is to exhibit inputs and results from Phase II of the implementation of the degraded states methodology which involved view average calculations. A secondary purpose is to compare the DAL-based metrics with degraded states metrics.</p>			
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## CONTENTS

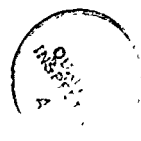
I. Introduction .....	1
II. Approach.....	1
III. Methodology.....	3
1. Damage Assessment List.....	3
2. Degraded States.....	3
3. View Average Required Code Changes .....	8
4. Outputs.....	10
IV. Results.....	13
1. Probability Distribution of Degraded States.....	13
2. Individual Cell Plots.....	14
a. Degraded States Kill Definitions.....	15
b. Comparison of Degraded States and DAL.....	16
3. Excursions .....	17
a. Range Sensitivities .....	17
b. Dispersion Sensitivities.....	18
c. Threat Sensitivities .....	18
d. Exposure Sensitivities.....	18
e. Azimuth Sensitivities .....	18
4. Degraded States vs. DAL Comparisons.....	19
a. Modified DAL Comparisons .....	20
b. Aggregated DS Probability Comparisons .....	23

V. Summary.....	24
REFERENCES.....	26
APPENDIX A: Degraded States Fault Trees.....	A-1
APPENDIX B: Individual Cell Plots.....	B-1
APPENDIX C: Sensitivity Excursions.....	C-1
APPENDIX D: Degraded States vs. DAL Comparisons.....	D-1
APPENDIX E: Aggregated Degraded States vs. DAL Comparisons.....	E-1
DISTRIBUTION LIST.....	27

## LIST OF TABLES

TABLE 1. Damage Assessment List.....	4
TABLE 2. List of Kill Definitions for AFV .....	6
TABLE 3. Example Degraded States for One Cell.....	9
TABLE 4. Example DS Cell Output.....	9
TABLE 5. Example of Degraded States Output .....	11
TABLE 6. Example of DS Formatted Output .....	12
TABLE 7. Aggregated DS Probabilities.....	14
TABLE 8. Kill Definitions Plotted.....	15
TABLE 9. Range/Delivery Error Pairings.....	17
TABLE 10. Numerical Differences Between DS (Hardware Only) and DAL.....	21
TABLE 11. Numerical Differences Between Aggregated DS and DAL.....	24

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## I. Introduction

In 1988, the Ballistic Research Laboratory (BRL) and the Army Materiel Systems Analysis Activity (AMSAA) began a joint program to develop improved metrics for expressing the results of vulnerability assessments, especially of ground combat vehicles. Phase I was completed in May 1989;<sup>1</sup> this report documents the Phase II effort of the pilot program.

For Phase I, vulnerability assessments were compared for four different Damage Assessment Lists (DAL). In addition, the new Degraded States Vulnerability approach was implemented and the results were compared with the DAL results. Single shots involving a broad range of initial conditions (i.e. threat, range, azimuth, etc.) were used to generate the results for the comparisons.

In Phase II, view average vulnerability estimates were calculated for a representative set of initial conditions. An average estimate was calculated based on the estimates of each cell in a particular view or azimuth of fire. This average can be weighted uniformly or by the munition's delivery error relative to a given aimpoint. These estimates were calculated for both the Degraded States Vulnerability approach and the DAL approach.

The purpose of this report is to exhibit view average results for both the Degraded States and DAL metrics. We will show, as we did in Phase I, that the Degraded States metrics give a much more detailed vulnerability assessment of a vehicle. A secondary purpose is to illustrate typical output from the Degraded States metrics for view average vulnerability estimates.

## II. Approach

The same methodology was used to calculate the view average vulnerability estimates for both the Degraded States and DAL metrics. This methodology was an adapted version of BRL's current Monte Carlo vulnerability code for point burst modeling,

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1. J. M. Abell, L. K. Roach, M. W. Starks, "Degraded States Vulnerability Analysis", USA Ballistic Research Laboratory, TR-3010, June 1989, (Unclassified).

SQuASH (Stochastic Quantitative Analysis of System Hierarchies)<sup>2 3</sup>, developed by the Vulnerability Methodology Branch (VMB) of BRL. For this analysis, only the portion of the code which calculates loss of combat functions was required. This portion of the code, called "SQuASHed", was used to generate loss of function values given a hit (LOF/H) for the DAL and probability of Degraded States given a hit (PDS/H) for the Degraded States approach. There are several published reports which describe the SQuASH model, so there will be no further discussion of the model in this report. However, the specific changes which were made for purposes of performing view average calculations will be addressed in sections III.3 and III.4.

The inputs to the "SQuASHed" model were provided by the VMB-BRL. The model requires two separate sets of inputs. The first set contains the component identification numbers from the computer generated target description of the AFV, a verbal description of these components and the DAL. The verbal description section, called the association table, acts as a liaison between the component identification table and the DAL. When a component is killed, "SQuASHed" uses this set of inputs to trace the component to the DAL.

The second set of inputs provides "SQuASHed" with a set of killed components. For each cell in the view (i.e. azimuth), a series of iterations (i.e. shot-lines) are performed by the main SQuASH program: ten iterations per cell were made for this analysis. For each iteration, SQuASH generates a set of killed components and initial loss of function (LOF) values and writes both to a file called "Damage.States." The "Damage.States" file contains the initial loss of function values for Mobility (M), Firepower (F), Catastrophic (K) and Mobility or Firepower (M/F). These initial loss of function values are for hits to the ammunition and/or fuel compartments that do not result in a catastrophic event. When a catastrophic event does occur, these values are all set to 1.00 (i.e. total loss of function). The "SQuASHed" code uses this information to calculate M, F, K and M/F final loss of function values via the DAL or probability of degraded states via the Degraded States fault trees (see section III.2).

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2. Aivars Ozolins, "Stochastic High-Resolution Vulnerability Simulation for Live-Fire Programs," *The Proceedings of Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association (ADPA)*, held at the Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988, (UNCLASSIFIED).

3. Paul H. Deitz, Aivars Ozolins, "Computer Simulations of the Abrams Live-Fire Field Testing," USA Ballistic Research Laboratory, MR-3755, May 1989, (UNCLASSIFIED).

A "Damage.States" file was generated for each threat, azimuth and range combination. There were two kinetic energy (KE) penetrators fired from six ranges (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 kilometers) at four azimuths (0, 30, 60 and 90 degrees). The elevation was zero degrees. In the "SQuASHed" code, the delivery errors (1, 2, 3, 5 and 10 foot sigmas) were varied for each threat, range and azimuth combination. Also, two exposures (fully exposed and hull defilade) were used in the model for each of the combinations. For each combination (threat, range, azimuth, delivery error and exposure), the "SQuASHed" code calculated both loss of functions values (M, F, K and M/F) using the DAL and probability of degraded state using the Degraded States approach.

### **III. Methodology**

#### **1. Damage Assessment List**

The Damage Assessment List used in this analysis was obtained from the BRL-VMB. The list contains M, F, K and M/F loss of function values for each component(s) addressed. This DAL is shown in Table 1.

#### **2. Degraded States**

The Degraded States (DS) methodology describes vehicle loss of function in terms of six kill categories: mobility, firepower, acquisition, crew, communications and ammunition. The ammunition kill category was recently developed and added to the Degraded States approach; this is an improvement over the Phase I work. This approach represents a more robust set of metrics when compared to the traditional DAL metrics which provide only a single LOF value for both mobility and firepower. Each DS kill category contains a set of kill definitions which define degraded, but operational, states of the vehicle to include a "no damage" state. Also, in a particular kill category (except for crew), it is possible for two or more kill definitions to occur simultaneously; therefore, all possible combinations of kill definitions are considered in each kill category. Due to the inclusion of these combinations and the "no damage" state, the kill definitions are both exhaustive and mutually exclusive within a particular kill category. For any given damage to the vehicle, one kill definition from each of the six kill categories will be satisfied. The kill category combination represents the degraded state of the vehicle. The K-kill definition, K4, represents hits to the ammunition and fuel compartments and is included in the ammunition kill category in order to reduce the possible number of vehicle degraded states. The complete list of degraded state kill definitions for each kill category is contained in Table 2.

**TABLE 1. Damage Assessment List for AFV**

Event No.	M	F	K	M/F	Association Table No(s).	Component(s)
1	.30	.50	.00	.50	472 -473 -474 -475	commander only
1	.10	.50	.00	.50	473 -472 -474 -475	gunner only
1	.10	.30	.00	.30	474 -472 -473 -475	loader only
1	.30	.20	.00	.30	475 -472 -473 -474	driver only
1	.35	.75	.00	.75	472 474 -473 -475	commander & loader
1	.60	.75	.00	.75	472 475 -473 -474	commander & driver
1	.35	.80	.00	.80	472 473 -474 -475	commander & gunner
1	.20	.70	.00	.70	473 474 -472 -475	gunner & loader
1	.60	.75	.00	.75	474 475 -472 -473	loader & driver
1	.60	.75	.00	.75	473 475 -472 -474	gunner & driver
1	.95	.10	.00	.95	473 474 475 -472	commander sole survivor
1	.95	.90	.00	.95	472 474 475 -473	gunner sole survivor
1	.95	.95	.00	.95	472 473 475 -474	loader sole survivor
1	.90	.95	.00	.95	472 473 474 -475	driver sole survivor
1	1.00	1.00	.00	1.00	472 473 474 475	no survivors
2	1.00	.00	.00	1.00	481	engine
3	1.00	.00	.00	1.00	488	transmission
4	1.00	.00	.00	1.00	OR426OR427	final drive (any side or both)
5	1.00	.00	.00	1.00	OR503OR504OR430OR431	sprocket (wheel & hub)
6	.05	.00	.00	.05	478 -479	one sponson tank
6	.05	.00	.00	.05	479 -478	one sponson tank
6	.10	.00	.00	.10	478 479	both sponson tanks
7	.15	.00	.00	.15	476 -477	one bow fuel tank
7	.15	.00	.00	.15	477 -476	one bow fuel tank
7	.20	.00	.00	.20	476 477	both bow fuel tanks
8	1.00	.00	.00	1.00	480	fuel supply
9	.10	.00	.00	.10	553	intermediate roadwheel - 1
9	.20	.00	.00	.20	554	intermediate roadwheel - 2
9	.40	.00	.00	.40	555	intermediate roadwheel - 3
9	.50	.00	.00	.50	556	intermediate roadwheel - 4
9	.70	.00	.00	.70	557	intermediate roadwheel - 5
9	.85	.00	.00	.85	558	intermediate roadwheel - >5
10	1.00	.00	.00	1.00	OR507OR508OR552	track (any side & edge)
11	.25	.00	.00	.25	432 -433	right support roller - 1
11	.25	.00	.00	.25	433 -432	right support roller - 1
11	.50	.00	.00	.50	432 433	right support rollers - both
12	.25	.00	.00	.25	434 -435	left support roller - 1
12	.25	.00	.00	.25	435 -434	left support roller - 1
12	.50	.00	.00	.50	434 435	left support rollers - both
13	1.00	.00	.00	1.00	OR505OR506OR346OR351	idler (wheel & hub)
14	1.00	.00	.00	1.00	OR350OR355	track adjusting link
15	.65	.00	.00	.65	489 490	1st roadwheel (both sides)
15	.65	.00	.00	.65	489 -490 361	1st roadwheel (both sides)
15	.65	.00	.00	.65	490 -489 356	1st roadwheel (both sides)
15	.65	.00	.00	.65	-489 -490 356 361	1st roadwheel (both sides)
15	.50	.00	.00	.50	490 -489 -356	1st roadwheel (one side)
15	.50	.00	.00	.50	489 -490 356 -361	1st roadwheel (one side)

TABLE 1. Damage Assessment List for AFV (continued)

Event No.	M	F	K	M/F	Association Table No(s).	Component(s)
15	.50	.00	.00	.50	489 -490 -356 -361	1st roadwheel (one side)
15	.50	.00	.00	.50	-489 -490 356 -361	1st roadwheel (one side)
15	.50	.00	.00	.50	-489 -490 -356 361	1st roadwheel (one side)
16	.30	.00	.00	.30	501 -502	7th roadwheel (one side)
16	.30	.00	.00	.30	502 -501	7th roadwheel (one side)
16	.40	.00	.00	.40	501 502	7th roadwheel (both sides)
17	1.00	.00	.00	1.00	135	batteries
18	.65	.00	.00	.65	516	dc - shift
19	1.00	.00	.00	1.00	518	dc - steer
20	.65	.00	.00	.65	517	dc - throttle
21	.25	.00	.00	.25	519 -520	dc - service brake only
21	.00	.00	.00	.00	520 -519	dc - parking brake only
21	.40	.00	.00	.40	519 520	dc - all brake
22	.10	.00	.00	.10	565	driver's vis blk - 1
22	.25	.00	.00	.25	566	driver's vis blk - 2
22	.50	.00	.00	.50	567	driver's vis blk - all
23	.00	.20	.00	.20	154	cmdr's GPS extension
24	.01	.05	.00	.05	155	cmdr's weapon sight
25	.00	.00	.00	.00	559	cmdr's vis blk - 1
25	.00	.05	.00	.05	560	cmdr's vis blk - 2
25	.10	.05	.00	.10	561	cmdr's vis blk - 3
25	.15	.10	.00	.15	562	cmdr's vis blk - 4
25	.20	.20	.00	.20	563	cmdr's vis blk - 5
25	.50	.25	.00	.50	564	cmdr's vis blk - all
26	.00	.10	.00	.10	-537 536	GPS - daylight only
26	.00	.25	.00	.25	537 -536	GPS - TIS only
26	.00	.75	.00	.75	-153 537 536	GPS - both
26	.00	.97	.00	.97	153 536 537	GPS (both) & GAS
27	.00	.00	.00	.00	162	loader's sight
28	.00	.95	.00	.95	531	main gun
29	.00	.02	.00	.02	532	coaxial weapon
30	.00	.02	.00	.02	OR534OR535	cmdr's weapon
31	.00	.01	.00	.01	533	loader's weapon
32	.00	.01	.00	.01	247	coax ammo - ready only
33	.00	.01	.00	.01	256	loader's ammo - ready only
34	.00	.01	.00	.01	252	cmdr's ammo - ready only
35	.00	.24	.00	.24	539 -540 -541	fc - MHP (normal)
35	.00	.24	.00	.24	539 -540 541	fc - MHP (normal & emergency)
35	.00	.35	.00	.35	539 540 -541 -542	fc - MHP & AHP (normal)
35	.00	.35	.00	.35	539 540 -541 542	fc - MHP (norm) & AHP (norm & emerg)
35	.00	.35	.00	.35	539 540 541 -542	fc - MHP (normal & emergency) & AHP (normal)
35	.00	.80	.00	.80	-543 539 540 541 542	fc - all power
35	.00	.97	.00	.97	543 539 540 541 542	fc - all
36	.00	.40	.00	.40	538	target range
37	.30	.30	.00	.30	OR546OR547OR549	intercoms
38	.30	.00	.00	.30	548	driver's intercom
39	.00	.20	.00	.20	OR550OR551	external communications

Table 2. List of AFV Kill Definitions

**Mobility Kill Category**

- MO--> No mobility damage
- M1--> Reduced speed (slight)
- M2--> Reduced speed (significant)
- M3--> Total immobilization

**Firepower Kill Category**

- FO--> No firepower damage
- F1--> Loss of main armament
- F2--> Unable to fire on the move
- F3--> Increased time to fire
- F4--> Reduced delivery accuracy
- F5--> Loss of secondary armament
- F6--> F2 and F3
- F7--> F2 and F4
- F8--> F3 and F4
- F9--> F2 and F3 and F4
- F10--> F2 and F5
- F11--> F3 and F5
- F12--> F4 and F5
- F13--> F2 and F3 and F4 and F5
- F14--> F2 and F3 and F5
- F15--> F2 and F4 and F5
- F16--> F3 and F4 and F5
- F17--> F1 and F5 (total loss of firepower)

**Acquisition Kill Category**

- AO--> No acquisition damage
- A1--> Reduced acquisition capability
- A2--> Unable to acquire while moving
- A3--> A1 and A2

**Crew Kill Category**

- CO--> 0 crew casualties
- C1--> 1 crew casualties
- C2--> 2 crew casualties
- C3--> 3 crew casualties
- C4--> 4 crew casualties

**Communications Kill Category**

- XO--> No communication damage
- X1--> No internal communications
- X2--> No external communications >300 feet
- X3--> No external communications
- X4--> X1 and X2
- X5--> X1 and X3

**Ammo Kill Category**

- KO--> No ammo lost
- K1--> Bustle ammo lost
- K2--> Hull ammo lost
- K3--> K1 and K2
- K4--> K Kill

Combinations

$$M(0-3) \quad F(0-17) \quad A(0-3) \quad C(0-4) \quad X(0-5) \quad K(0-4)$$

$$4 \quad X \quad 18 \quad X \quad 4 \quad X \quad 5 \quad X \quad 6 \quad X \quad 5 = 43,200 \text{ states}$$

For shorthand purposes, the alphanumeric name assigned to each of the kill definitions in Table 2 will be used throughout the remainder of this report. For example, state M3 represents the kill definition for total immobilization of the vehicle. The total number of possible combinations of vehicle degraded states is shown at the bottom of Table 2.

Mathematical fault trees were developed to represent the degraded state kill definitions in each kill category. These fault trees consisted of a list of critical vehicle components that, if killed, would result in that particular kill definition being satisfied. For a particular kill category, a kill definition is achieved when no uninterrupted path can be traced from top to bottom in the fault tree. The fault tree path configurations can be described as having components arranged in series or in parallel or as some combination of the two. If listed in series, the loss of any component would cause an interruption in the path whereas those components listed in parallel must all be killed to interrupt the path. The components listed in the fault trees can represent either a single critical component or a system of critical components. The systems of components were developed into fault tree configurations in the criticality analysis performed by the BRL-VMB.<sup>4</sup> The criticality analysis also provided a list of approximately five hundred critical components from which the degraded state fault trees were developed. After the initial strawman trees were developed, they were reviewed by the appropriate personnel at BRL, AMSAA, the US Army Ordnance Center and School (USAOC&S) and the US Army Armor Center and School (USAAC&S). Recommended changes to the trees from these groups were incorporated in the final fault tree configurations for each kill definition in all six kill categories. The final fault trees are shown in Appendix A.

The fault trees were incorporated into the "SQuASHed" code using the BRL-VMB's Interactive Criticality Evaluator (ICE) program. The ICE program translated the fault trees into mathematical FORTRAN statements called SHOTPK equations. These mathematical expressions depict the appropriate Boolean operation for each component (i.e. series or parallel). Once the set of killed components has been determined (via the "Damage.States" file), the SHOTPK equations use them to determine which fault trees have been cut. Since cutting a fault tree equates to achieving that kill definition, the SHOTPK equations determine which kill definition is satisfied for each of the six kill categories. The combination of one kill definition from each of the six kill categories represents the degraded state for the vehicle.

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4. Joseph J. Ploskonka, Theodore M. Muchl, Cynthia J. Dively, "Criticality Analysis of the M1A1 Tank," US Army Ballistic Research Laboratory, BRL-MR-3671, June 1988, (UNCLASSIFIED).

### 3. View Average Required Code Changes

As stated earlier, the purpose of this report is to compare view average results for both the Degraded States and the DAL approaches. To produce view average results, several changes had to be made to the "SQuASHed" program used in the Phase I analysis. As part of the SQuASH program processing (performed by the VMB), a grid system must be overlaid on the target in order to perform the cell by cell analysis; a 4 inch grid cell system was used for this analysis. The results of the cell by cell vulnerability analysis are stored in the "Damage.States" file; recall, this file contains the set of killed components for each iteration (i.e. shotline) of each grid cell. Since there were ten Monte Carlo iterations per grid cell and 749, 1400, 1630 and 1503 cells for 0 , 30 , 60 and 90 azimuth, respectively, VMB provided the data in packed binary form to reduce the required computer storage. To read this data as input for "SQuASHed," an input routine was developed to unpack the packed binary input file, assign the values to the appropriate variables, and print the header information to confirm that the file was read correctly. The data were provided for all cells which covered any part of the vehicle.

After the "Damage.States" file was read, "SQuASHed" calculated the vulnerability estimates via the DS fault trees or the DAL for each iteration. The next change to the program involved the handling of the ten iterations per cell. For the DAL case, the output for each shotline was the four LOF values, M, F, K, and M/F, thus, generating ten sets of LOF values for each grid cell. The LOF values for each cell were calculated by taking the average of the ten values in that cell. Then, averaging over the number of cells in that view, an unweighted view average LOF value was computed for these four kill criteria.

For the Degraded States case, the process was more complex. The Degraded States procedure produced a single vehicle degraded state per iteration; therefore, each cell could have contained up to ten different vehicle degraded states. For example, Table 3 shows the different vehicle degraded states that could be obtained from a single cell (see Table 2 for Degraded States kill definitions).

**TABLE 3. Example Degraded States for One Cell**

ITERATION	STATE					
	M	F	A	C	X	K
	--	--	--	--	--	--
1	0	1	3	1	0	0
2	0	0	0	0	0	0
3	0	1	3	1	0	0
4	0	1	3	1	0	0
5	0	1	3	1	5	0
6	0	1	3	1	0	0
7	0	1	3	1	0	0
8	0	1	3	1	0	0
9	0	1	3	1	5	0
10	0	1	3	1	0	0

Since a different vehicle degraded state could occur for each iteration, "SQuASHed" kept track of each different vehicle degraded state and its probability for each cell. For example, given the set of vehicle degraded states in Table 3 for a certain cell, Table 4 shows how the data would be consolidated and sorted.

**TABLE 4. Example DS Cell Output**

STATE						PROBABILITY	CUMULATIVE
M	F	A	C	X	K		
--	--	--	--	--	--		
0	1	3	1	0	0	0.7	0.7
0	1	3	1	5	0	0.2	0.9
0	0	0	0	0	0	0.1	1.0

After the degraded states of the vehicle were calculated for each cell, a consolidating/sorting algorithm was used to combine like degraded states. This routine summed the probabilities of identical vehicle degraded states and sorted them in descending order by their probabilities. The DS average was taken uniformly, as was the LOF average.

Up to this point in the calculations it has been implicitly assumed that each cell has the same probability of being hit. This probability distribution, relative to the aimpoint, is unrealistic for assessing the vulnerability of vehicles given the delivery error of the threat. A more realistic approach is to assume a normal probability distribution about the aimpoint, weighting the probability of hitting the target more heavily about the aimpoint and less for cells farther from the aimpoint; therefore, a normal distribution was assumed on the horizontal and vertical axes of the vehicle with the mean on the aimpoint and the standard deviation representing the delivery error of the threat (i.e. dispersion value). Dispersion values used were 1, 2, 3, 5, and 10 feet.

The changes to the "SQuASHed" program to implement the weighted view average procedures involved creating a weighting algorithm to calculate the probability of hitting a certain cell on the target given an aimpoint and dispersion value. The aimpoints used for the four azimuths and two exposures were center of presented area. Once the processing for each cell was completed, the values in the cell, both DAL LOF values and DS probabilities, were weighted by the probability of hitting that cell. The consolidating/sorting algorithm described above was used to calculate the weighted view average results.

#### **4. Outputs**

For this analysis, the "SQuASHed" program provided two forms of output. The first form of results was the DAL and Degraded States individual cell results, unweighted and weighted. An example of a single cell result for Degraded States was displayed in Table 4. The second form of results was the vehicle degraded states/DAL metrics and their associated probabilities/LOF values given a hit to the vehicle in descending order. An example of the DS form of output is shown in Table 5.

**TABLE 5. Example of Degraded States Output**

STATES						PROBABILITY	CUMULATIVE
M	F	A	C	X	K		
--	--	--	--	--	--		
3	9	3	1	5	0	0.108	0.108
0	0	0	0	0	0	0.107	0.215
3	17	3	4	5	4	0.090	0.305
3	1	3	1	5	0	0.084	0.389
3	1	3	1	0	0	0.062	0.451
3	9	3	0	5	0	0.038	0.489
0	1	3	1	0	0	0.037	0.526
3	0	0	0	0	0	0.036	0.562
0	1	0	0	0	0	0.036	0.598
3	1	3	2	5	0	0.034	0.632
3	9	3	1	0	0	0.033	0.665
0	1	3	0	0	0	0.031	0.696
0	1	3	2	0	0	0.028	0.724
3	1	3	2	0	0	0.028	0.752
3	1	3	0	5	0	0.017	0.769
0	1	3	3	5	0	0.014	0.783
3	1	3	3	5	0	0.014	0.797
3	8	3	1	0	0	0.013	0.810
3	9	3	2	5	0	0.013	0.823
0	1	3	3	0	0	0.013	0.836
3	1	3	0	0	0	0.011	0.847
---	---	---	---	---	---	---	---
---	---	---	---	---	---	---	---
---	---	---	---	---	---	---	---
0	1	2	0	5	0	0.001	0.992
2	1	3	0	0	2	0.001	0.993
1	0	1	1	0	0	0.001	0.994
2	1	3	1	5	1	0.001	0.995
0	1	1	0	0	1	0.001	0.996
3	0	1	0	0	0	0.001	0.997
2	1	3	2	5	1	0.001	0.998
2	9	3	3	0	0	0.001	0.999
3	8	3	0	5	0	0.001	1.000

Finally, an output algorithm was developed to consolidate the DS and DAL output according to initial conditions (threat, exposure, azimuth, range, and dispersion). An example of the DS output is shown in Table 6. The first column contains the vehicle degraded states; the next four columns contain the probabilities for the four azimuths (views); the sixth column contains the uniform average probability over the four views; and the final column contains the cardioid average probability.

TABLE 6. Example of DS Formatted Output

Exposure: Fully exposed  
 Threat: Pl  
 Range: 1000 meters  
 Dispersion: 2 feet

Damage (M F A C X K)	Views				Uniform Average	Cardioid Average
	0	30	60	90		
3 9 3 1 5 0	0.108	0.018	0.014	0.008	0.037	0.039
0 0 0 0 0 0	0.107	0.077	0.044	0.123	0.088	0.089
3 1 7 3 4 5 4	0.090	0.090	0.045	0.028	0.063	0.062
3 1 3 1 5 0	0.084	0.095	0.095	0.027	0.075	0.073
3 1 3 1 0 0	0.062	0.023	0.010	0.009	0.026	0.026
3 9 3 0 5 0	0.038	0.048	0.030	0.026	0.036	0.035
0 1 3 1 0 0	0.037	0.016	0.014	0.010	0.019	0.020
3 0 0 0 0 0	0.036	0.066	0.020	0.017	0.035	0.033
0 1 0 0 0 0	0.036	0.012	0.005	0.002	0.014	0.014
3 1 3 2 5 0	0.034	0.058	0.045	0.010	0.037	0.035
3 9 3 1 0 0	0.033	0.006	0.005	0.006	0.012	0.013
0 1 3 0 0 0	0.031	0.023	0.017	0.009	0.020	0.020
0 1 3 2 0 0	0.028	0.013	0.004	0.004	0.012	0.013
3 1 3 2 0 0	0.028	0.017	0.007	0.000	0.017	0.013
3 1 3 0 5 0	0.017	0.048	0.032	0.016	0.028	0.027
0 1 3 3 5 0	0.014	0.004	0.002	0.011	0.008	0.008
3 1 3 3 5 0	0.014	0.009	0.004	0.002	0.007	0.007
3 8 3 1 0 0	0.013	0.003	0.006	0.001	0.006	0.006
3 9 3 2 5 0	0.013	0.003	0.001	0.000	0.006	0.004
0 1 3 3 0 0	0.013	0.010	0.001	0.001	0.006	0.006
3 1 3 0 0 0	0.011	0.016	0.017	0.014	0.014	0.014
3 9 3 0 0 0	0.009	0.038	0.042	0.047	0.034	0.034
0 1 3 0 5 0	0.008	0.017	0.018	0.008	0.013	0.012
0 1 3 2 5 0	0.007	0.006	0.008	0.009	0.007	0.007
0 1 3 1 5 0	0.006	0.012	0.015	0.008	0.010	0.010

## IV. Results

The results of this analysis were voluminous due to the number of initial condition combinations and the nature of the degraded states output; therefore, when appropriate, only examples or portions of the results will be presented. All DAL or Degraded States results (except the individual cell plots) are LOF or probability of degraded states (PDS), respectively, given a hit.

### 1. Probability Distribution of Degraded States

A probability distribution of vehicle degraded states was generated for each set of initial conditions (all possible combinations of threat, range, azimuth, exposure and dispersion). The distribution consisted of a set of vehicle degraded states listed in descending order according to their probabilities, to include their associated cumulative probabilities. The vehicle degraded states are combinations of the six kill categories and represent the form of output provided to AMSAA for input to their force-level model, Degraded States Weapons Analysis Research Simulation (DSWARS). In all the runs, the number of vehicle degraded states realized was considerably less (no more than approximately 200) than the 43,200 possible combinations. Table 5 provided an example of a probability distribution of vehicle degraded states. For force-level comparisons, a set of traditional DAL metrics (M, F, K & M/F) for each set of initial conditions was also provided to AMSAA. In addition to the probability of vehicle degraded states and the final loss of function values for each view, uniform and Cardioid averages were calculated over the four views or azimuths (0, 30, 60 and 90 degrees). For the Cardioid average, the weighting factors for 120, 150 and 180 degrees were added to the factor at 90 degrees azimuth.

A numerical comparison of the two approaches is not possible with this form of output. The damage to a particular kill category is accounted for in several vehicle degraded states and probabilities whereas the DAL provides a single LOF value. Later in this report, these DS probabilities will be aggregated so that numerical comparisons can be made with the DAL LOF values.

The probability distribution of these vehicle degraded states provides a much fuller description of the damage to the vehicle than does the traditional DAL metrics. The distribution describes, in detail, the frequency and degree of the damage to each of the six kill categories. The higher resolution of the Degraded States output provides information which is aggregated away in the DAL process. For example, using the Degraded States distribution, the frequency of inflicting one, two, three or four crew casualties can be determined. Also, the probability of a particular kill definition in one kill category occurring simultaneously with a particular kill definition in another kill category can be calculated. For example, when making the numerical comparisons (discussed later) to the DAL metrics, it was of interest to know how probable it was to have no firepower damage, yet still have crew and/or communications damage.

The remainder of the results involve comparisons between the two approaches. Since the DS full probability distribution cannot be compared to the DAL LOF values, each individual kill definition and its associated probability were extracted from this distribution (see Appendix D). There were two reasons for displaying the DS output in this manner. First, the kill definition probabilities clearly illustrate the detailed data on vehicle damage available with the full distribution of degraded states. Second, it allows for numerical comparisons in magnitude between the two methodologies. In the following sets of DS results, the DS probabilities were aggregated in one of two ways to allow for comparison with the DAL LOF values. Either, the kill definition probabilities were summed within each of the six kill categories, referred to as "hardware only" aggregations, or the kill category probabilities were aggregated in order to include those components which are lumped into the DAL M, F and M/F LOF values. Table 7 identifies these two DS aggregations.

**TABLE 7. Aggregated DS Probabilities**

**Hardware Only**

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$$P(M) = P(M1) + P(M2) + P(M3)$$

$$P(F) = P(F1) + P(F2) + \dots + P(F17)$$

$$P(A) = P(A1) + P(A2) + P(A3)$$

$$P(C) = P(C1) + P(C2) + P(C3) + P(C4)$$

$$P(X) = P(X1) + P(X2) + P(X3) + P(X4) + P(X5)$$

$$P(K) = P(K1) + P(K2) + P(K3)$$

$$K\text{-Kill} = P(K4)$$

$$M \text{ or } F = P(M) \text{ or } P(F)$$

**Aggregated**

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$$M = P(M) \text{ or } P(C) \text{ or } P(X) \text{ or } P(K)$$

$$F = P(F) \text{ or } P(A) \text{ or } P(C) \text{ or } P(X) \text{ or } P(K)$$

$$K\text{-Kill} = P(K4)$$

$$M \text{ or } F = P(M) \text{ or } P(F) \text{ or } P(A) \text{ or } P(C) \text{ or } P(X) \text{ or } P(K)$$

**2. Individual Cell Plots**

The highest resolution form of the "SQuASHed" output was used to generate individual cell plots for both the DAL LOFs (M, F, K, M/F) and DS probabilities. This output contained the PDS or DAL LOFs for each of the ten iterations in each four inch cell. The number of cells output depended on the azimuth of fire. The PDS/LOF values used for these individual cell plots were not weighted.

The cell-by-cell output was reformatted so that the BRL program, "cell-Fb", could be used to generate the individual cell probability plots. For the DAL, the average (over the ten iterations) LOF values for M, F, K and M/F were read for each cell. For the Degraded States, the vehicle degraded states and their

probabilities were read, but certain calculations had to be performed before the plots could be made. The probability of a particular kill definition was calculated by summing the number of times that kill definition was satisfied in a given cell and dividing by the number of iterations. For a Degraded States kill category, the probabilities of all the kill definitions in that kill category, except the "no damage" state, were summed; therefore, the M or F Degraded States probability represents the union of the two kill category probabilities. It is important to note here that the Degraded States cell plots do not contain the damage to other kill categories, such as communications, crew and acquisition, which are aggregated into the DAL LOF cell plots. The Degraded States K-kill value was the probability of kill definition K4 for each cell. Finally, the probabilities or LOF values were formatted for the "cell-Fb" program which generated the plots. The plots are color coded on a scale of 0 (white) to 1 (red).

Individual cell plots were generated for Degraded States kill definitions and kill categories, and DAL LOF values. All of the plots are for the larger KE penetrator (P1) at a range of 1 kilometer for a fully exposed target. These plots are contained in Appendix B of this report.

a. **Degraded States Kill Definitions.** The individual kill definition cell plots illustrate the amount of detail that is available from these new, improved metrics. The probability of a kill definition is depicted in each cell by color. The following kill definitions were plotted:

**TABLE 8. Kill Definitions Plotted**

M1 - Reduced speed, slight	F1 - Loss of main armament
M2 - Reduced speed, significant	F8 - Increased time to fire & Reduced delivery accuracy
M3 - Total immobilization	F9 - Unable to fire on the move & Increased time to fire & Reduced delivery accuracy
C1 - One crew casualty	F17 - Total loss of firepower
C2 - Two crew casualties	
C3 - Three crew casualties	
C4 - Four crew casualties	

In the mobility kill category, Figure B-1 shows that when kill definition M1 is satisfied, components in the lower portions of the vehicle are killed. In a couple of the higher probability cells, roadwheels were the most frequently killed components. The kill definition M2 plot, also in Figure B-1, shows a concentration in the driver's area. Analysis of various cells proved that the loss of driver's controls is the main reason for satisfying this kill definition. Even the cells in the upper portion of the vehicle reflect killed cables which ultimately eliminate some driver's control. A large concentration of high probability cells exists in the lower half of the vehicle for kill definition M3 as shown in Figure B-2. The loss of systems such as engine, transmission, track and fuel control was the cause.

In the firepower kill category, kill definitions F1, F17, F8 and F9 were plotted. As seen in Figure B-3, kill definition F1 showed a high probability concentration near the center of the vehicle which represented losing the main gun, all gunner's sights and/or all ability to traverse or elevate the turret. The majority of the occurrences of kill definition F17 are due to catastrophic events; therefore, Figure B-3 mainly shows hits to the fuel and ammunition compartments. As seen in Table 8, kill definition F9 included the vehicle's inability to fire on the move and kill definition F8 did not. This equates to losing the main hydraulic power (traverse or elevation), which will achieve kill definition F8, or losing the main and auxiliary hydraulic power (traverse or elevation) which equates to achieving kill definition F9. As Figure B-4 shows, the probability of losing the main and not the auxiliary power (i.e. kill definition F8) was small.

In the crew kill category, Figures B-5 and B-6 show where and how frequently, one or two and three or four crew casualties, respectively, occurred. The location helps determine which particular crew member(s) was killed. Loss of four crew members is due mainly to catastrophic events; therefore, the C4 plot in Figure B-6 depicted hits to the fuel and ammunition compartments. Figure B-7, the plot for all crew casualties, shows the summation of the probabilities of kill definitions C1 through C4 in each cell.

This resolution of vehicle damage can not be obtained with DAL LOF plots. For this reason, there was no comparison to the DAL at this level. These individual cell plots show the location and frequency of kill definitions and allow particular component losses to be associated with specific loss of capability.

**b. Comparison of Degraded States and DAL.** To compare the two methodologies using cell plots, the kill definition probabilities were summed over the mobility and firepower kill categories, respectively. This comparison was not completely appropriate for two reasons. First, the Degraded States kill category probabilities did not include components from other kill categories such as acquisition, crew and communications whereas the DAL plots represented LOF values due to all killed components. The second reason was that, numerically, probabilities were being compared to LOF values.

The comparisons revealed similar plots for both mobility and firepower as seen in Figures B-8 and B-9, respectively. Recall, no conclusions can be drawn numerically since the values (represented by colors) for each cell had different meanings for the two methodologies. Comparing the location of the colored areas indicates that both methodologies considered the same group of components as critical to the function of the vehicle in terms of mobility and firepower. Also, those colored areas that were not in common revealed components which were treated differently by the two methodologies. For example, when killing only the batteries, the DAL reported total loss of function in terms of mobility whereas the degraded states approach, which follows the VMB criticality analysis, reports no mobility damage. Also, the loss of sponson and/or bow fuel tanks gave M LOF

values, but were not included in the Degraded States fault trees.

### 3. Excursions

For both methodologies, a set of excursions was performed to determine the sensitivity of the results to changes in the initial conditions. The intent of these excursions was to show that no unexpected trends occurred in the results. This was accomplished by comparing the results across the various parameters which represented the initial conditions (range, dispersion, threat, exposure and azimuth). For the DAL, the kill criterion compared was the M/F LOF value. For the DS methodology, the probability of some mobility kill definition (other than M0) or some firepower kill definition (other than F0) was used. This probability was calculated from the probability distribution of vehicle degraded states. The results of sensitivity comparisons are displayed in bar charts contained in Appendix C.

a. **Range Sensitivities.** There were two range sensitivity excursions performed. One kept the delivery error constant across the six ranges and the other varied the error according to the range. The error selected for each range was based on a "rule of thumb"<sup>1</sup> as shown in Table 9.

**TABLE 9.** Range/Delivery Error Pairings

Range	Associated Delivery Error (sigma)
0.5 km	1 foot
1 km	2 foot
1.5 km	3 foot
2.0 km	5 foot
2.5 km	5 foot
3.0 km	10 foot

The comparisons were performed for both threats and exposures at zero and ninety degrees azimuth.

Figures C-1 through C-4 display the results of the excursions where the dispersion was held constant. As these figures show, the results decrease as the range increases (for both bullets and exposures) since residual penetration decreases. The same was true when the dispersion values were varied, as one can see from Figures C-5 through C-8. However, there was one exception; in Figure C-7, the vehicle was fully exposed and the smaller KE penetrator's results slightly increase as the range increases at zero degrees azimuth. In most armored fighting

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1. Private conversation with Cynthia Dively of the VMB.

vehicles, the front, center portion of the vehicle is the most heavily armored area; therefore, the smaller threat does not penetrate. In this excursion, the dispersion values increase with range, thus presenting target area that is not as heavily armored. In all of the range sensitivities, both methodologies show similar trends for this kill criterion.

b. **Dispersion Sensitivities.** Excursions were performed to show the sensitivity of the results to dispersion values. For both threats and exposures, the results were compared at two different ranges (1 and 3 km) and azimuths (0 and 90 degrees) for the five dispersion values (1, 2, 3, 5 and 10 foot sigmas).

The results, contained in Figures C-9 through C-16, decrease when the dispersion values increase in all cases except one. Since the aimpoint is at the center of the target, the more dispersed the threat is from the aimpoint, the less damage is inflicted. The exception is with the smaller KE penetrator for a fully exposed vehicle at zero degrees azimuth. Inspection of Figures C-11 and C-15 illustrates the opposite trend for both ranges (1 and 3 km). The explanation given in the range sensitivity excursions, where dispersion values were varied with range, also holds true for these cases. Both trends are consistent with results from previous studies involving this vehicle. The trends for both methodologies are similar for all dispersion excursions.

c. **Threat Sensitivities.** The next set of excursions illustrates the sensitivity of the results to the threat employed. The results of threats P1 and P2 were compared for two range/dispersion combinations, both exposures and all four azimuths. The range/dispersion combinations were 1 and 3 kilometers with two and ten foot sigmas, respectively. In all cases, as shown in Figures C-17 through C-20, the damage inflicted by threat P1 was more severe, as expected. The trends between the two threats' results are similar for both methodologies for this kill criterion.

d. **Exposure Sensitivities.** Next, the sensitivity of the results to exposure (either fully or hull defilade) was investigated. The same set of initial conditions for the threat excursions was used for these comparisons. Figures C-21 through C-24 show, as expected, that the larger presented area for the fully exposed vehicle results in a higher PDS/LOF in all of the comparisons. Again, the trends for each azimuth are similar for both methodologies with respect to this kill criterion.

e. **Azimuth Sensitivities.** The final set of sensitivity excursions was performed on the azimuth or view. Using the same range/dispersion combinations, the results for all threat/exposure combinations were compared across the four azimuths (0, 30, 60 and 90 degrees). In general, the lowest PDS/LOF values are observed at 0 degrees azimuth and the highest at 60 or 90 degrees azimuth. This is due to the armor protection afforded and the presented area for each azimuth. These results are contained in Figures C-25 through C-28. The trends across the azimuths are similar for both methodologies with respect to this kill criterion.

#### 4. Degraded States vs. DAL Comparisons

Ultimately, the goal of this analysis was to make comparisons between the two methodologies. In addition, AMSAA is using the BRL data for a comparison of DAL and DS results in an adapted version of their force-level model, GROUNDWARS. GROUNDWARS, which uses the traditional DAL metrics, was adapted to also accept the DS metrics. The new model, DSWARS, was run using the BRL results for both methodologies and the outputs compared. AMSAA's analysis was completed in the third quarter FY90.<sup>5</sup>

There were two numerical comparisons of the Degraded States probabilities and the DAL LOF values. Both comparisons were made at the 1 kilometer range with a 2 foot dispersion value for both KE penetrators and exposures across all four azimuths (0, 30, 60 and 90 degrees). In the first set of comparisons, the basic and modified DAL M and F LOF values were compared to the DS "hardware only" aggregated M and probabilities (see Table 7). The DAL was modified so that the contributions of crew, communications and acquisition components were not included in M and F LOF values since the DS "hardware only" aggregated probabilities for mobility and firepower do not include contributions from these components. In the second set, the DS kill category probabilities were aggregated such that mobility and firepower included the contributions from the other kill categories which are in the DAL LOF values (see Table 7). Also, the format of the comparisons was different; one was tabular and the other graphical.

Before discussing the implications of these comparisons, the difference in the numerical calculations of both methodologies will be discussed. The numerical comparison of the two was an apples/oranges type of comparison. However, since the DAL LOF values have been used incorrectly as probabilities for years, it was of interest to compare magnitudes. These calculations are the same once the results of each cell have been determined. The difference comes when calculating the DS probabilities and DAL LOF values for each cell. The DS calculation counts the number of times a kill definition is satisfied and divides by the number of iterations (i.e. ten). The DAL calculation involves combining the various DAL LOF values for the killed components (via the survivor rule) and taking the average LOF value over the ten iterations. It is important to note that the closer the DAL LOF value is to 1.00 for a given iteration, numerically, the closer the two calculations are to each other since achieving a LOF value of 1.00 is equivalent to satisfying a kill definition.

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5. Gary R. Comstock, "The Degraded States Weapon Analysis Research Simulation (DSWARS): An Investigation of the Degraded States Vulnerability Methodology in a Combat Simulation", US Army Materiel Systems Analysis Activity, DRAFT, (Unclassified).

a. **Modified DAL Comparisons.** The first set of comparisons matched the Degraded States, by kill category, to the basic DAL LOF values for M, F and K. Since the DAL lumped crew, communications and acquisition into the M and F LOF values and DS provided these probabilities separately, additional DAL M and F LOF values, which excluded the crew, communications and acquisition components' contributions, were calculated and then compared. The DAL LOF values, which do not include the crew, communications and acquisition contributions, will be called the modified DAL LOF values. The probability of each kill definition was extracted from the full probability distribution and reported by kill category. The sum of the kill definition probabilities for the mobility and firepower kill categories was compared to the DAL M and F LOF values, respectively. These comparisons are contained in Appendix D.

Some explanation is required for the format of the tables in Appendix D. The top of the table shows the initial conditions for that set of results. A verbal description of the realized kill definitions and their associated probabilities are listed by kill category and are read from top to bottom. Within a kill category, if more than one individual kill definition occurred simultaneously, then the verbal descriptions are read sequentially with the associated probability found next to the last verbal entry. The kill definition probabilities are summed for each kill category and compared to the DAL LOF values. This procedure is consistent with the DAL's intended purpose of capturing both those missions that cannot be executed at all and those that can be done "less well".

There were three different cases seen in these comparisons. The first case has the basic DAL LOF value larger than the DS probability, but upon removing the contributions of the crew, communications and acquisition components, the DAL LOF value is smaller than the DS probability. In the second case, the DS probability was larger than the basic and modified DAL LOF values. The third case has both the basic and modified DAL values larger than the DS probability. Table 10 shows the percent differences between the DS probabilities and both basic and modified DAL values for all three cases. The term "hardware only" means the DS mobility and firepower probabilities are summations of probabilities of kill definitions in their respective kill categories only. The differences are reported for mobility and firepower separately. The cases refer to the 16 sets of initial conditions selected for these comparisons as described above. Although, in all 32 cases, no average difference is larger than 12 percent, the figures in Appendix D illustrate that the DS approach provides higher resolution results which give a much fuller assessment of the damage to the vehicle.

**TABLE 10. Numerical Differences Between DS (Hardware Only) and DAL**

Mobility Differences

Case	Basic DAL vs. DS		Mod DAL vs. DS	
	range	average	range	average
1) Basic DAL > DS > Mod DAL (12 cases)	1-21%	10%	0-13%	5%
2) DS > Basic DAL > Mod DAL (3 cases)	2-4%	3%	6-15%	12%
3) Basic DAL > Mod DAL > DS (1 case)	3%	3%	0%	0%

Firepower Differences

Case	Basic DAL vs. DS		Mod DAL vs. DS	
	range	average	range	average
1) Basic DAL > DS > Mod DAL (7 cases)	2-12%	7%	0-1%	0.8%
2) DS > Basic DAL > Mod DAL (8 cases)	0-3%	2%	0-9%	5%
3) Basic DAL > Mod DAL > DS (1 case)	2%	2%	1%	1%

There were two reasons for the first case. The basic DAL LOF value was larger because it included contributions from the crew, communications and acquisition components which are reported separately within the Degraded States approach. The DS probability was greater than the modified DAL LOF values because of the way that calculations are performed for the two methodologies. Since, numerically, every occurrence of a kill definition is equivalent to a DAL LOF value of 1.00, components which gave DAL LOF values less than 1.00 and satisfied a kill definition, caused the DAL calculations to be less than the DS calculation. This is true for both the basic and modified DAL LOF values, but it's effect on the basic DAL LOF comparisons is overcome by the contributions of the crew, communication and acquisition components.

For the mobility kill category, this case can be seen in the following figures: D-1, D-2, D-4, D-5, D-6, D-7, D-8, D-12, D-13, D-14, D-15 and D-16. Kill definitions M1 and M2 components yielded DAL LOF values ranging from 0.20 to 0.50 and 0.65 to 0.87, respectively. The higher the DS probability of these two

kill definitions, the larger the difference between the DS probability and the modified DAL LOF value. The DAL LOF value was almost always 1.00 for kill definition M3 components.

In Figures D-5, D-6, D-7, D-8, D-14, D-15 and D-16, the firepower kill category comparisons reflect the first case. Components killed when achieving kill definitions F8 and F9 yielded DAL LOF values ranging from 0.24 to 0.43 and 0.80 to 0.96, respectively. The higher the DS probability of these two kill definitions (especially F8), the greater the difference between the DS probability and the modified DAL LOF value for firepower. Kill definition F1 and F17 components yielded a DAL LOF value of 1.00 for the firepower.

The reason for the second case was different for the two kill categories. In the mobility kill category, this case was seen in Figures D-3, D-10 and D-11. In these cases, the probability of kill definition M1 (reduced speed, slight) simultaneously occurring with the "no damage" states of the other five kill categories was high. This caused both the basic and modified DAL LOF values to lag behind the DS probability. In the firepower kill category, this case occurred in Figures D-1, D-2, D-3, D-4, D-9, D-10, D-11 and D-12. The probability of satisfying crew, communications and/or acquisition kill definitions (other than "no damage") without firepower damage was low; therefore, the numerical contributions of crew, communications and/or acquisition components to the DAL LOF value were overcome relative to the DS probability by the simultaneous satisfaction of a DS firepower kill definition. Specifically, the basic and modified DAL LOF values lagged due to the occurrences of kill definitions F8 and F9.

The third case was due to the effects of the initial DAL LOF values calculated by the main SQUASH program. The basic DAL LOF value was larger for the same reason as the first case. However, the modified DAL LOF values were larger than the DS probability because the initial LOF values, which contribute to the final DAL value, have no impact on the DS probability. In the mobility kill category, this occurred in Figure D-9. In this case, 95 percent of the mobility probability came from kill definition M3 (total immobilization) whose components contribute a 1.00 to the DAL LOF value. This caused the modified DAL LOF value and the DS probability to be equivalent except for the small contribution of the initial LOFs to the DAL. The same case occurred in Figure D-13 for the firepower kill category comparison. In this case, kill definition F9 contributed DAL LOF values close to 1.00. Along with the other two kill definitions (F1 and F17), this caused the two methodologies to be numerically equivalent in magnitude except for the contribution of the initial LOF values.

There are two general observations concerning the above comparisons which need to be mentioned. First, the vehicle degraded state combination(s) which had the most impact on these comparisons was the simultaneous occurrence of the "no damage" state for mobility or firepower and some crew, communications and/or acquisition kill definition(s). These occurrences contributed to the basic DAL LOF

value, but not to the DS probability or the modified DAL value; therefore, the higher the probability of these occurrences, the greater the basic DAL LOF value was relative to the DS probability. Using the full probability distribution of vehicle degraded states (see section IV.1) for the various sets of initial conditions, it was determined that this combination of kill definitions was more likely to occur in the mobility than the firepower kill category. The second observation is that the Degraded States approach, with its robust metrics, provided more information on the vehicle's damage assessment. The DS assessment was more informative because the kill definitions and their probabilities were calculated for six different kill categories as opposed to a LOF value for only two kill categories. Since the DS probability represented the sum of the probabilities of the kill definitions in that kill category and the DAL value represented total loss of function to the vehicle, numerical agreement could be misleading.

b. **Aggregated DS Probability Comparisons.** The second set of comparisons took the opposite approach from the first. That is, the first set extracted, from the DAL LOF value, the contributions of kill categories which were not included in the DS probability, while the second set added them to the DS probability. These comparisons were made for the same set of initial conditions as the first set. The basic DAL M, F and M/F LOF values were used. The DS probabilities aggregated the kill categories which contributed to the DAL. Table 7 illustrates how the DS aggregated M, F, K and M or F probabilities are calculated. When aggregating ammunition into the mobility and firepower probabilities, kill definition K4 was not included. Catastrophic events were implicitly included since the most severe kill definition for each kill category was selected upon the occurrence of a K-kill. In order to make these aggregations, the kill categories were assumed to be independent of one another, an assumption which is no worse than present practice with the DAL metrics. The DS probabilities denoted as "hardware only" are also described in Table 7. All comparisons were made at 1 kilometer with a 2 foot dispersion value and are contained in Appendix E.

These aggregated comparisons exhibit similar trends between the two methodologies. As seen in Figures E-1 through E-12, the aggregated DS probabilities were always larger than the DAL LOF values because of the difference in the way the two values are calculated. The comparisons of the DS "hardware only" probabilities to the DAL LOF values were discussed in the preceding section of this report. The differences in magnitude between the two methodologies were calculated for the aggregated comparisons and a summary of the percent differences are provided in Table 11 for M, F and M or F. The firepower comparisons exhibited closer agreement because the probability of simultaneously achieving the "no damage" state and some damage to another kill category was lower than for the mobility kill category; therefore, both the basic DAL LOF value and the aggregated DS probability were numerically closer to the DS "hardware only" probability for firepower. This phenomenon was more pronounced for the hull defilade results. Similar results were obtained for identical

comparisons made at ranges of 2 and 3 kilometers with dispersion values of 5 and 10 feet, respectively.

**TABLE 11.** Numerical Differences Between Aggregated DS and DAL

Aggregated DS > DAL						
Exposure	M		F		M or F	
	range	average	range	average	range	average
Fully	3-18%	12%	2-12%	7%	1-9%	6%
Defilade	3-24%	14%	2-6%	4%	2-5%	4%

### V. Summary

As the results in this report illustrate, the Degraded States methodology provides a more detailed assessment of the vehicle's damage than can be obtained using the DAL approach. The Degraded States approach assesses the damage in terms of six different vehicle kill categories (mobility, firepower, acquisition, crew, communications and ammunition). For a given damage to the vehicle, a kill definition for each of the six kill categories is determined based on the critical components killed. The probabilities of the various combinations of the kill definitions for each kill category are then calculated. The DS probability distribution explicitly shows how frequently the vehicle could complete its mission and how frequently it could do "less well" at its mission.

The Phase II results were provided to AMSAA for support in demonstrating the new metrics in force-level modeling. The DS full probability distribution, DS aggregated probabilities and DAL LOF values for all the initial condition combinations were provided to AMSAA as input to the force-level model, DSWARS. DSWARS ran both methodologies to allow for comparisons of results.

Numerically, the DS aggregated probabilities were compared with the DAL LOF values and the percent differences are shown in Table 11. To compare the numerical results of the two methodologies, the DS probability distribution was aggregated to represent the damage in terms of mobility and firepower only. Although the percent differences, on the average, are not higher than 14 percent, a more rigorous statistical analysis must be performed to determine the statistical significance of the differences between the results of the two methodologies. An analysis of variance (ANOVA) will be performed on the aggregated DS probabilities and DAL LOF values. The ANOVA will determine if the difference in the results of the two methodologies are statistically significant. A ERL technical report<sup>6</sup> will fully document this effort and is forthcoming. Finally, the ability to

make numerical comparisons between the two methodologies shows that the Degraded States approach can provide both a detailed account of the damage assessment and an aggregated set of results analogous to the traditional set.

The sensitivity comparisons of the two methodologies indicate similar trends. The Degraded States and DAL results were analyzed for their sensitivity to the various initial conditions (range, dispersion, azimuth, exposure and threat). These excursions, found in Appendix C, exhibit similar sensitivities for the two methodologies to these initial conditions for this vehicle. A quantitative statistical test of these sensitivities will be completed in the ANOVA.

A recommendation as a result of this analysis, is that, the DS methodology should be extended to other targets and classes of targets. Calculation of the more robust metrics for other classes of targets will provide a more detailed account of their vulnerability than is presently available.

Combined with AMSAA's proof that DS results can be practically implemented in force-level modeling, sufficient evidence exists for the Army to relinquish its reliance on the DAL methodology in favor of the Degraded States. This report demonstrates the feasibility of using this methodology in assessing view average vulnerability estimates.

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6. Jill H. Smith, "Quantitative Analyses of Vulnerability/Lethality Models", USA Ballistic Research Laboratory, DRAFT, (Unclassified).

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1. J. M. Abell, L. K. Roach, M. W. Starks, "Degraded States Vulnerability Analysis", USA Ballistic Research Laboratory, TR-3010, June 1989, (Unclassified).
2. Aivars Ozolins, "Stochastic High-Resolution Vulnerability Simulation for Live-Fire Programs," *The Proceedings of Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association (ADPA)*, held at the Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988, (UNCLASSIFIED).
3. Paul H. Deitz, Aivars Ozolins, "Computer Simulations of the Abrams Live-Fire Field Testing," USA Ballistic Research Laboratory, MR-3755, May 1989, (UNCLASSIFIED).
4. Joseph J. Ploskonka, Theodore M. Muehl, Cynthia J. Dively, "Criticality Analysis of the M1A1 Tank," US Army Ballistic Research Laboratory, BRL-MR-3671, June 1988, (UNCLASSIFIED).
5. Gary R. Comstock, "The Degraded States Weapon Analysis Research Simulation (DSWARS): An Investigation of the Degraded States Vulnerability Methodology in a Combat Simulation", US Army Materiel Systems Analysis Activity, DRAFT, (Unclassified).
6. Jill H. Smith, "Quantitative Analyses of Vulnerability/Lethality Models", USA Ballistic Research Laboratory, DRAFT, (Unclassified).

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**APPENDIX A**

**Degraded States Fault Trees**

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This appendix contains the fault trees developed for each of the Degraded States kill definitions used in this analysis. Components and/or systems are listed in either series or parallel. If in series, the loss of any component or system will result in the tree being cut; if in parallel, all components and/or systems must be killed in order to cut the tree. A kill definition is achieved if no uninterrupted path exists from the single asterisk to the double asterisk.

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STATE M1 - Reduced speed - slight

X

intermediate road wheels - 2

intermediate road wheels - 3

intermediate road wheels - 4

right support roller - 1

right support roller - 2

left support roller - 1

left support roller - 2

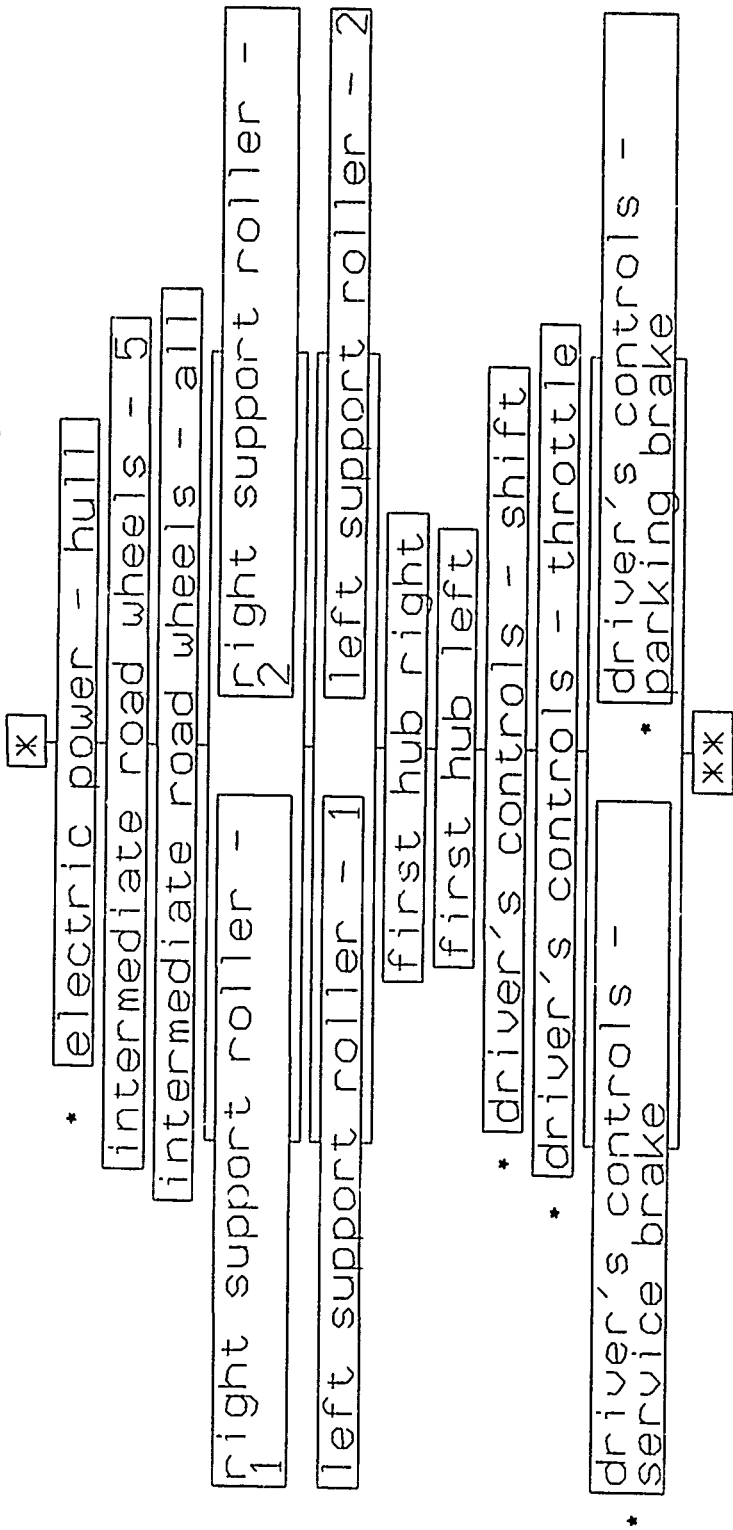
road wheel no. 7 - right

road wheel no. 7 - left

driver's controls - service brake

XX

STATE M2 - Reduced speed - significant



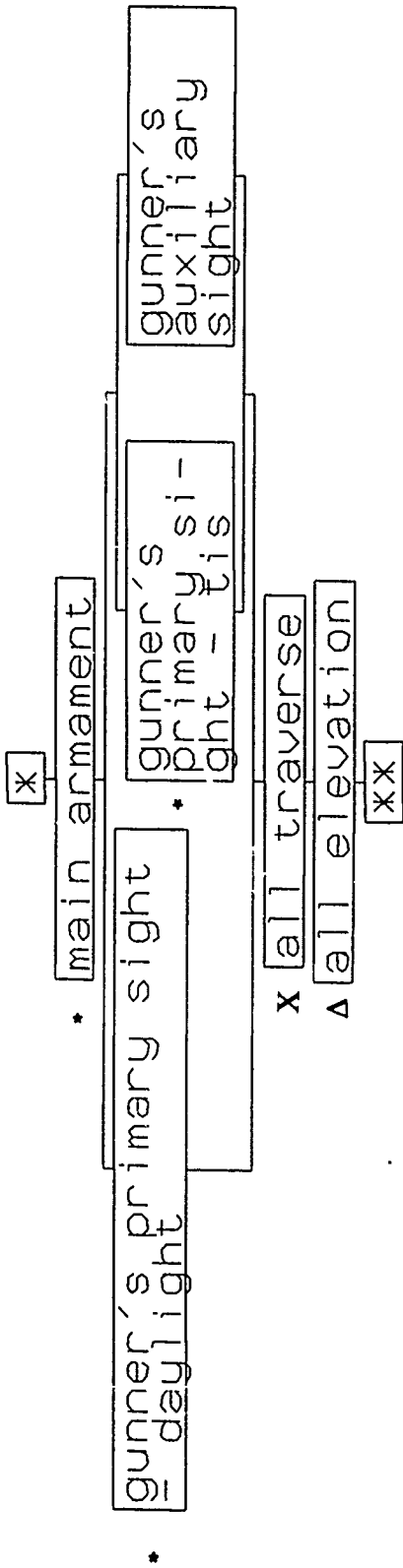
\* denotes a system of components

STATE M3 - Total immobilization

- \* [x] engine power
- \* engine power transfer
- final drive right
- final drive left
- \* fuel control system
- \* track tension/motion right
- \* track tension/motion left
- track edge
- \* driver's controls - steer
- \* vehicle electric power
- cable 2w104
- cable 2w105-9
- [xx]

\* denotes a system of components

STATE F1 - Loss of main armament

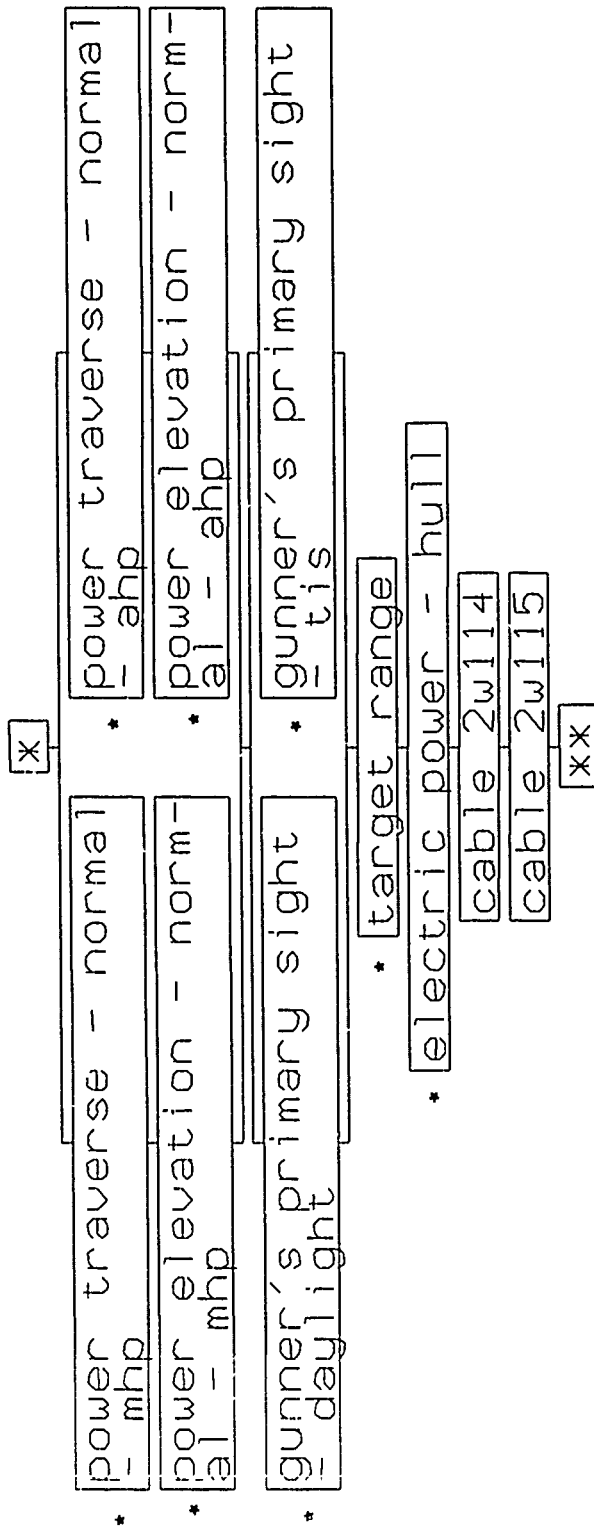


- X \* power traverse - normal - mhp
- \* power traverse - normal - ahp
- \* power traverse - emergency - mhp
- \* power traverse - emergency - ahp
- \* manual traverse

- Δ \* power elevation - normal - mph
- \* power elevation - normal - ahp
- \* power elevation - emergency - mph
- \* power elevation - emergency - ahp
- \* manual elevation

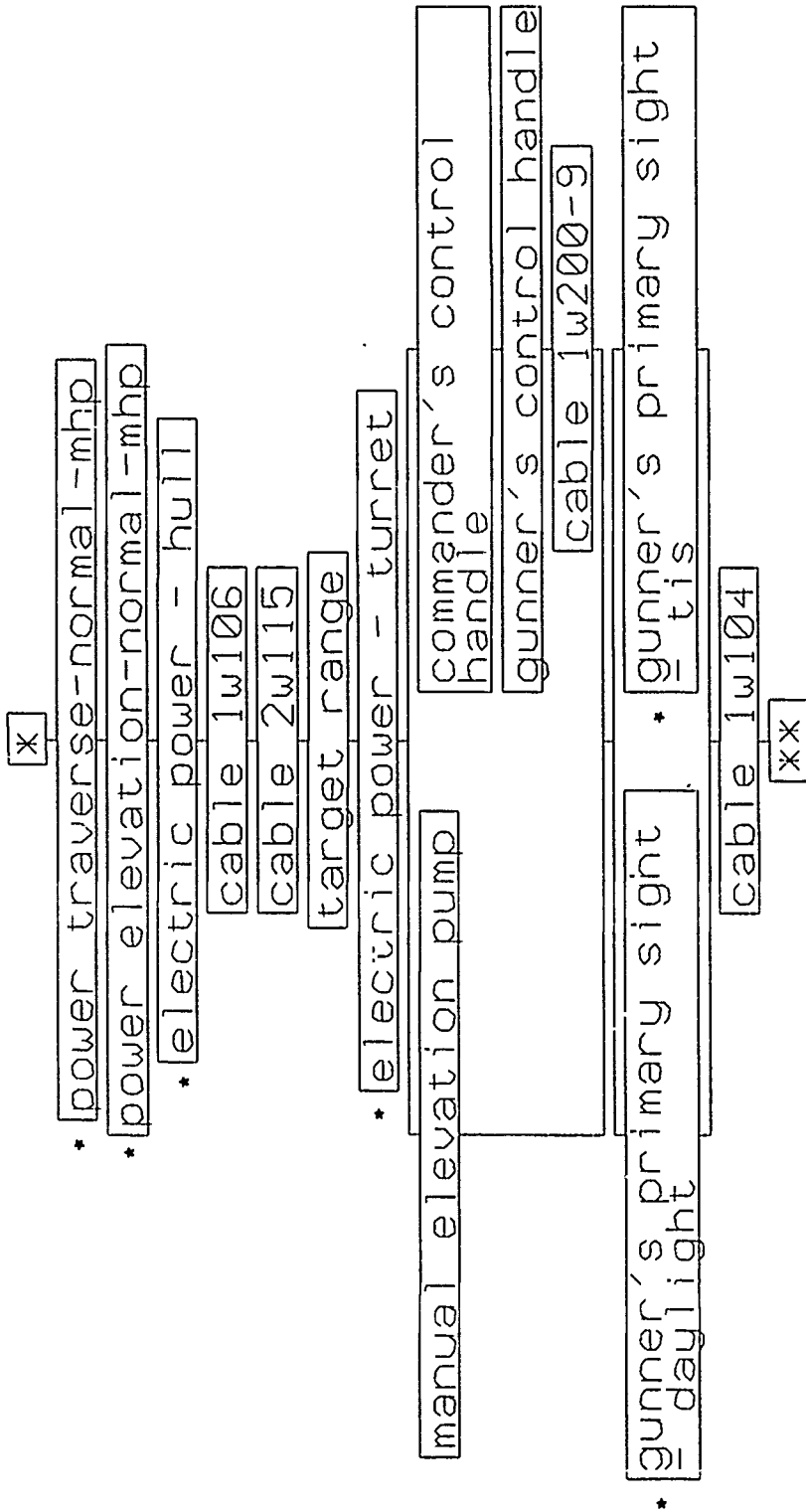
\* denotes a system of components

State F2 - Unable to fire on the move



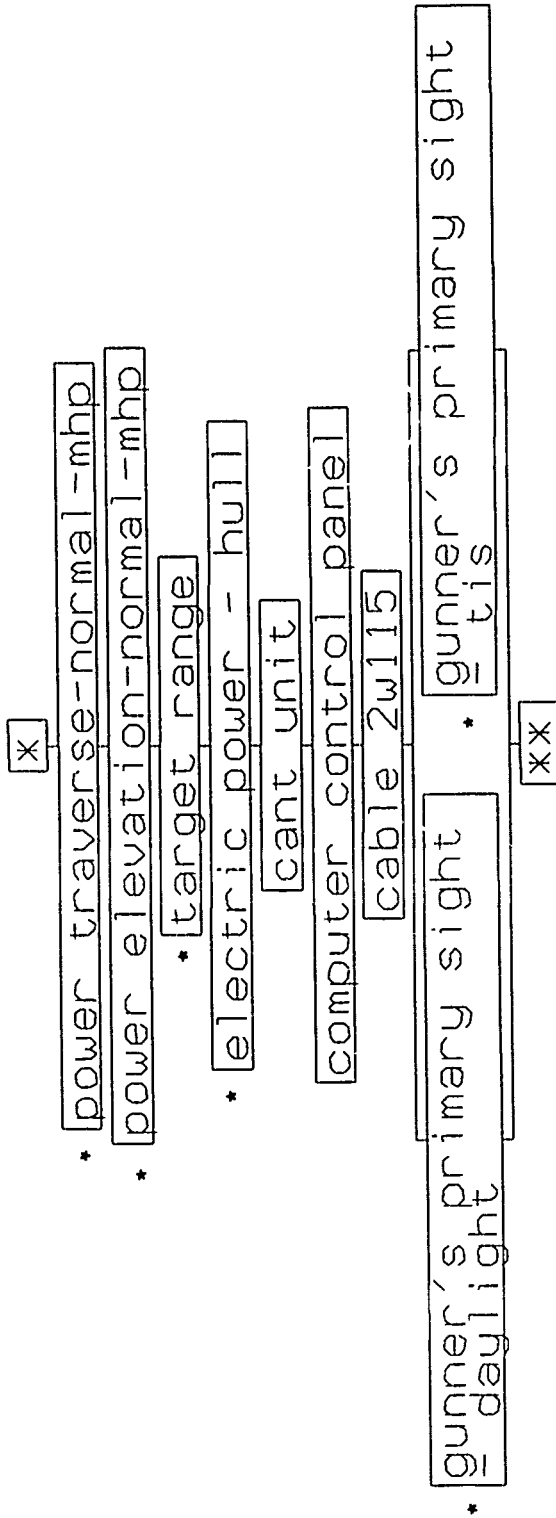
\* denotes a system of components

STATE F3 - Increased time to fire



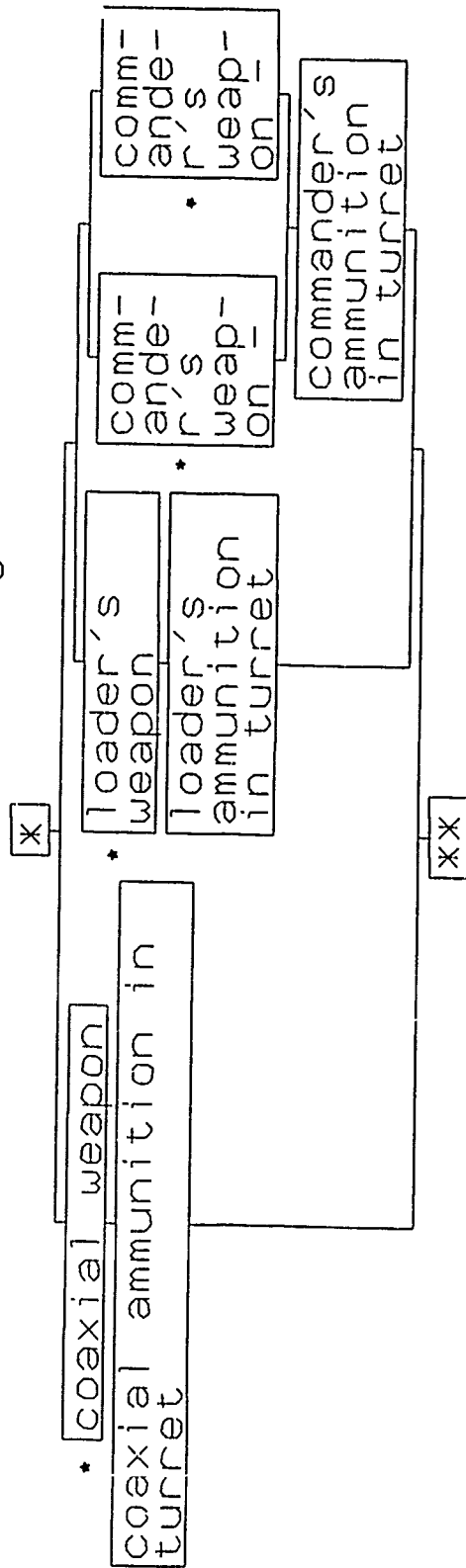
\* denotes a system of components

STATE F4 - Reduced delivery accuracy



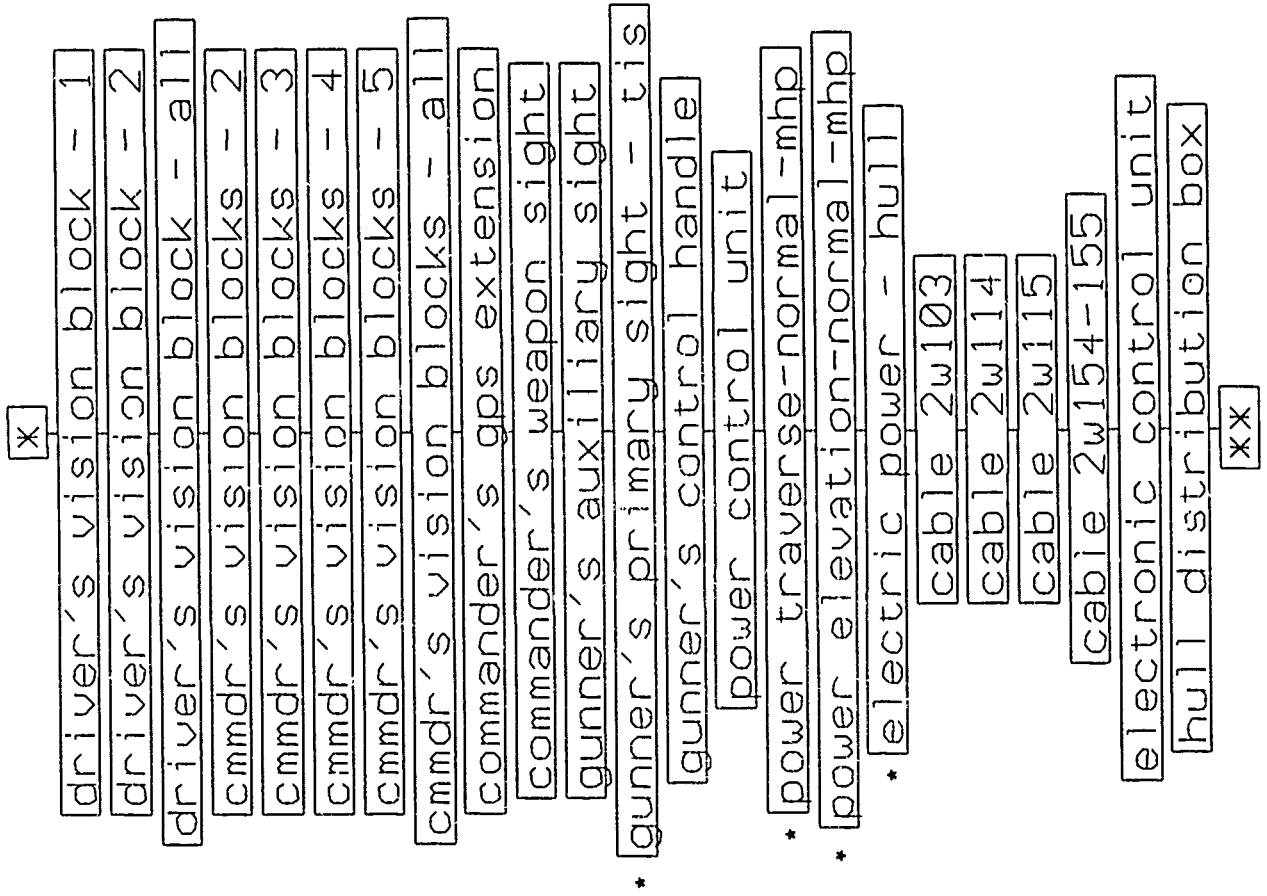
\* denotes a system of components

STATE F5 - Loss of secondary armament



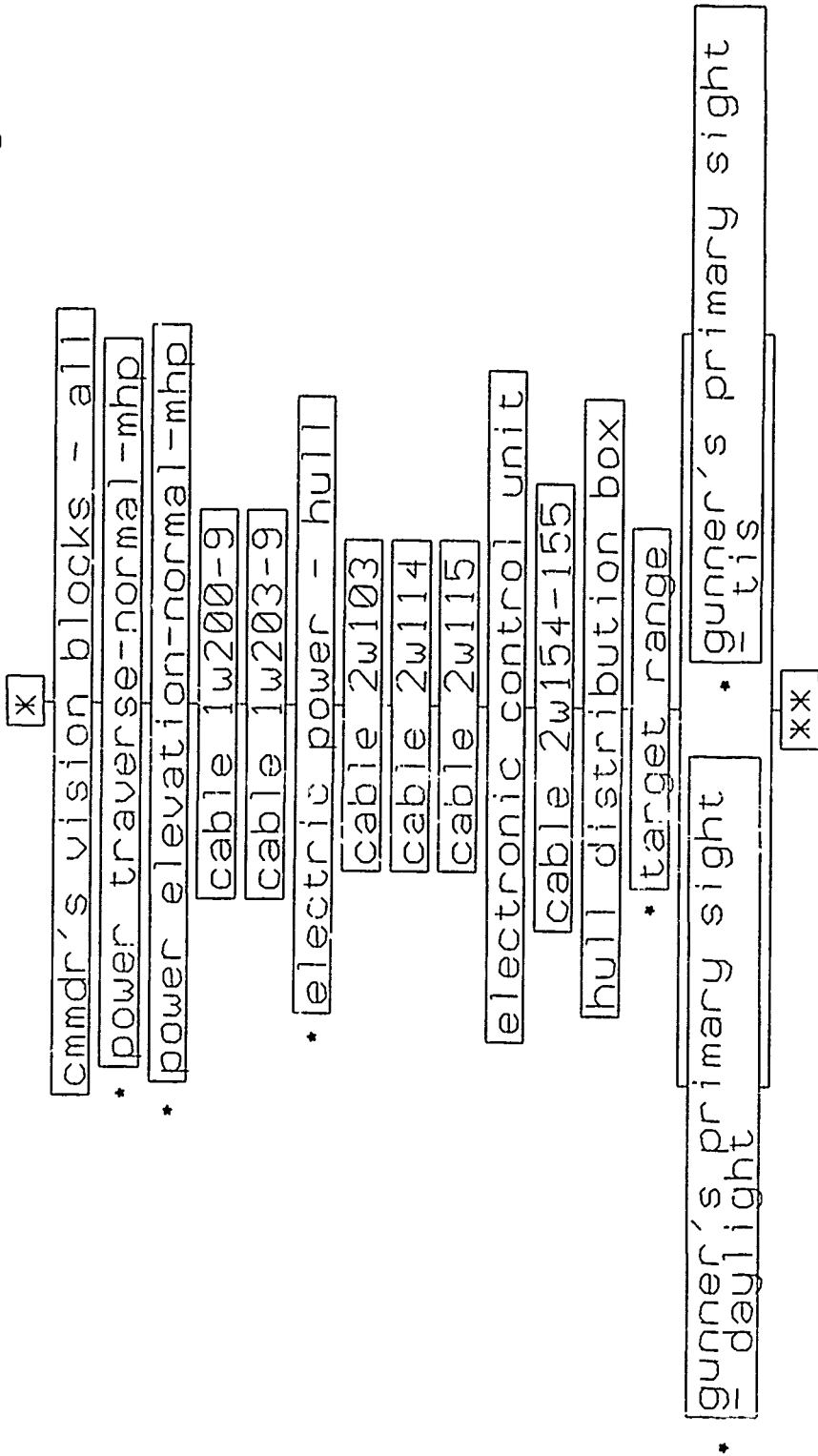
\* denotes a system of components

STATE A1 - Reduced acquisition capability



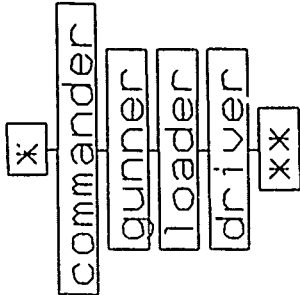
\* denotes a system of components

STATE A2 - Unable to acquire while moving

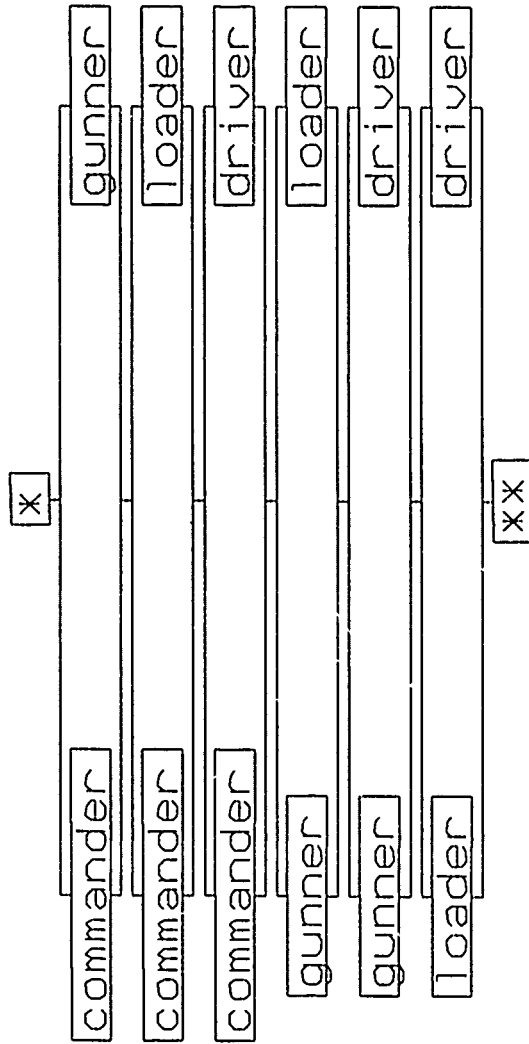


\* denotes a system of components

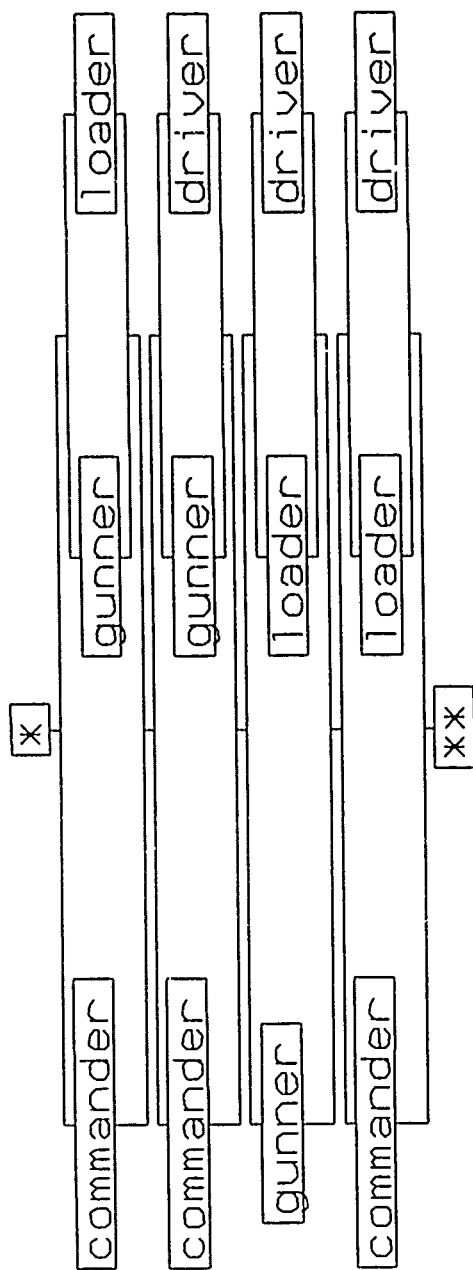
State C1 - one crew casualty



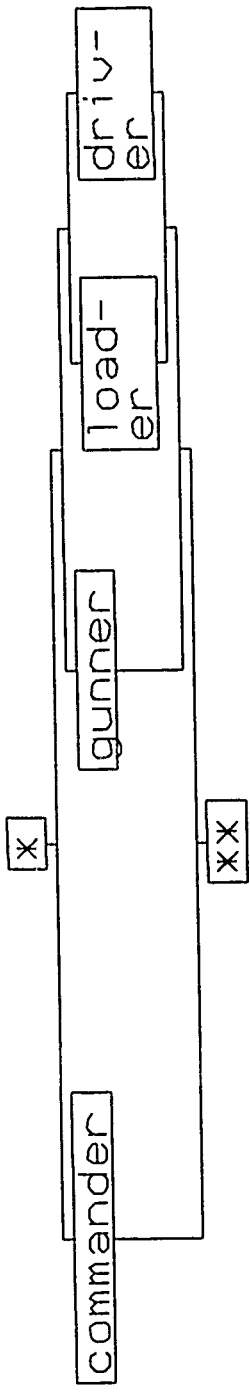
State C2 - two crew casualties



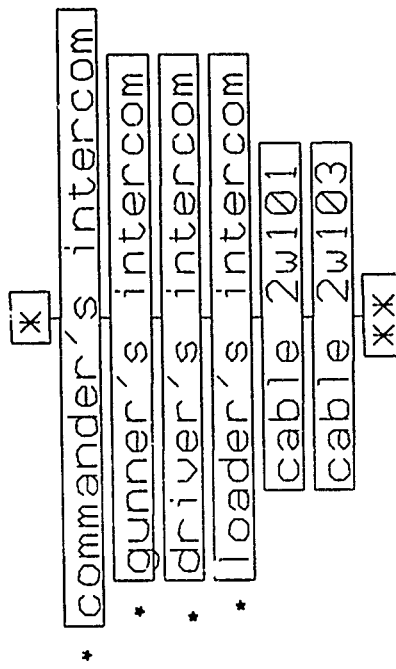
State C3 - three crew casualties



State C4 - four crew casualties

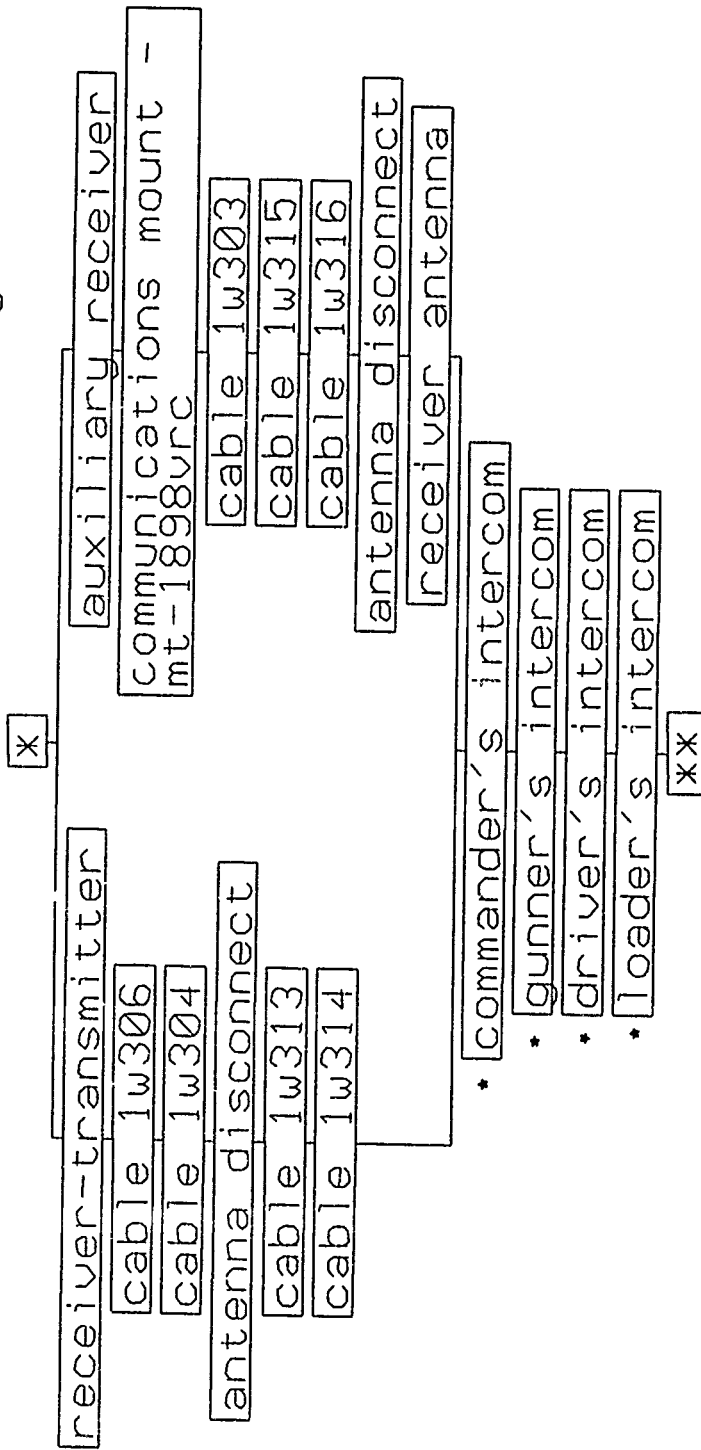


State X1 - No internal communication



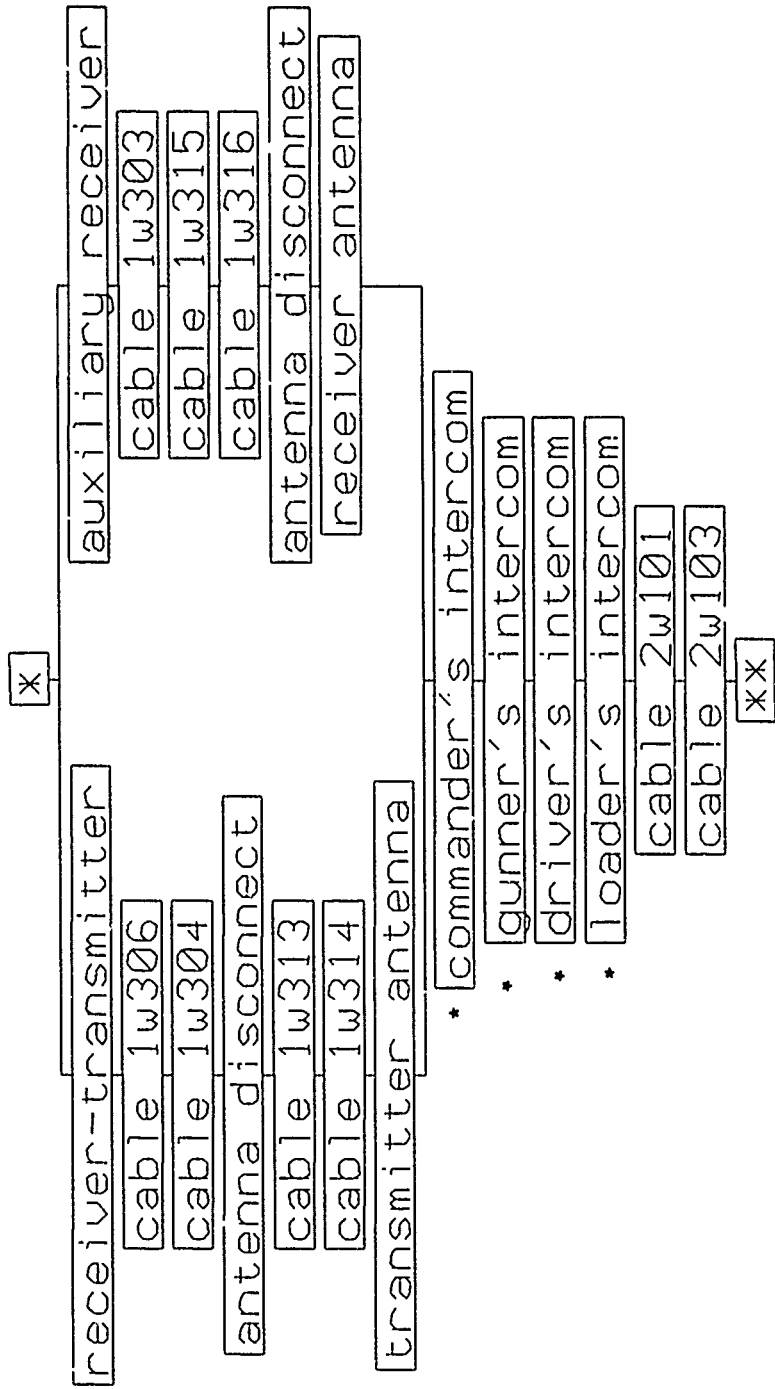
\* denotes a system of components

State X2 - No external communication beyond 300ft



\* denotes a system of components

State X3 - No external communication



\* denotes a system of components

STATE K1 - Bustle ammo lost - no K kill

x

SC propellant in bustle

SC warhead in bustle

KE propellant in bustle

xx

STATE K2 - Hull ammo lost - no K kill

x

SC propellant in hull

SC warhead in hull

KE propellant in hull

xx

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**APPENDIX B**

**Individual Cell Plots**

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The color coded cell plots are contained in this appendix. The plots show either the DS probabilities or DAL LOF values for each cell given a hit to the vehicle. These results assumed that each cell had the same probability of being hit (i.e. unweighted).

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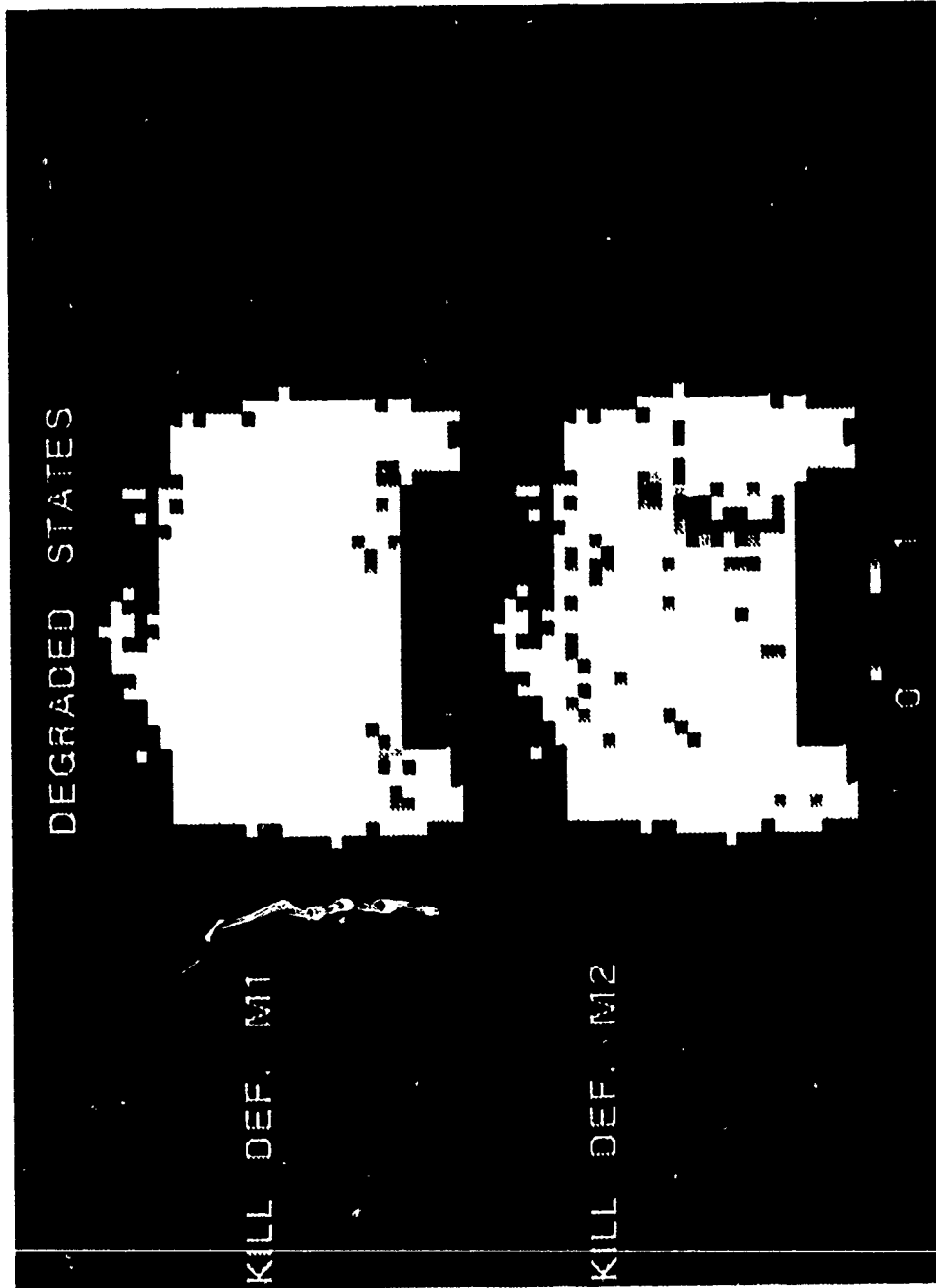


Figure B-1. Reduced speed, slight (M1) and significant (M2) cell plots

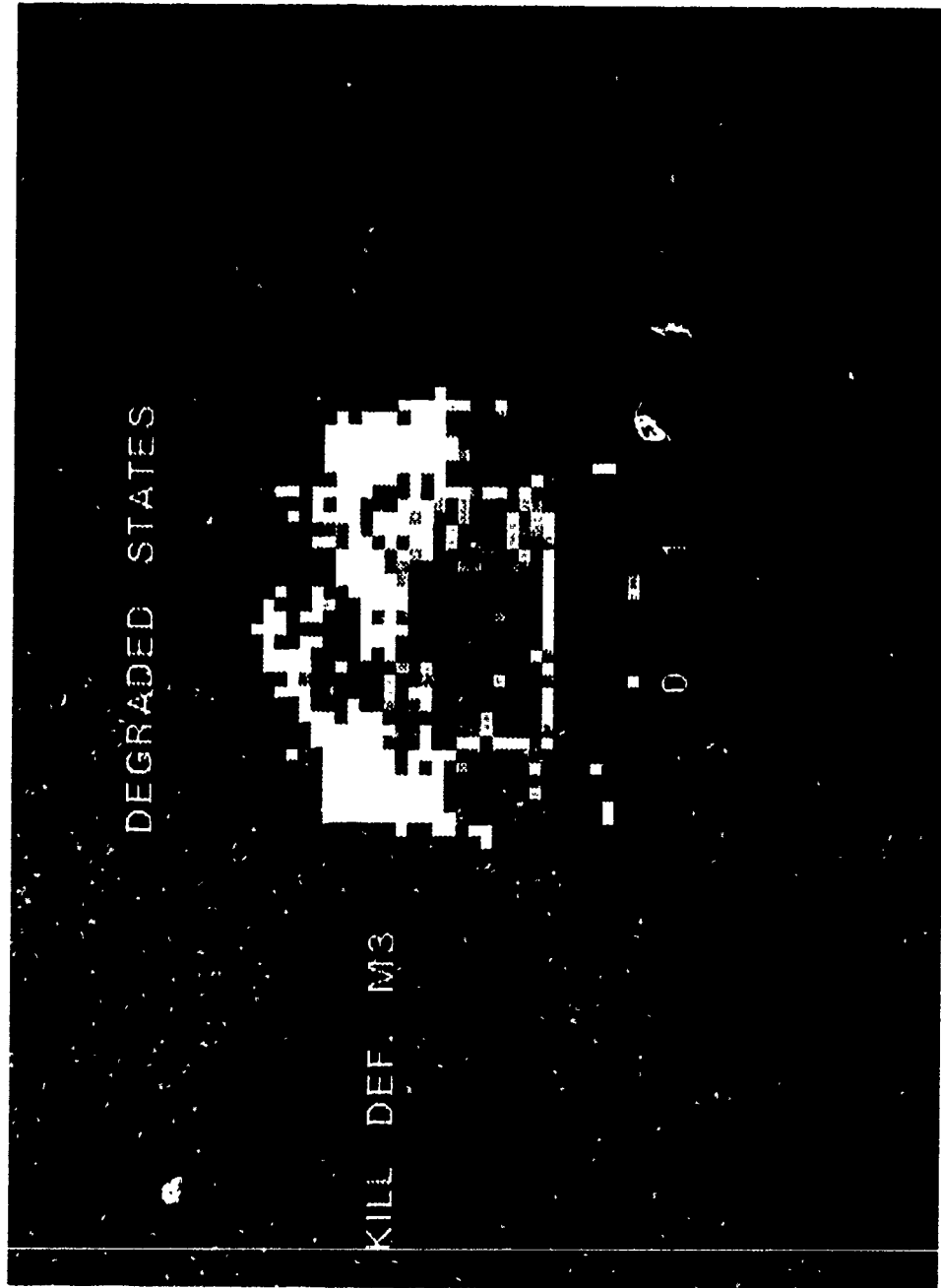


Figure B-2. Total immobilization (M3) cell plot

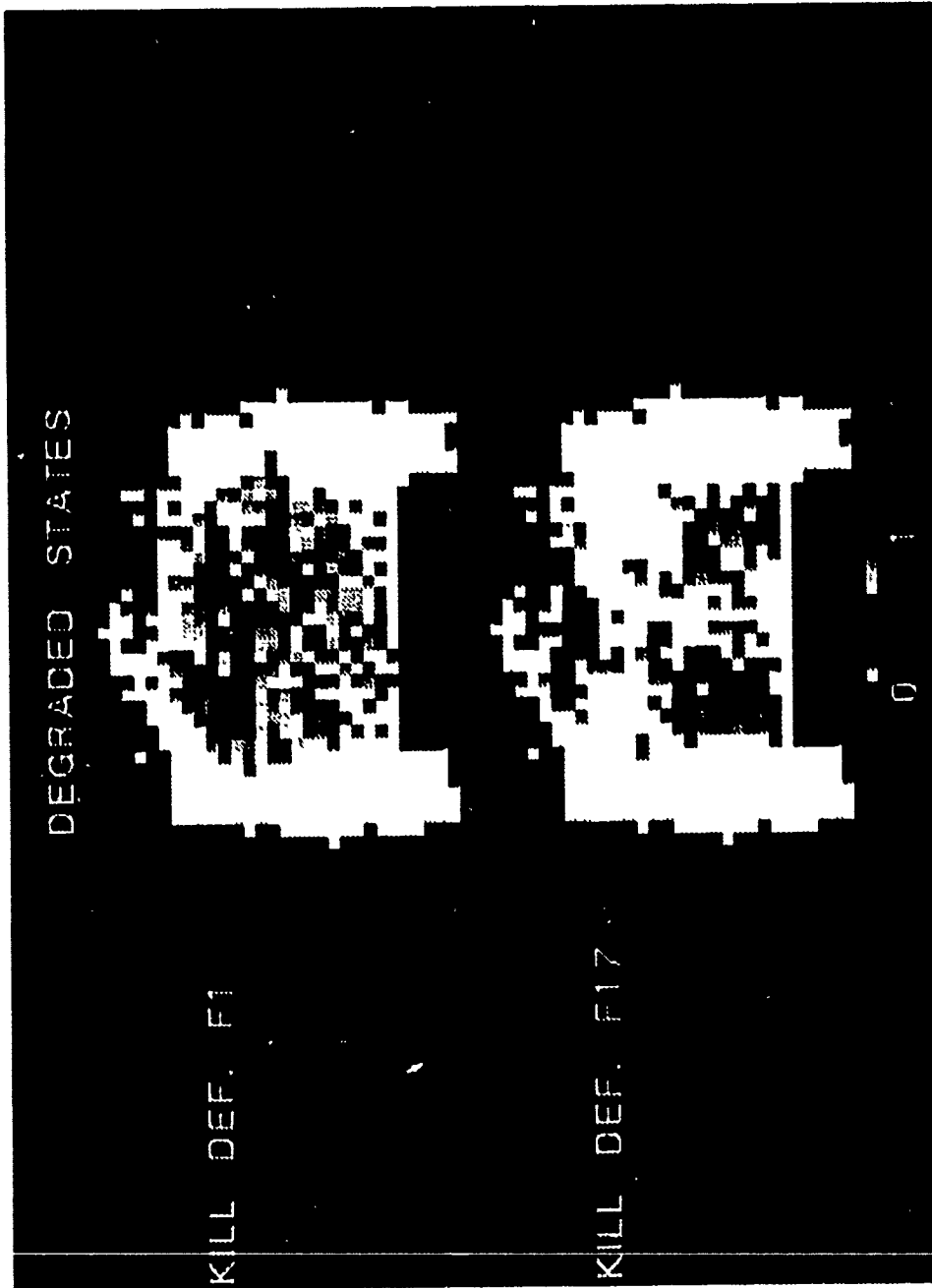


Figure B-3. Loss of main armament (F1) and loss of main armament and secondary armaments (F17) cell plots

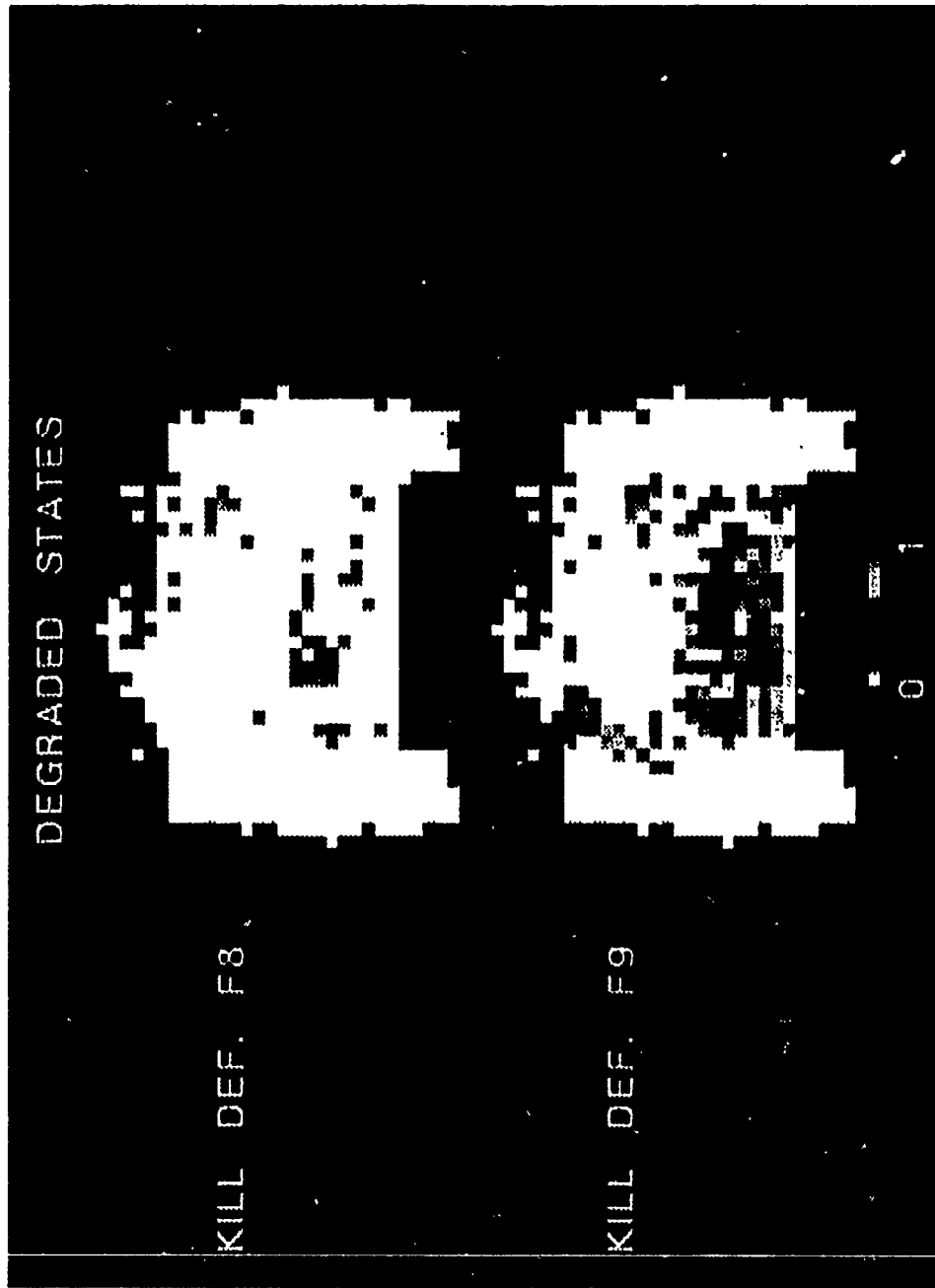


Figure B-4. Increased time to fire and reduced delivery accuracy (F8) and unable to fire on the move and increased time to fire and reduced delivery accuracy (F9) cell plots

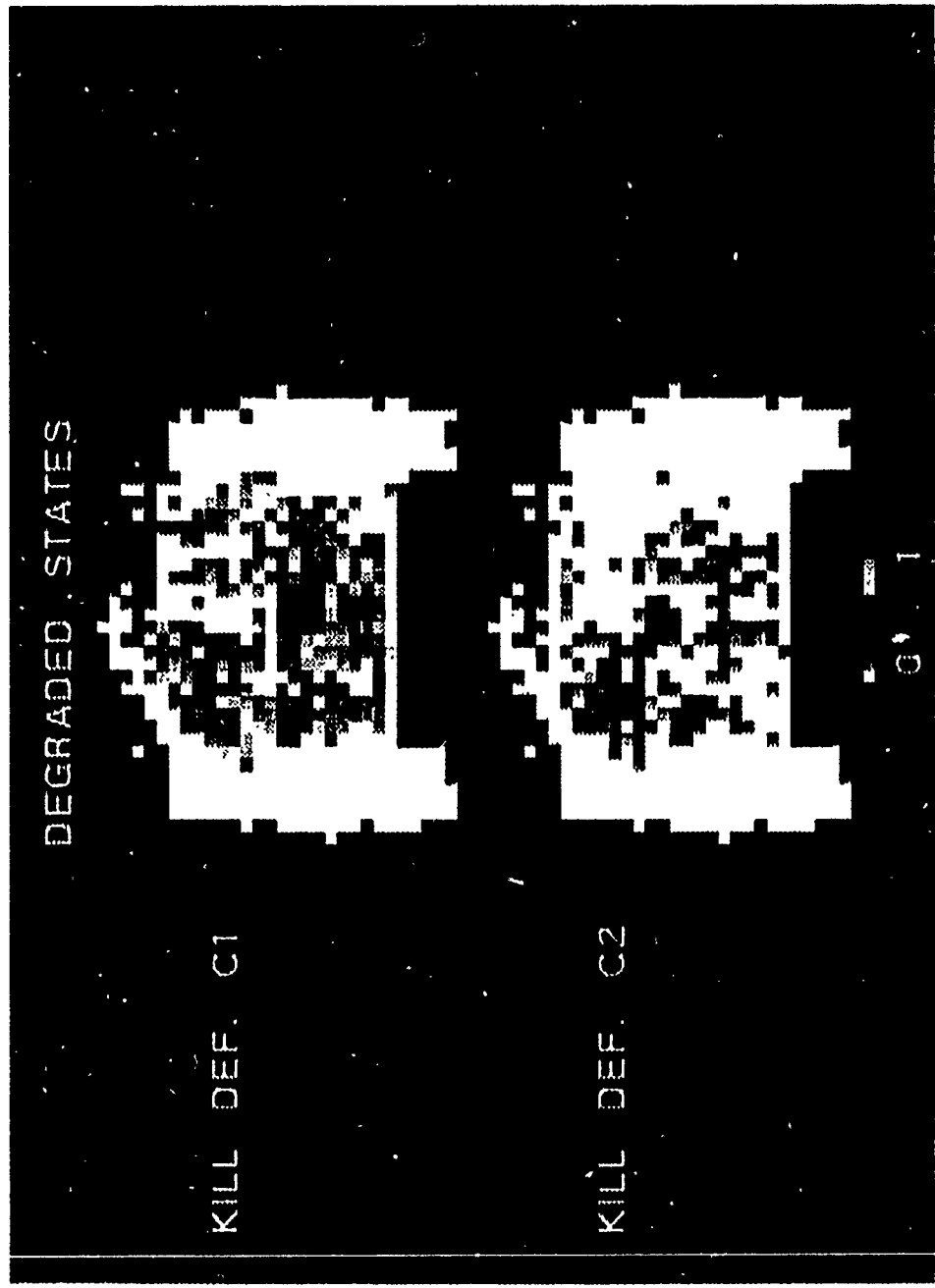


Figure B-5. One (C1) and two (C2) crew casualties cell plots

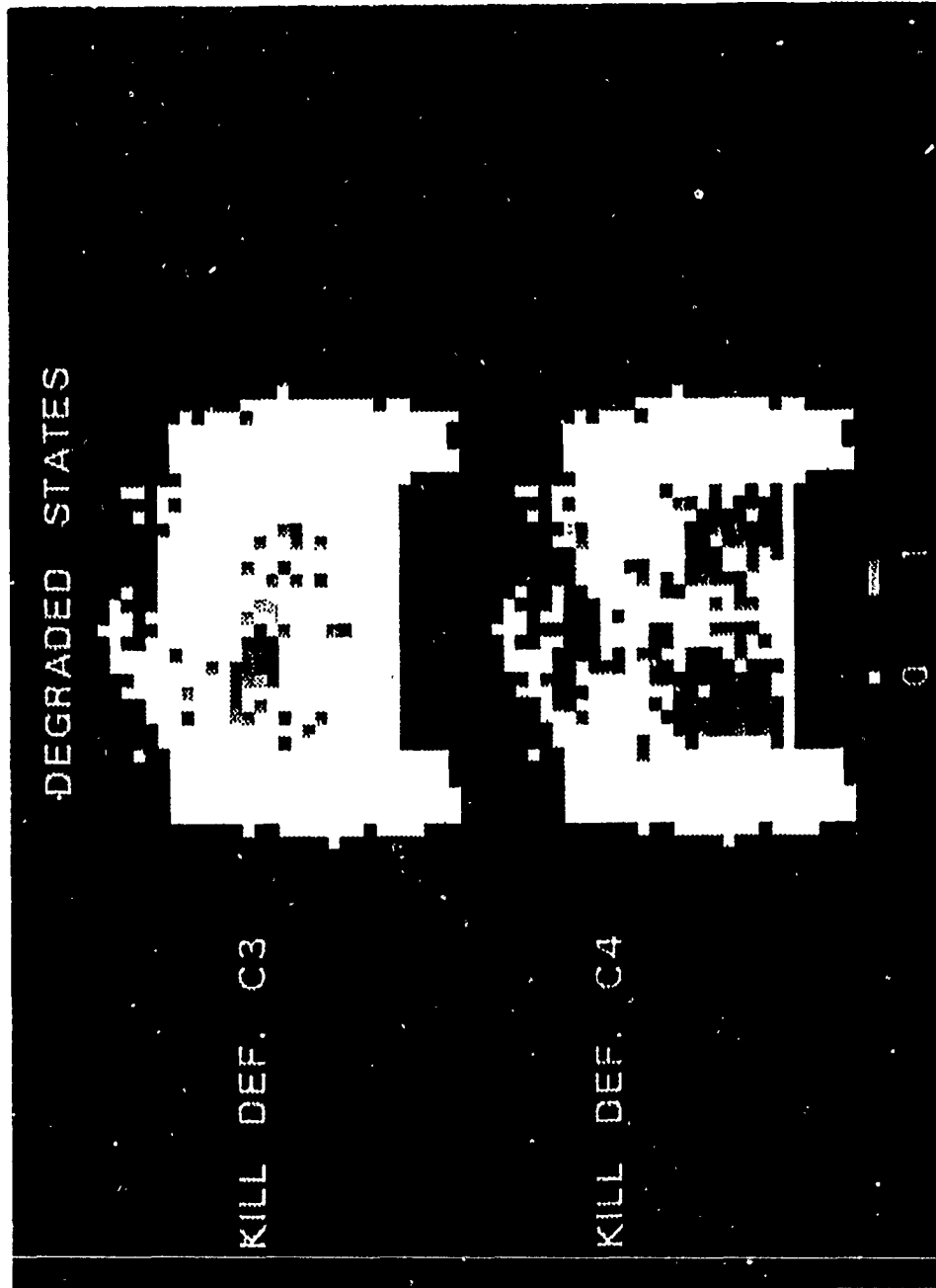


Figure B-6. Three (C3) and four (C4) crew casualties cell plots

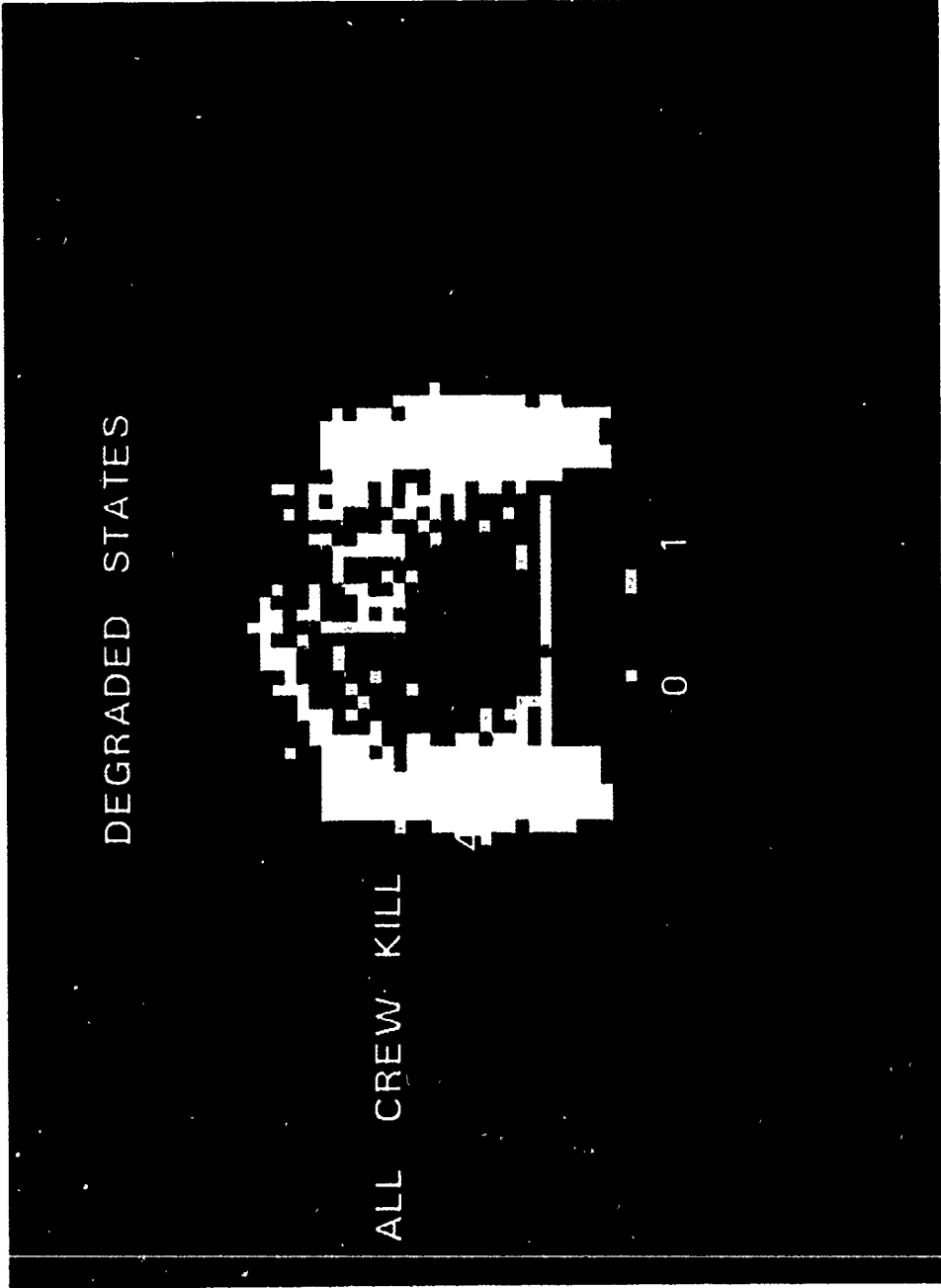


Figure B-7. All crew casualties cell plot

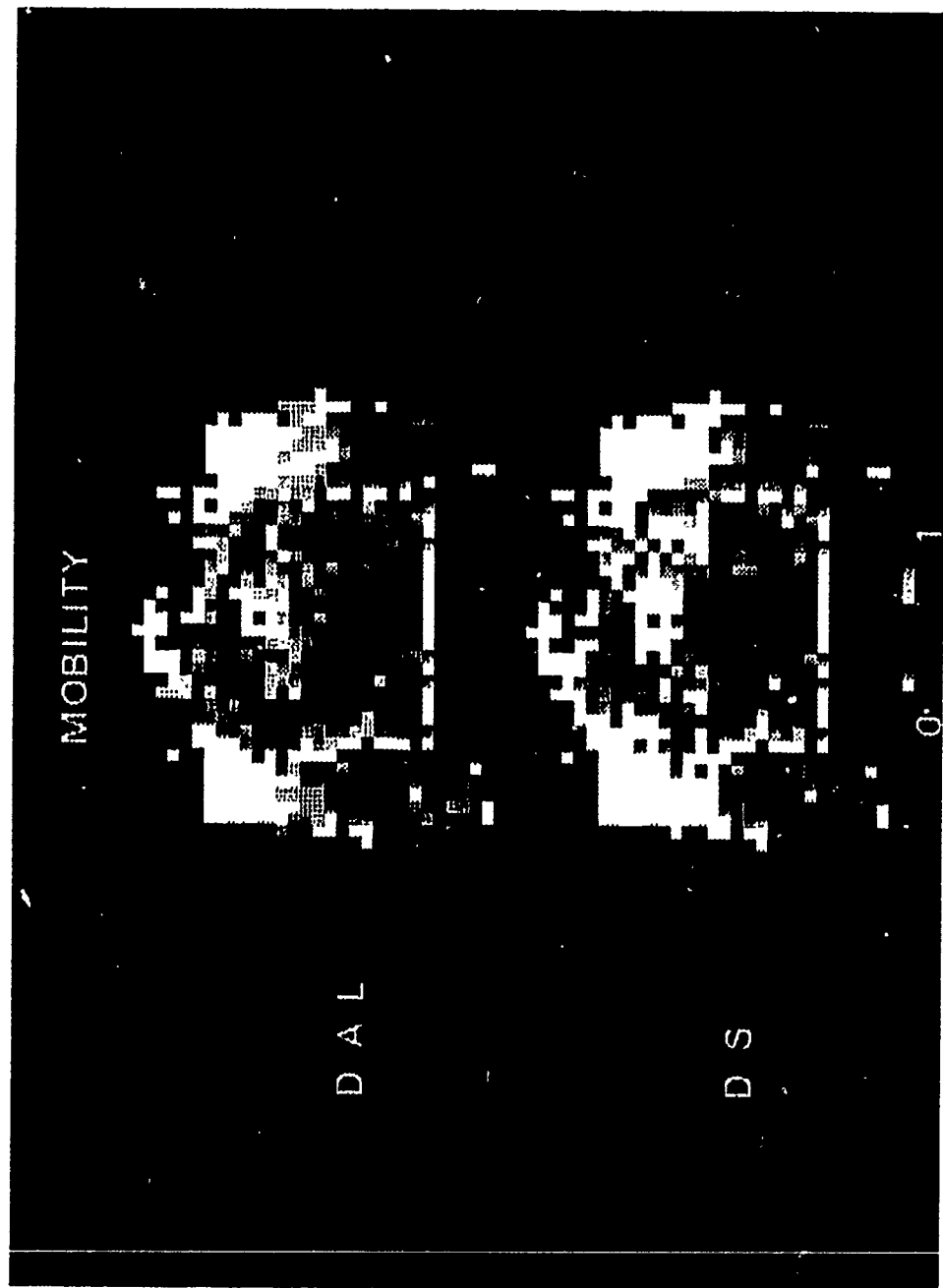


Figure B-8. DAL vs. DS mobility comparison

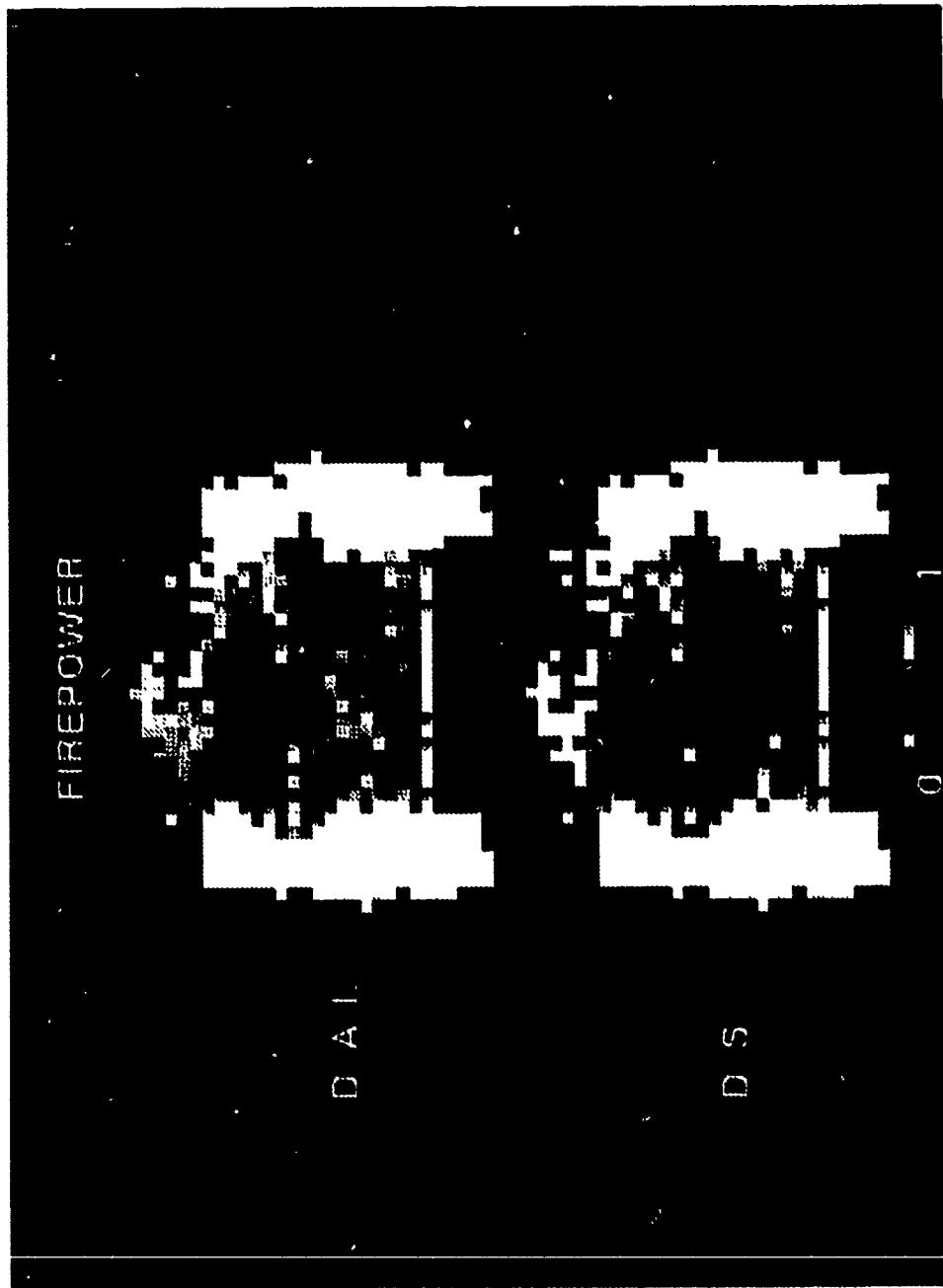


Figure B-9. DAL vs. DS firepower comparison



Figure B-10. DAL vs. DS mobility or firepower comparison

**APPENDIX C**

**Sensitivity Excursions**

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The following bar charts show the sensitivity of the two methodologies (DAL and DS) to range, dispersion, exposure, threat and azimuth. The DAL LOF values given a hit are the traditional M/F metrics. The DS values represent the probability of some kill definition (other than the "no damage" state) from either the mobility or firepower kill categories given a hit to the vehicle.

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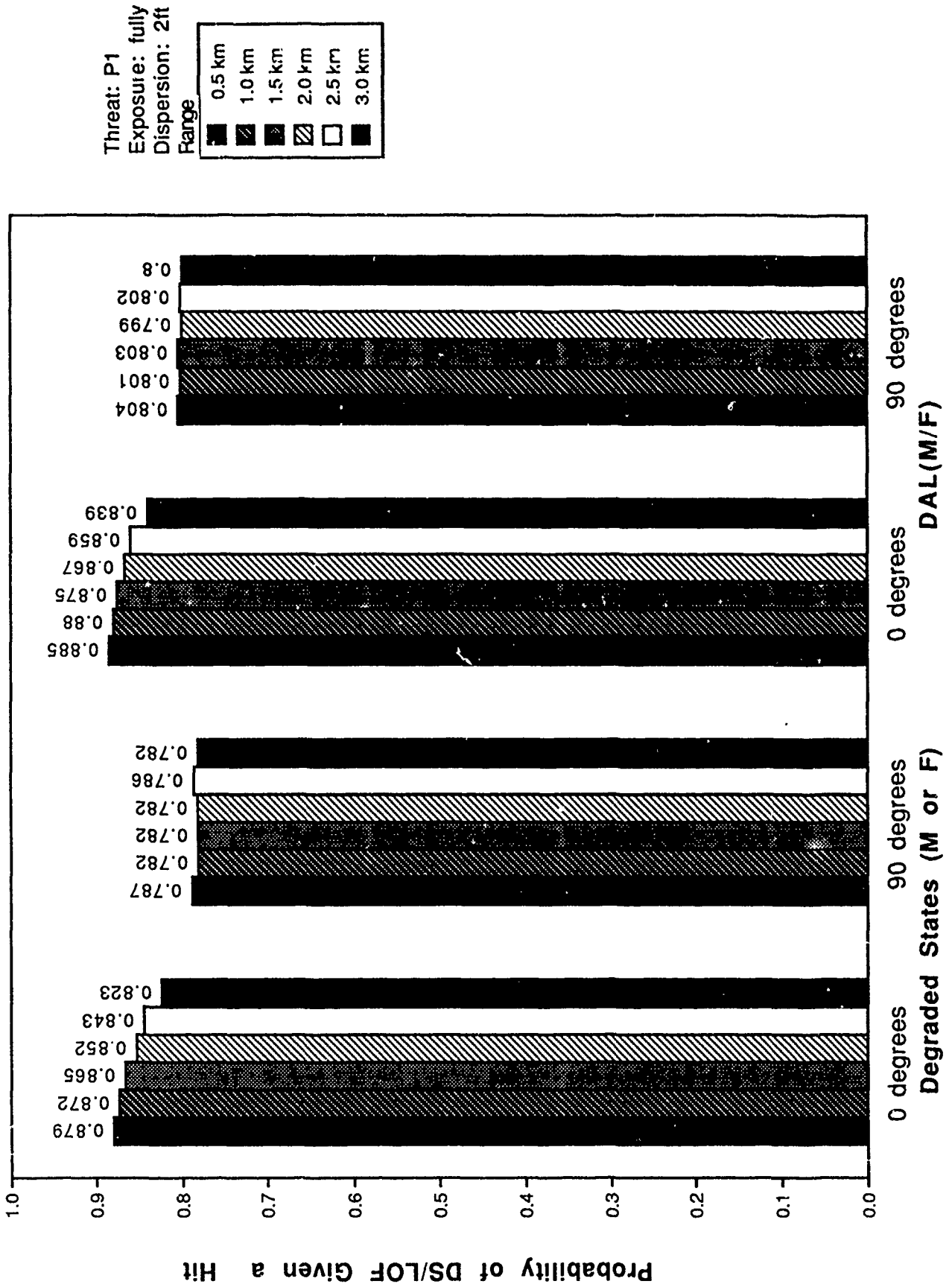


Figure C-1. Degraded States and DAL Range Sensitivity

Threat: P1  
 Exposure: defilade  
 Dispersion: 2ft  
 Range

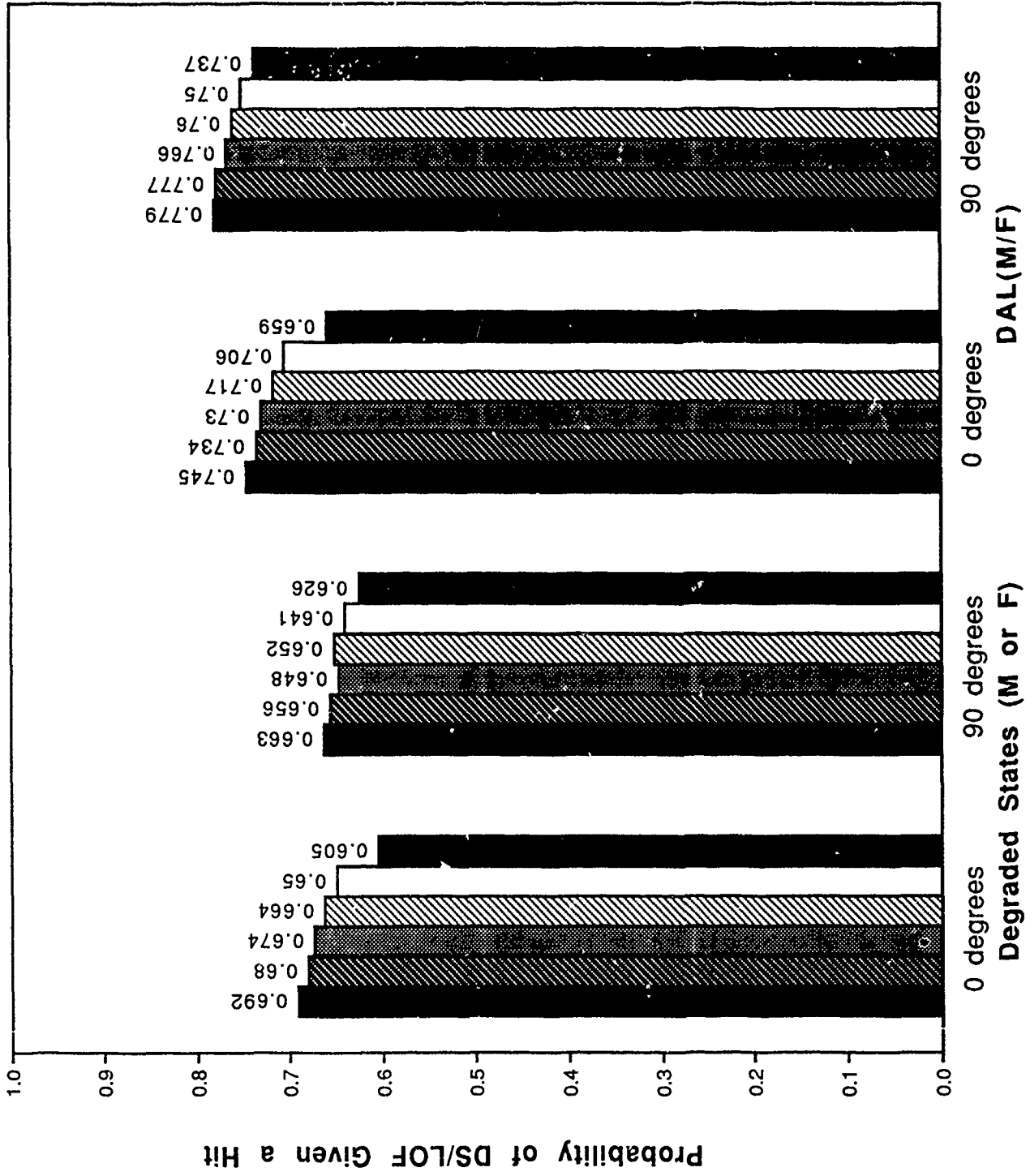
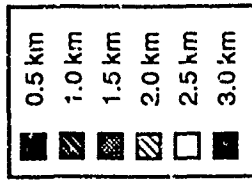


Figure C-2. Degraded States and DAL Range Sensitivity

Threat: P2  
 Exposure: fully  
 Dispersion: 2ft  
 Range

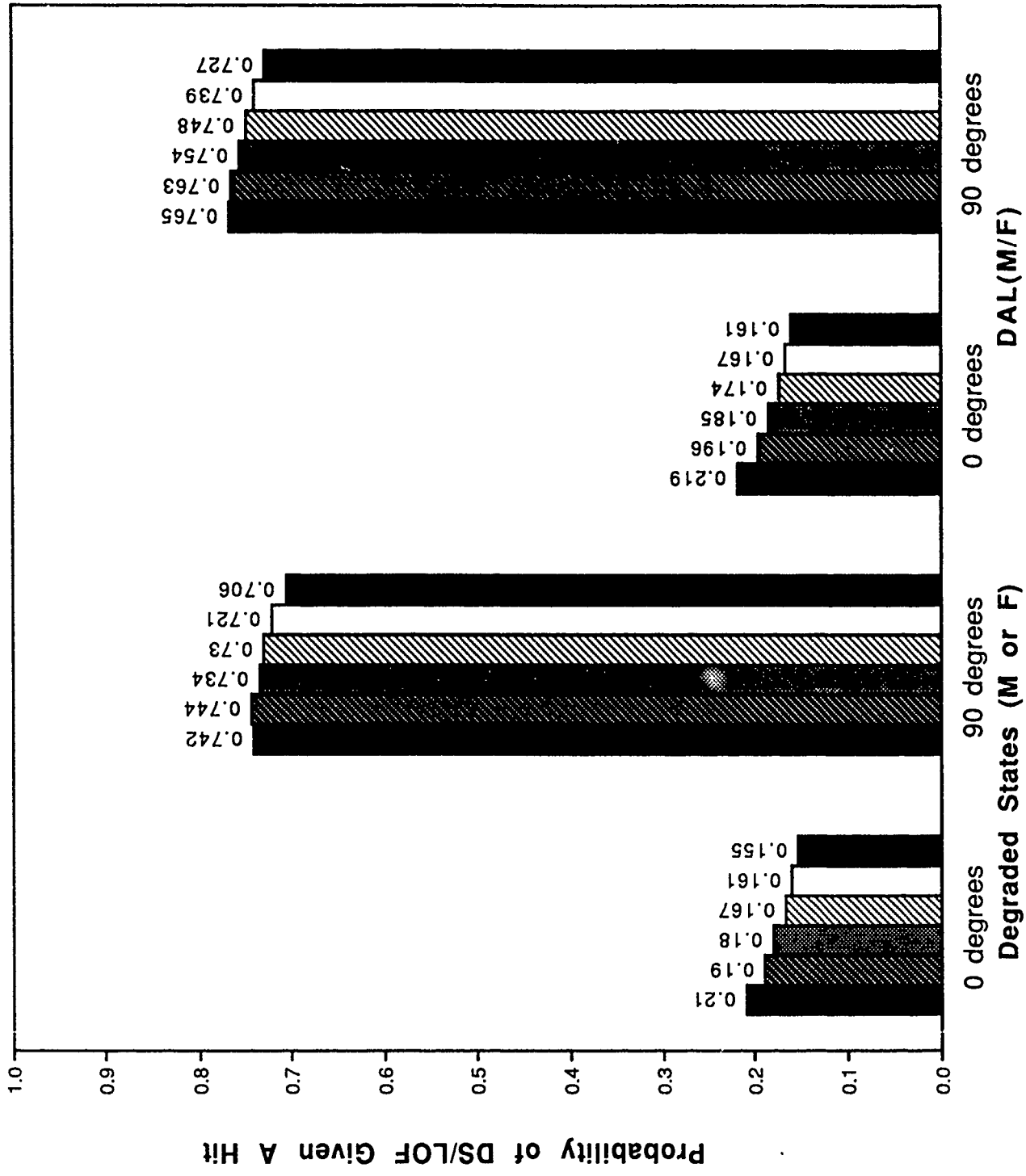
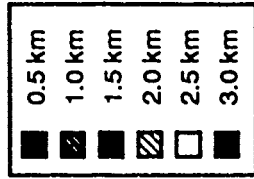


Figure C-3. Degraded States and DAL Range Sensitivity

Threat: P2  
 Exposure: defilade  
 Dispersion: 2ft  
 Range

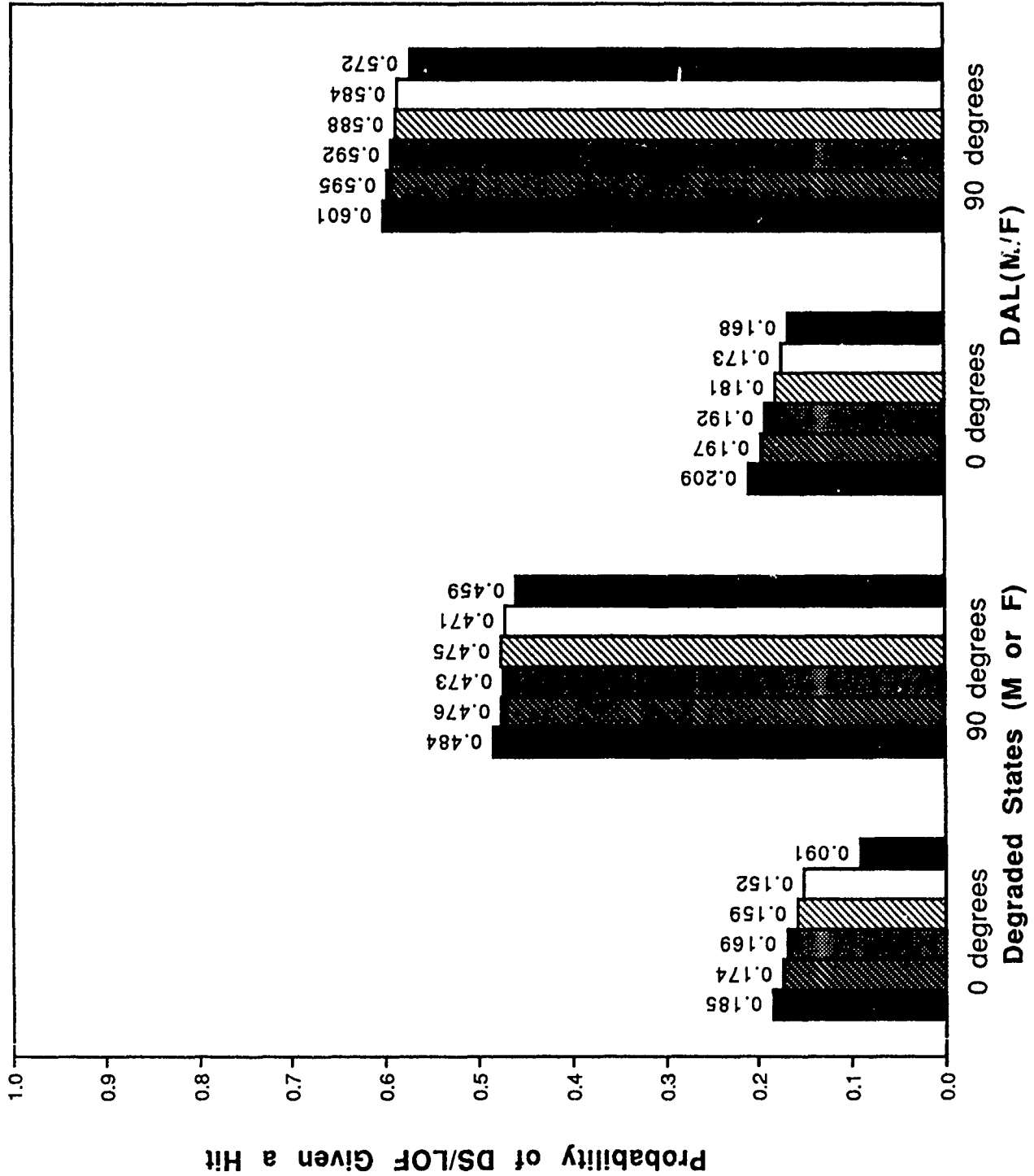
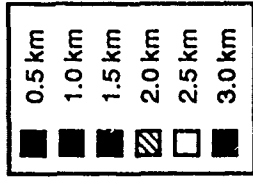


Figure C-4. Degraded States and DAL Range Sensitivity

Threat: P1  
 Exposure: fully  
 Range: (dispersion)

■	0.5km (1ft)
▨	1.0km (2ft)
▩	1.5km (3ft)
▧	2.0km (5ft)
□	2.5km (5ft)
■	3.0km (10ft)

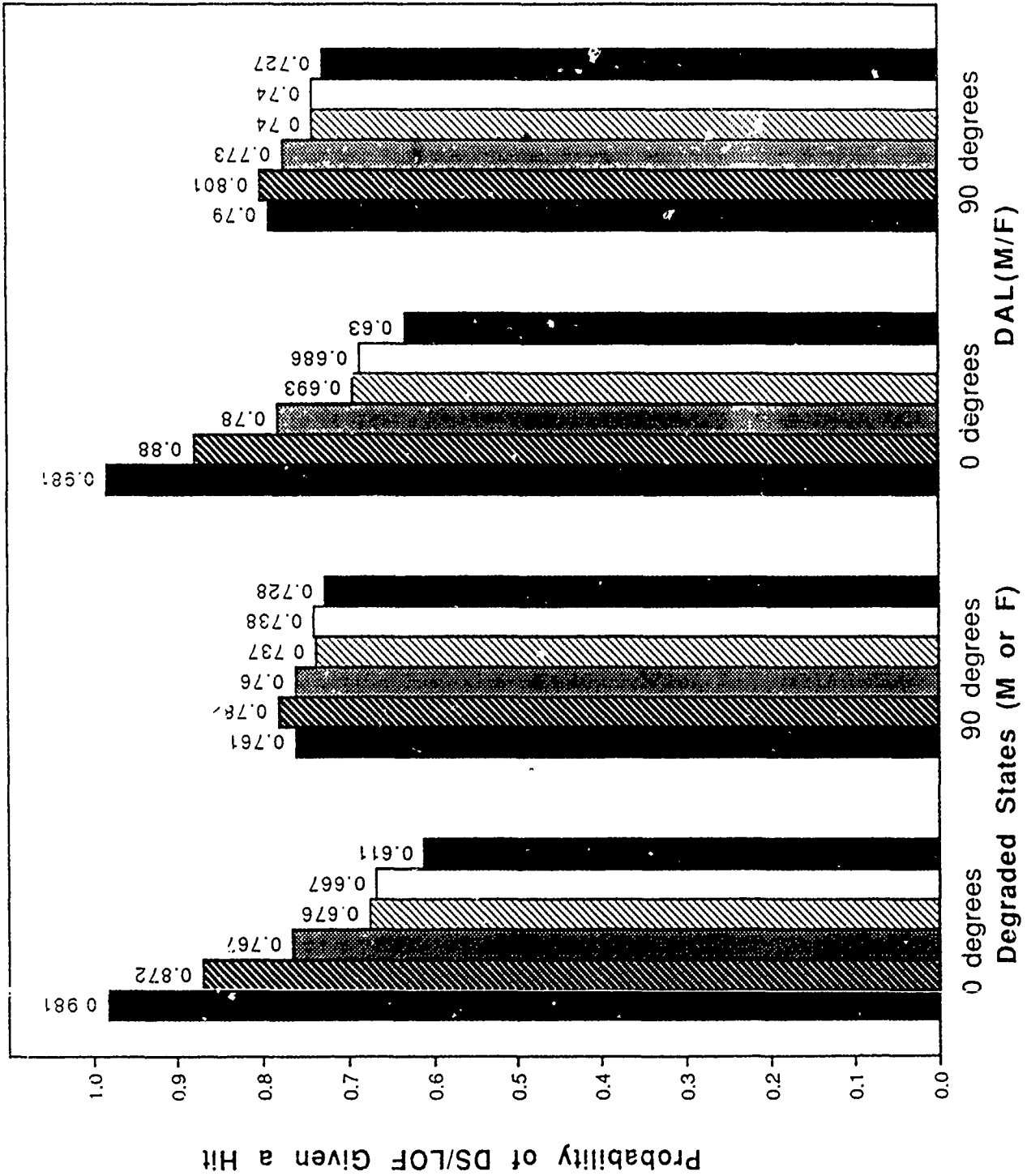


Figure C-5. Degraded States and DAL Range Sensitivity

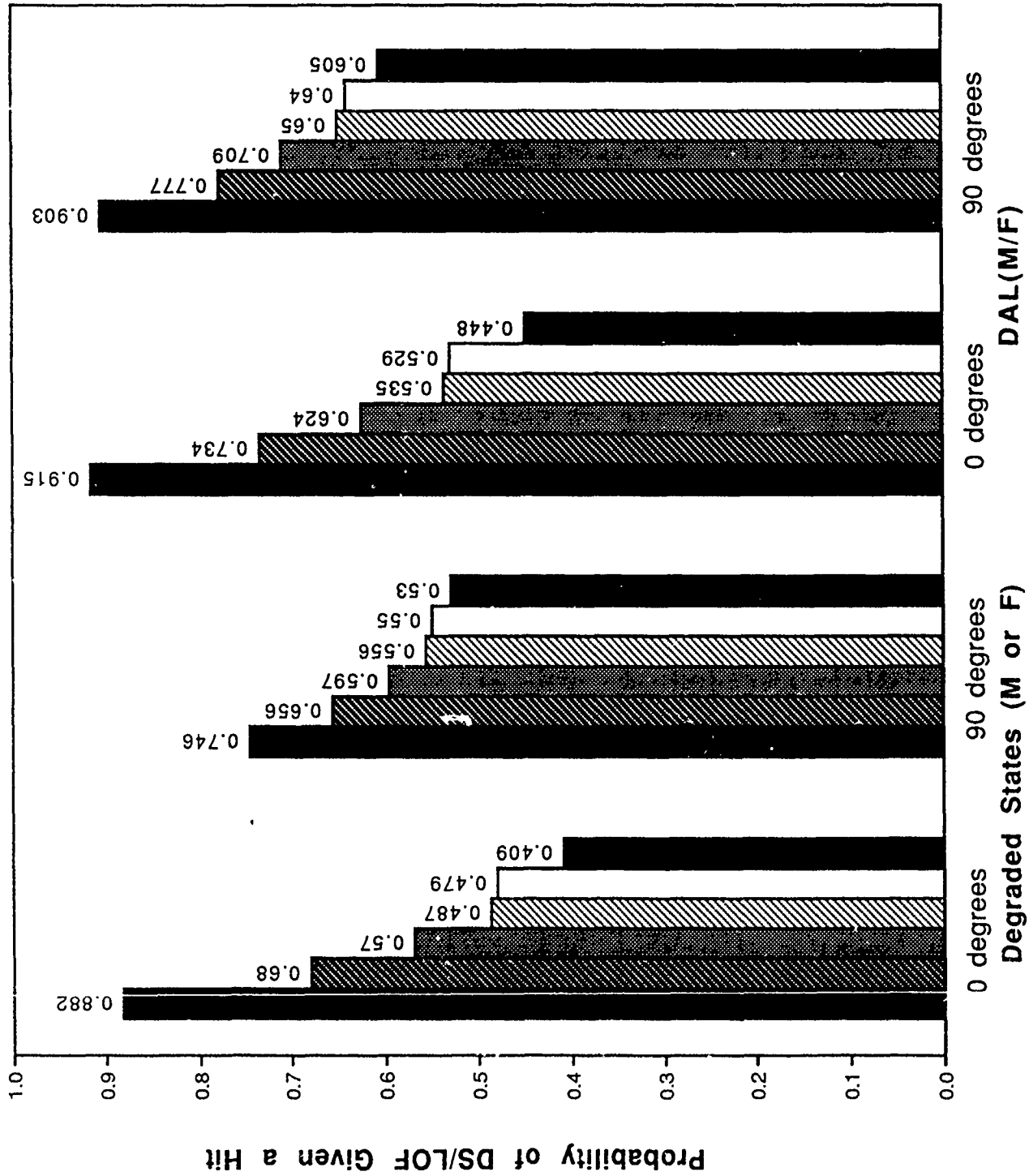


Figure C-6. Degraded States and DAL Range Sensitivity

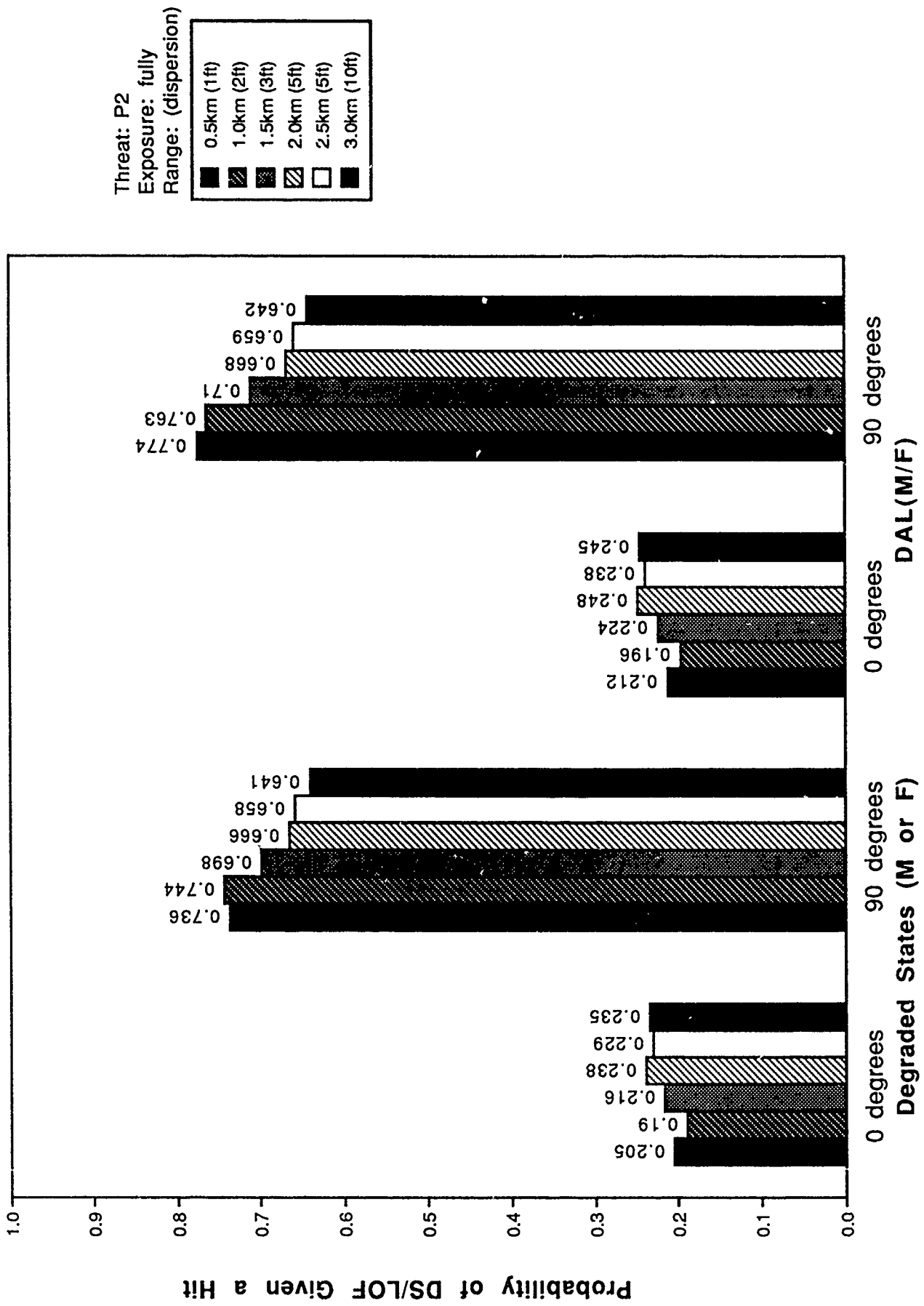


Figure C-7. Degraded States and DAL Range Sensitivity

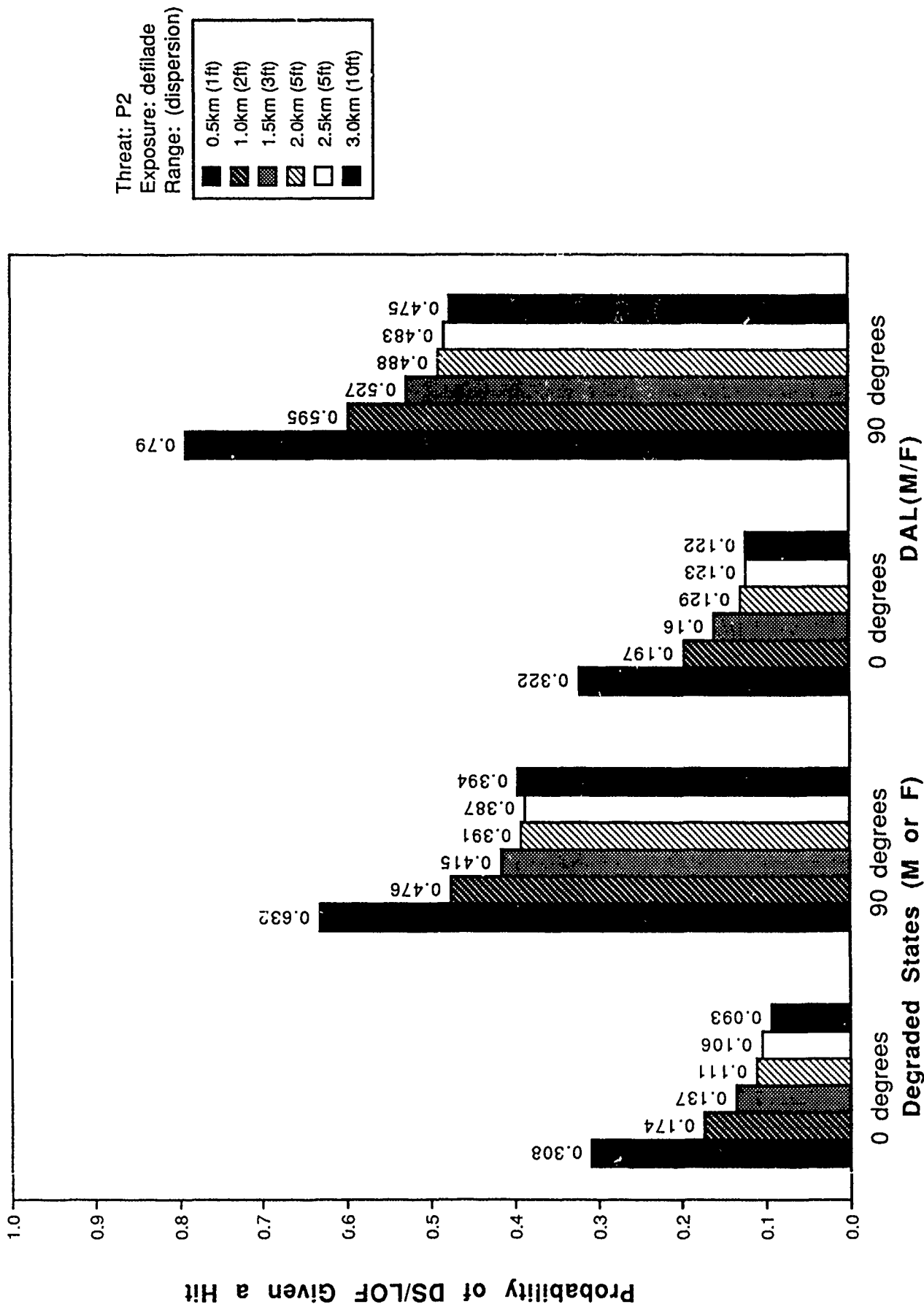


Figure C-8. Degraded States and DAL Range Sensitivity

Threat: P1  
 Range: 1 km  
 Exposure: fully  
 Dispersion

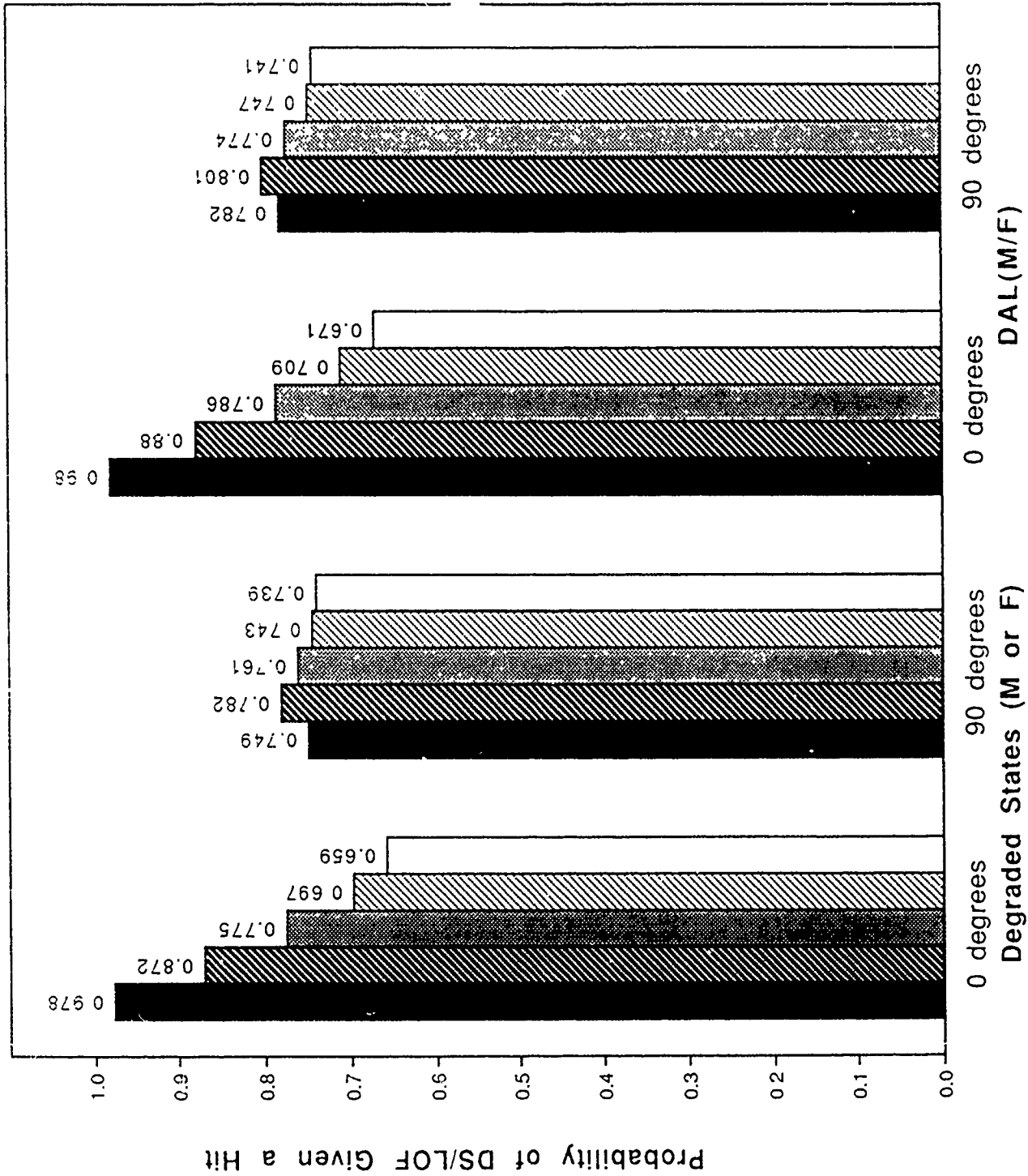
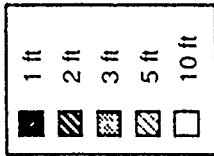


Figure C-9. Degraded States and DAL Dispersion Sensitivity

Threat: P1  
 Range: 1km  
 Exposure: defilade  
 Dispersion

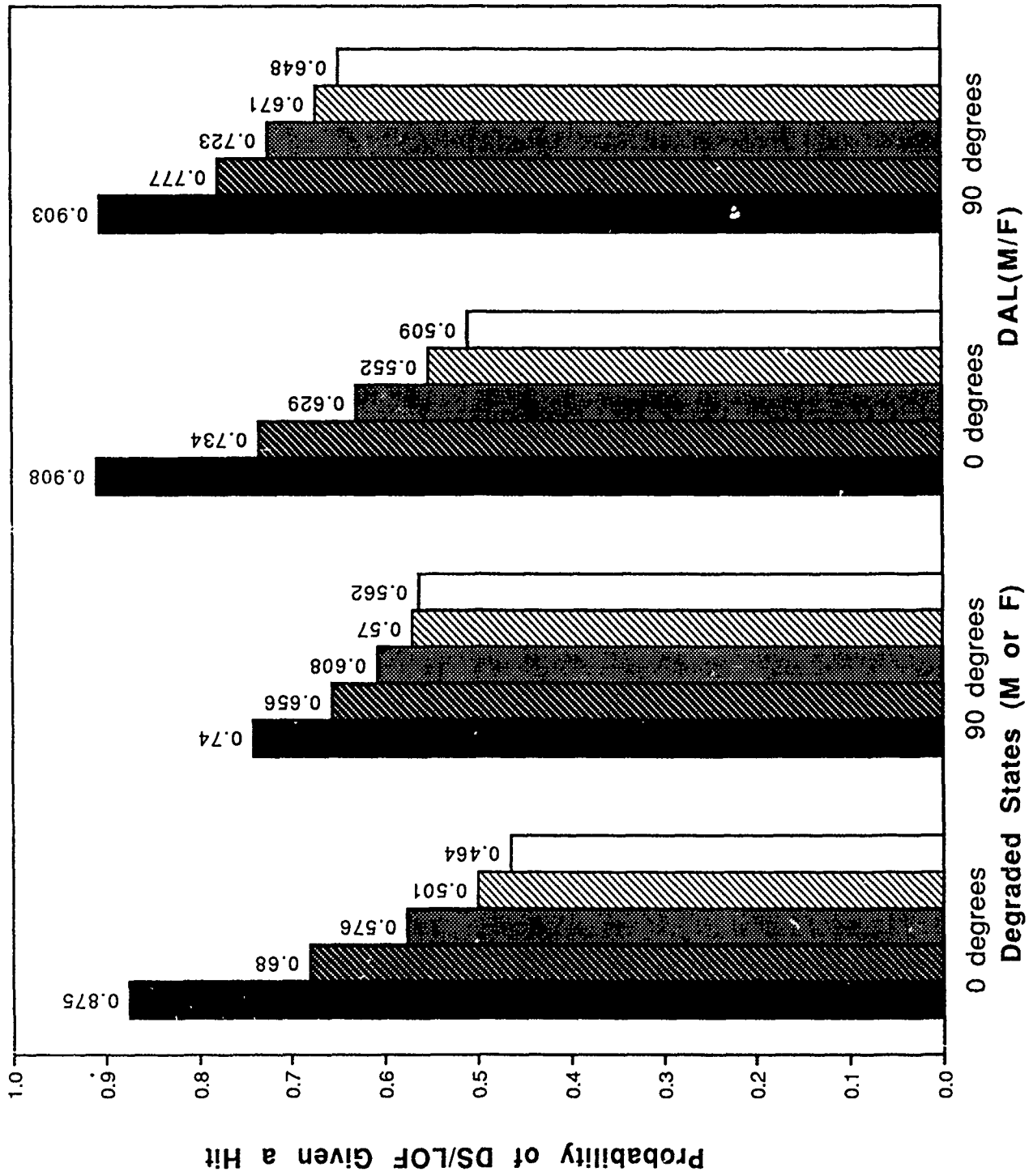
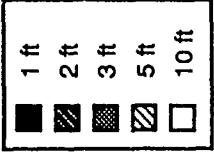


Figure C-10. Degraded States and DAL Dispersion Sensitivity

Threat: P2  
 Range: 1 km  
 Exposure: fully  
 Dispersion

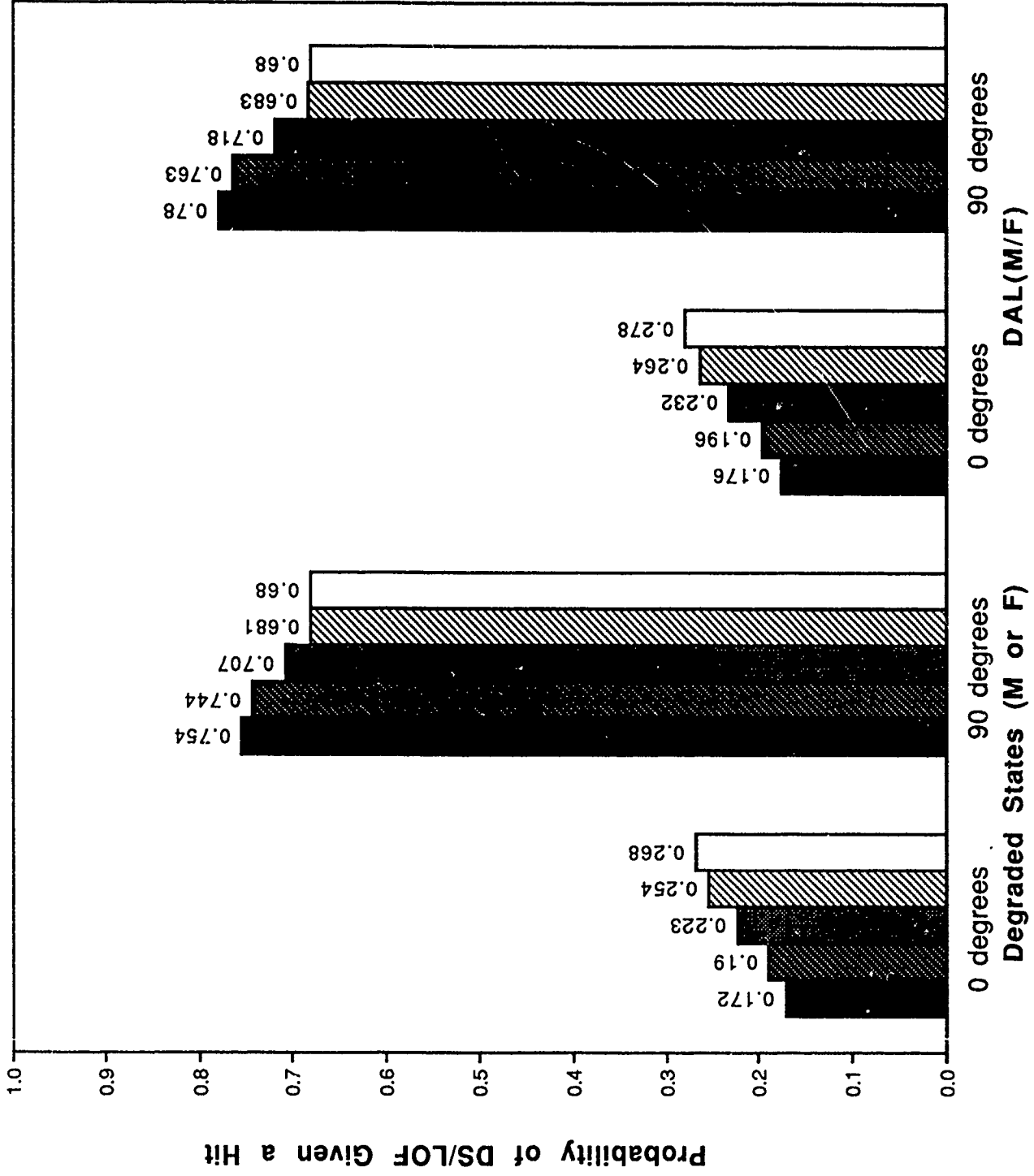
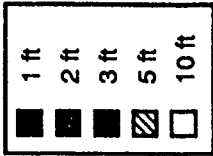


Figure C-11. Degraded States and DAL Dispersion Sensitivity

Threat: P2  
 Range: 1 km  
 Exposure: defilade  
 Dispersion

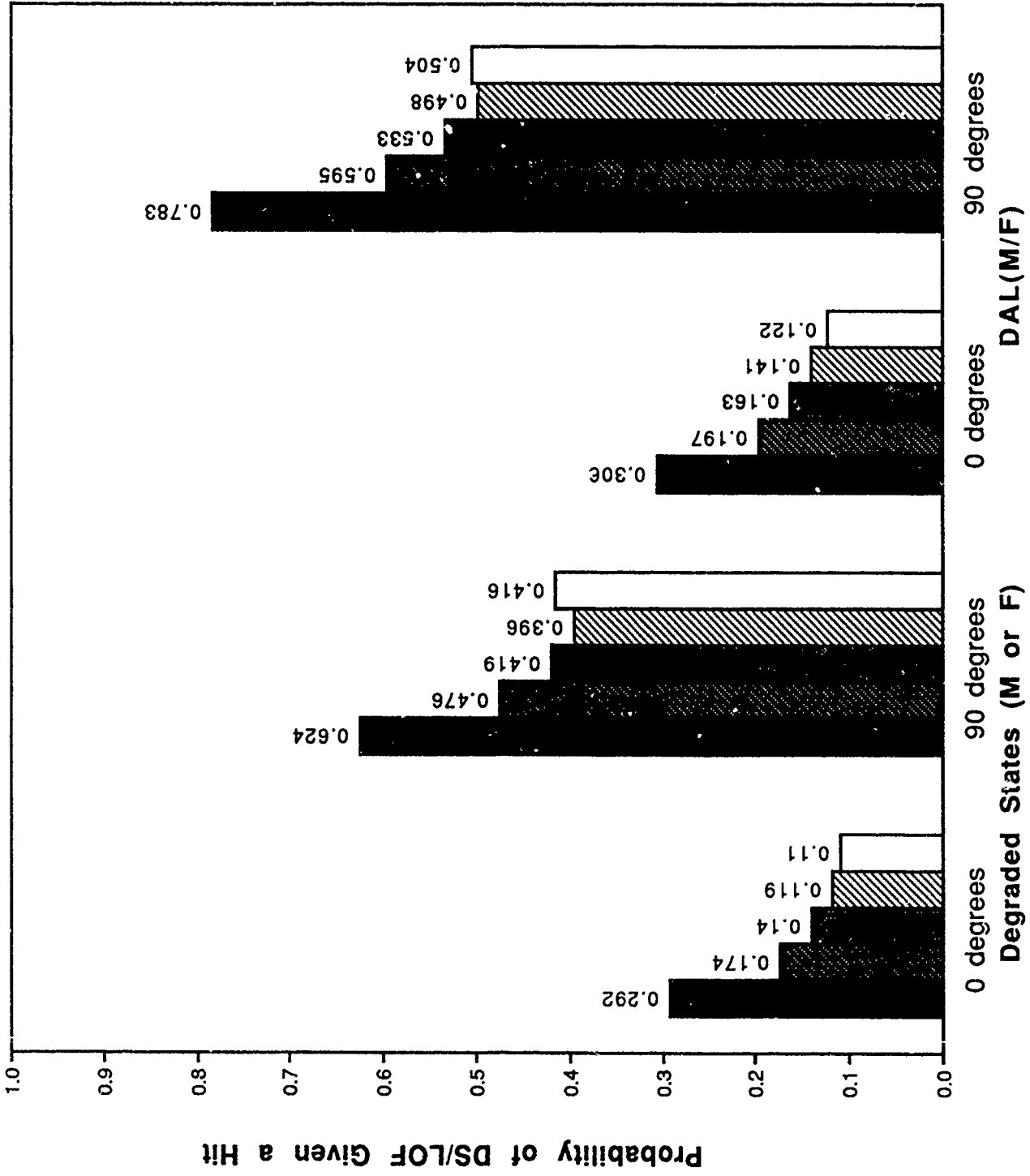
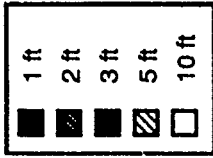


Figure C-12. Degraded States and DAL Dispersion Sensitivity

Threat: P1  
 Range: 3 km  
 Exposure: fully  
 Dispersion

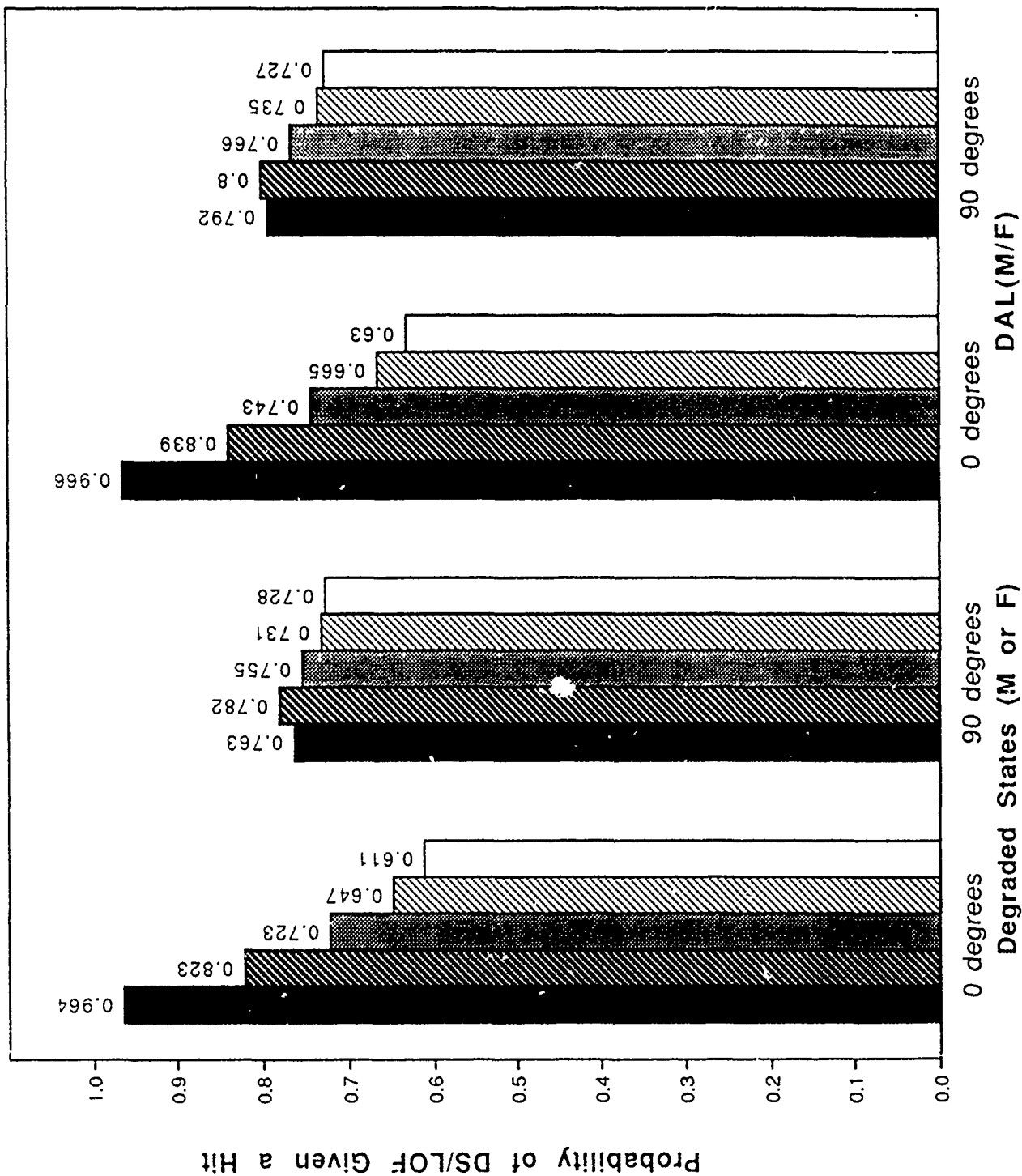
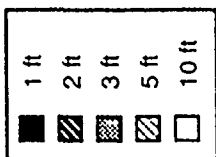


Figure C-13. Degraded States and DAL Dispersion Sensitivity

Threat: P1  
 Range: 3 km  
 Exposure: defilade  
 Dispersion

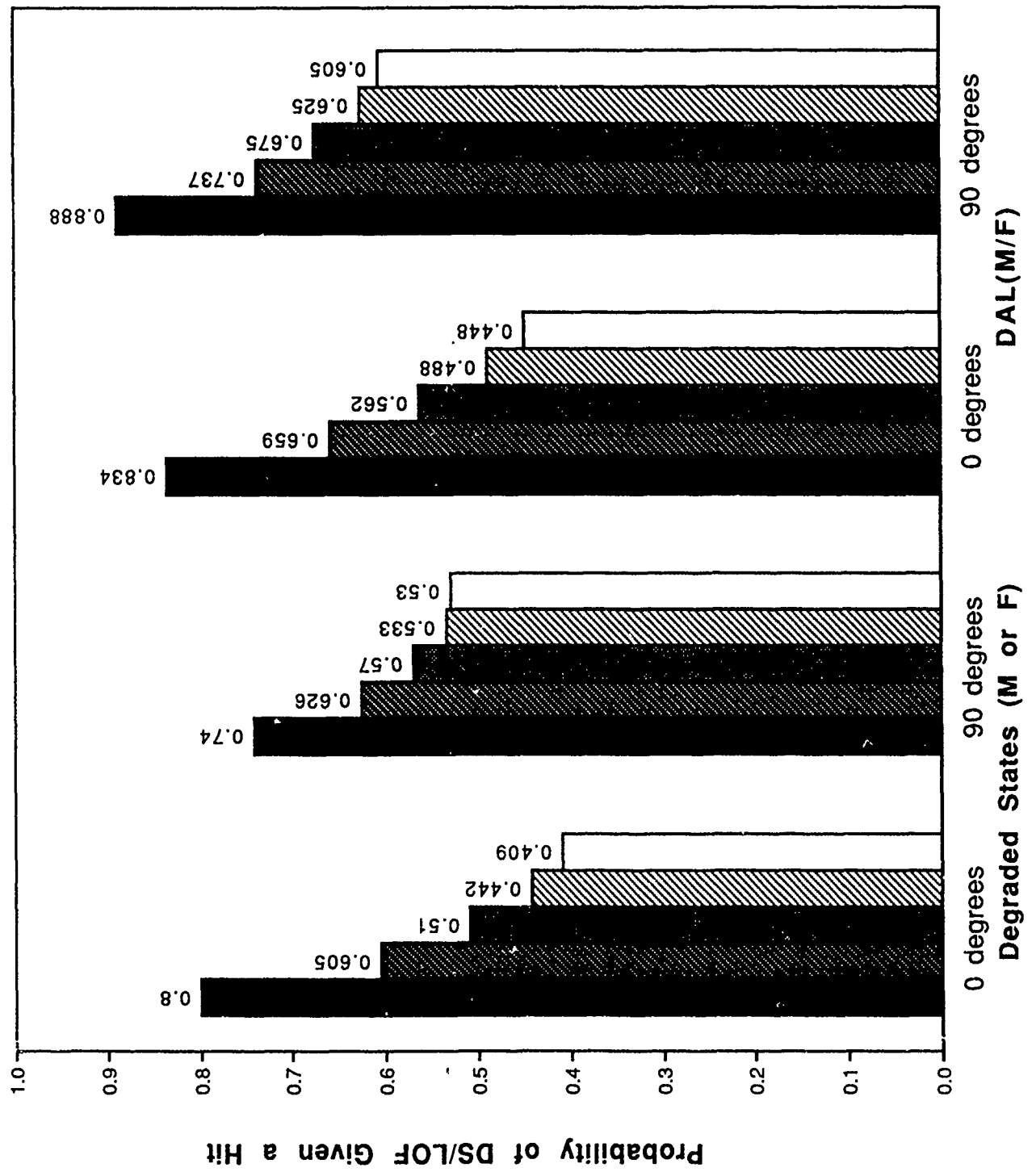
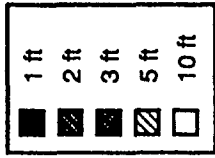


Figure C-14. Degraded States and DAL Dispersion Sensitivity

Threat: P2  
 Range: 3 km  
 Exposure: fully  
 Dispersion

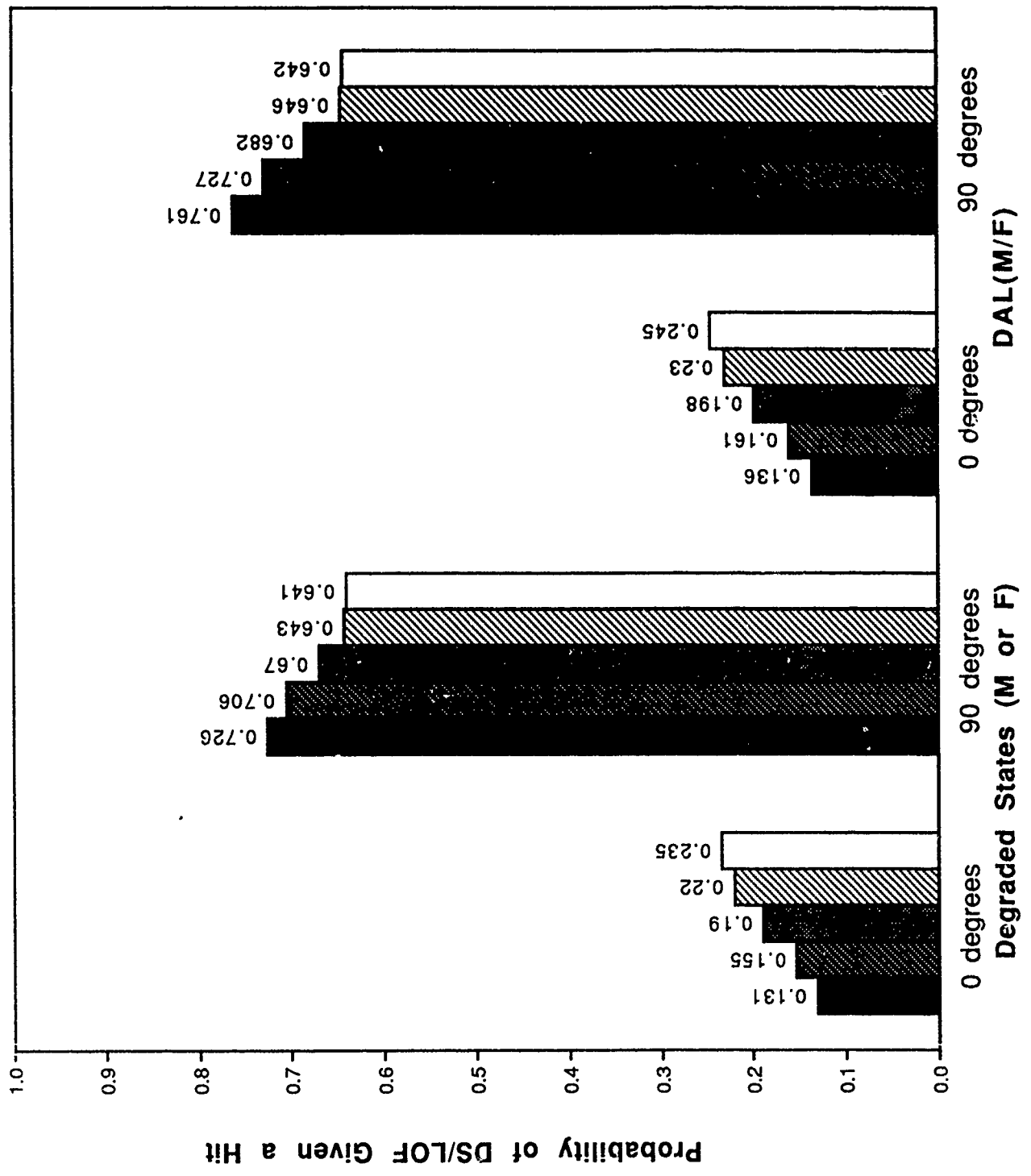
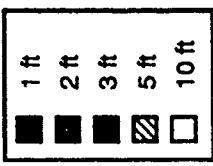


Figure C-15. Degraded States and DAL Dispersion Sensitivity

Threat: P2  
 Range: 3 km  
 Exposure: defilade  
 Dispersion

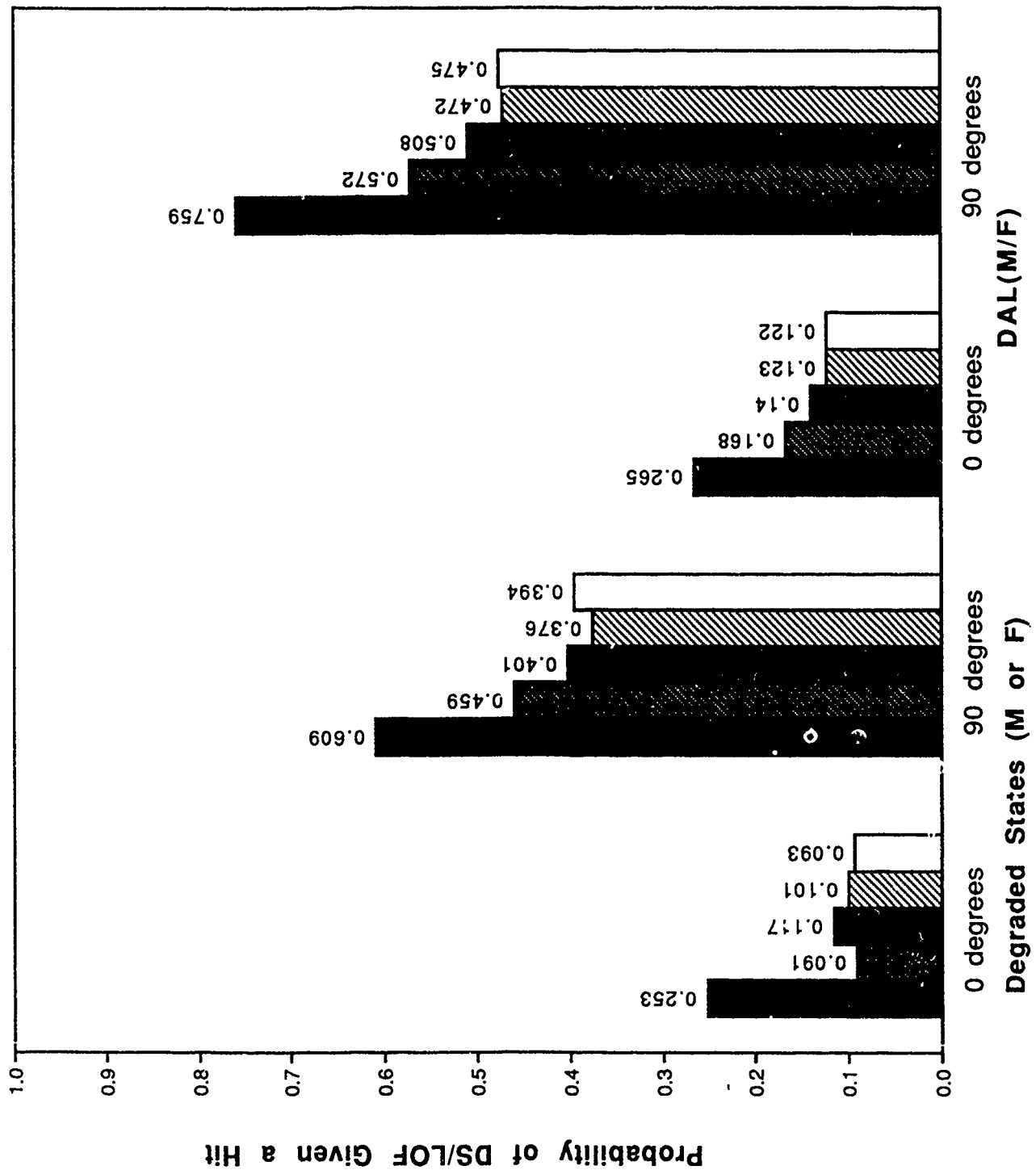
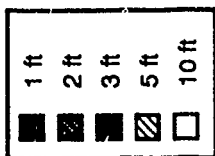


Figure C-16. Degraded States and DAL Dispersion Sensitivity

Threat: 1km  
 Exposure: fully  
 Dispersion: 2ft  
 Threat

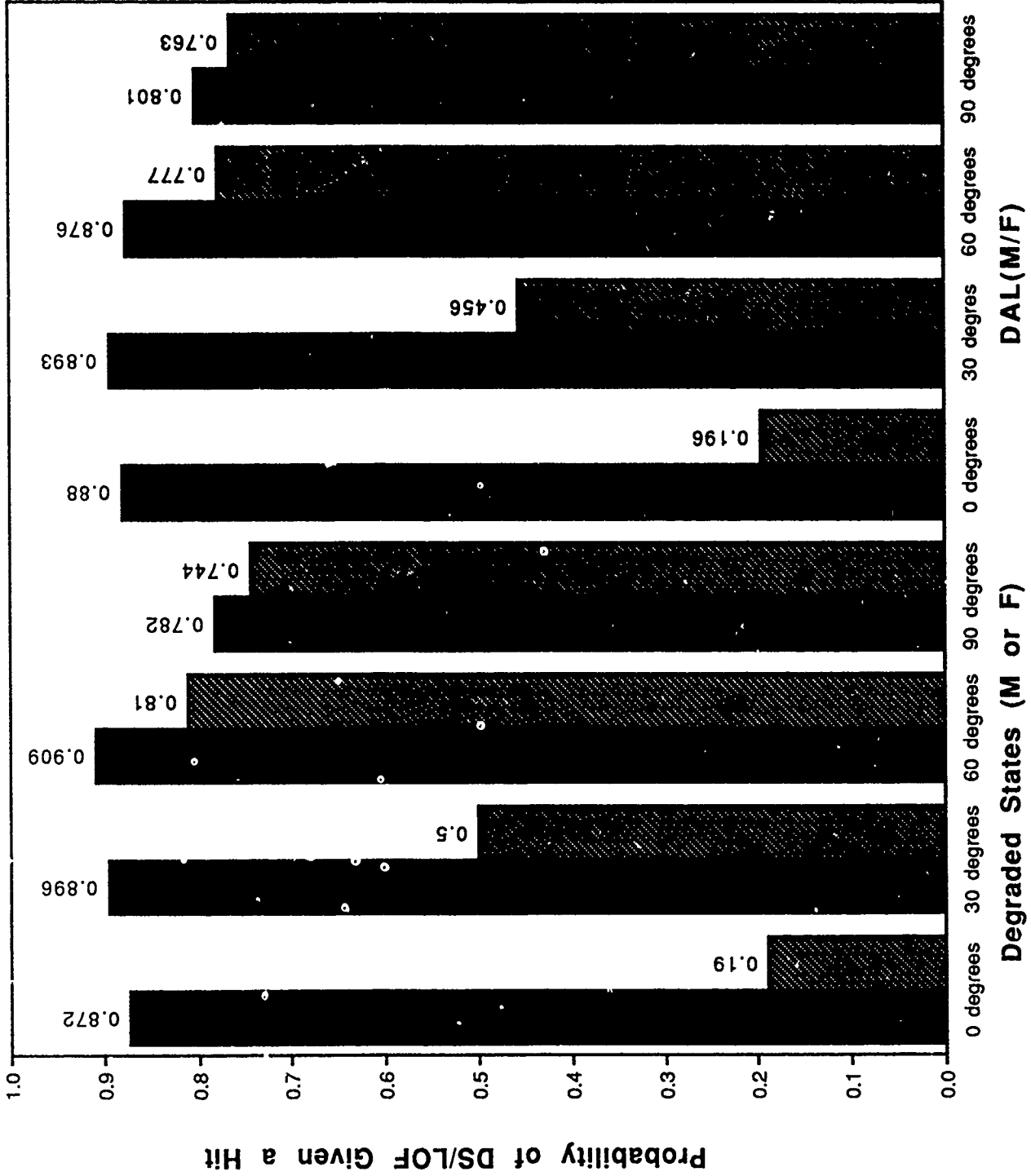
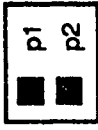


Figure C-17. Degraded States and DAL Threat Sensitivity

Threat: 1km  
 Exposure: defilade  
 Dispersion: 2ft  
 Threat

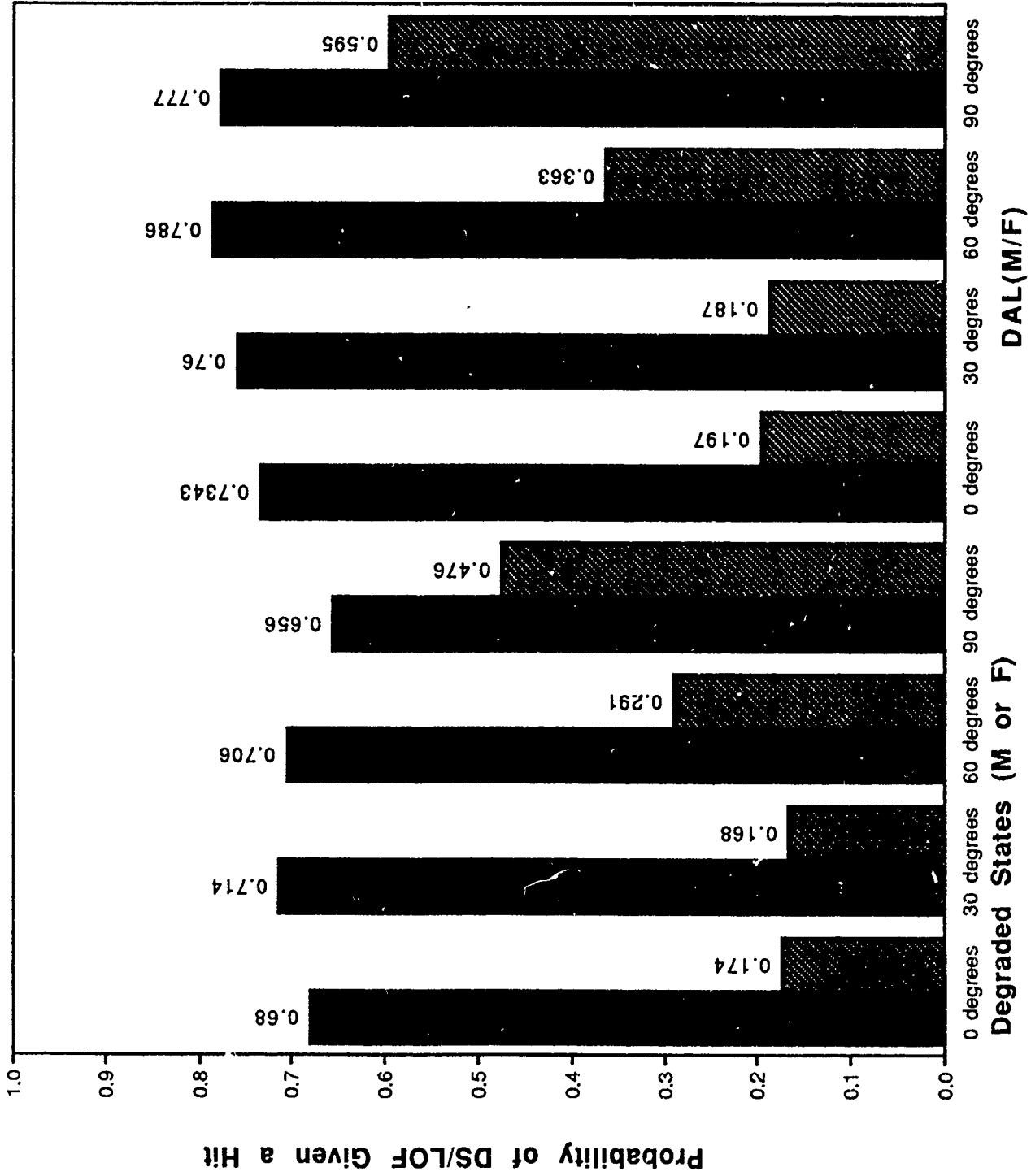
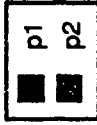


Figure C-18. Degraded States and DAL Threat Sensitivity

Threat: 3km  
 Exposure: fully  
 Dispersion: 10ft  
 Threat

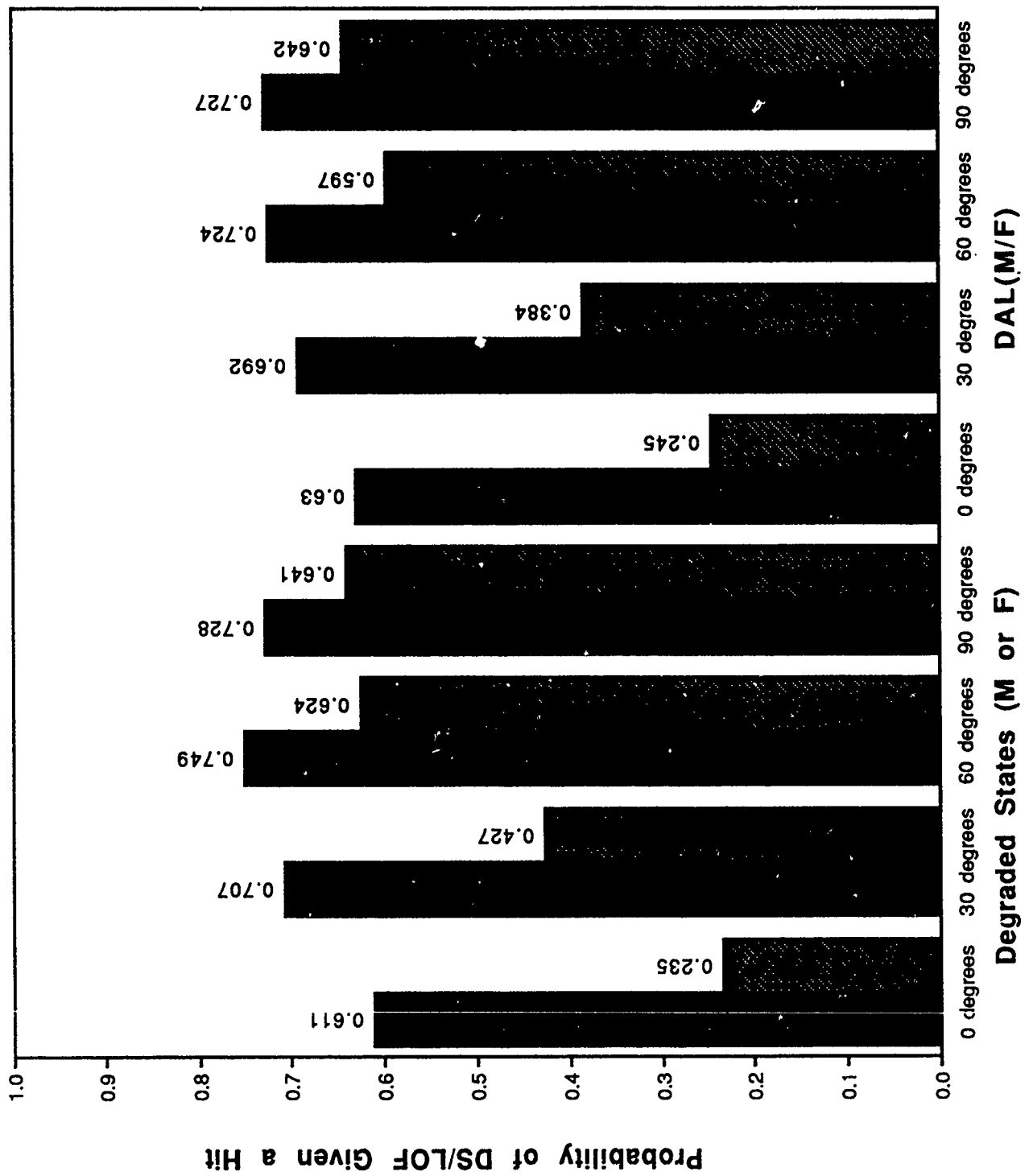
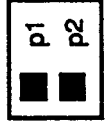


Figure C-19. Degraded States and DAL Threat Sensitivity

Threat: 3km  
 Exposure: defilade  
 Dispersion: 10ft  
 Threat

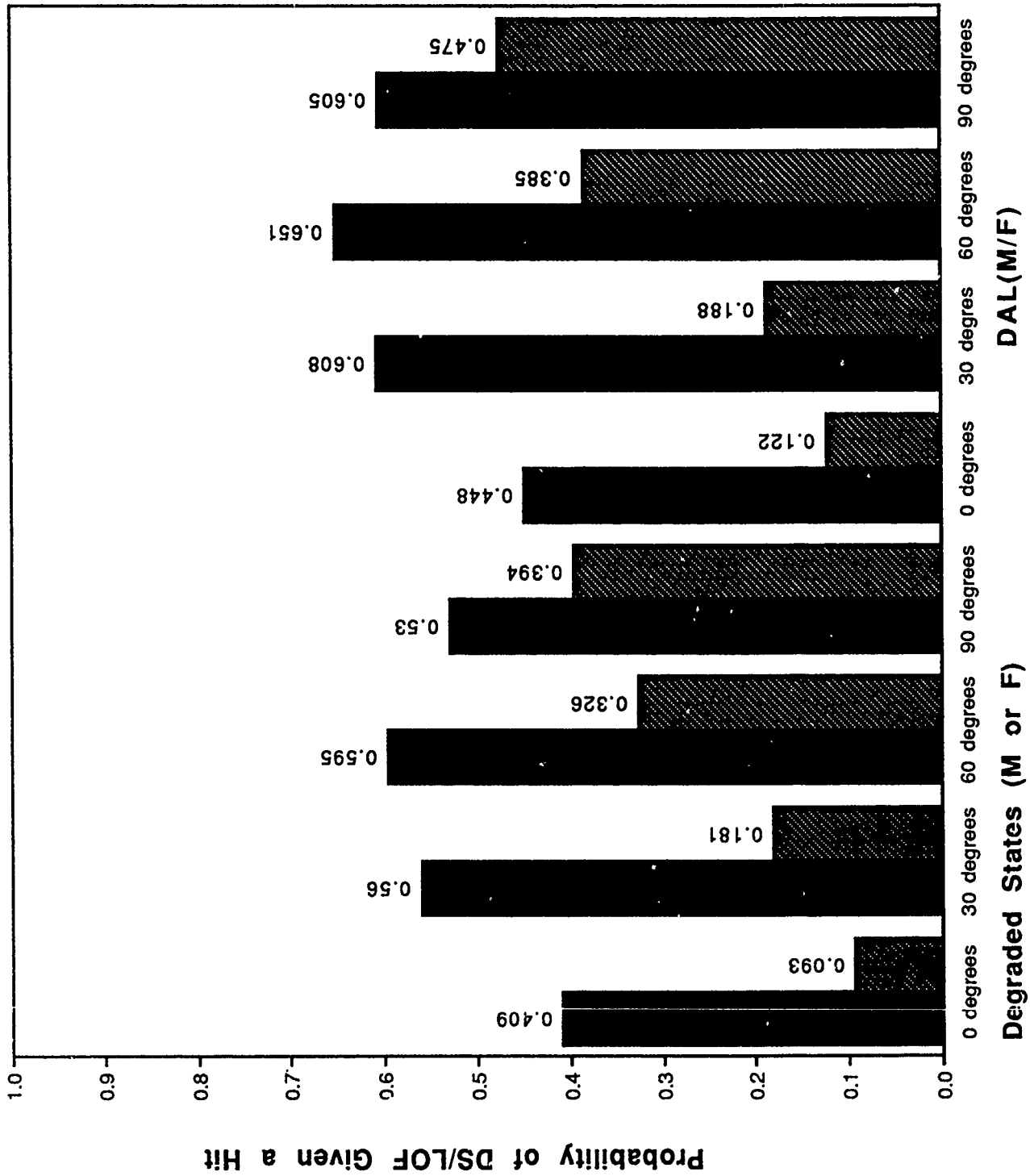
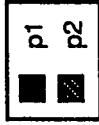


Figure C-20. Degraded States and DAL Threat Sensitivity

Threat: P1  
 Range: 1km  
 Dispersion: 2 ft  
 Exposure

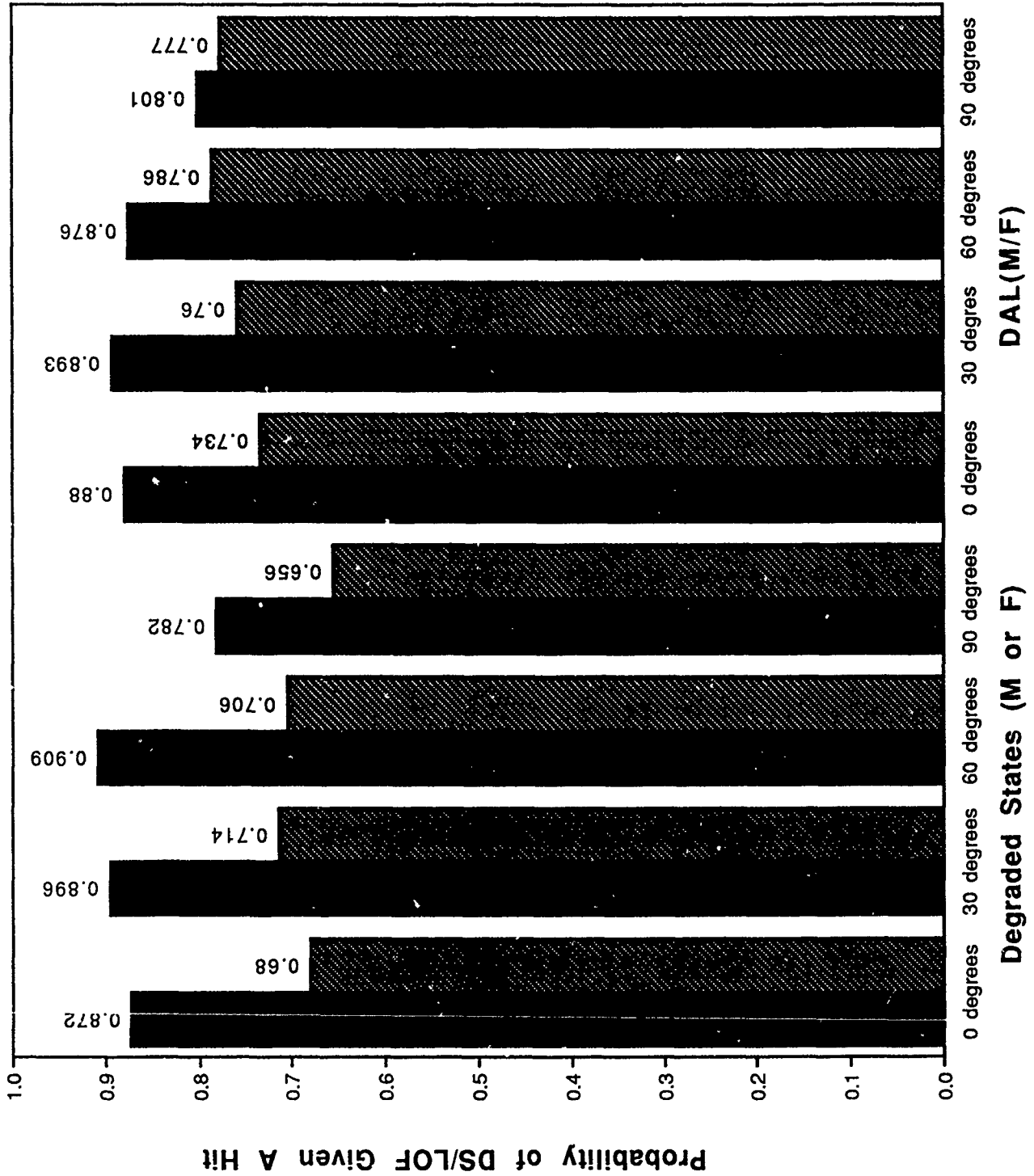
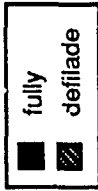


Figure C-21. Degraded States and DAL Exposure Sensitivity

Threat: P1  
 Range: 3km  
 Dispersion: 10ft  
 Exposure

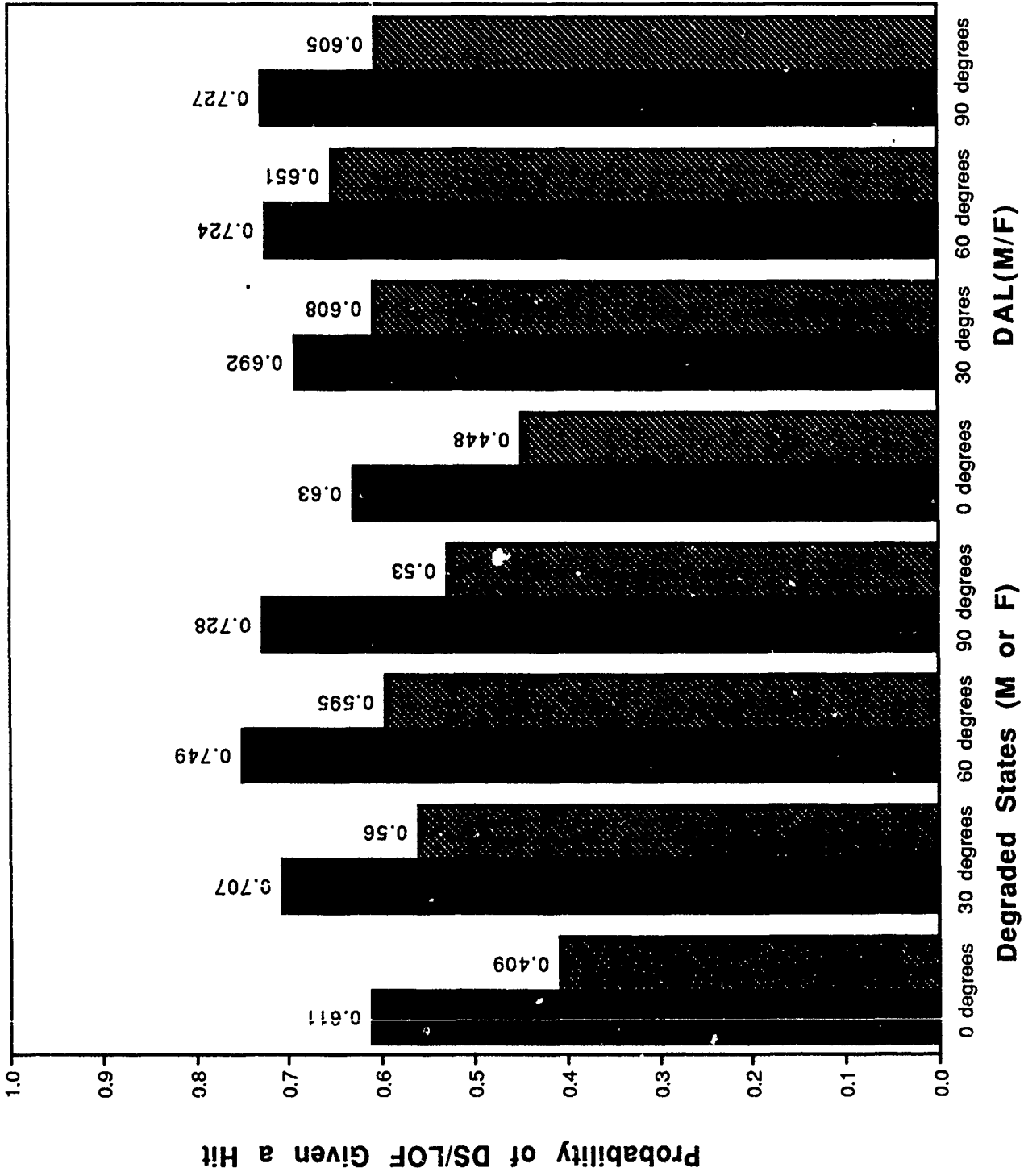


Figure C-22. Degraded States and DAL Exposure Sensitivity

Threat: P2  
 Range: 1km  
 Dispersion: 2ft  
 Exposure

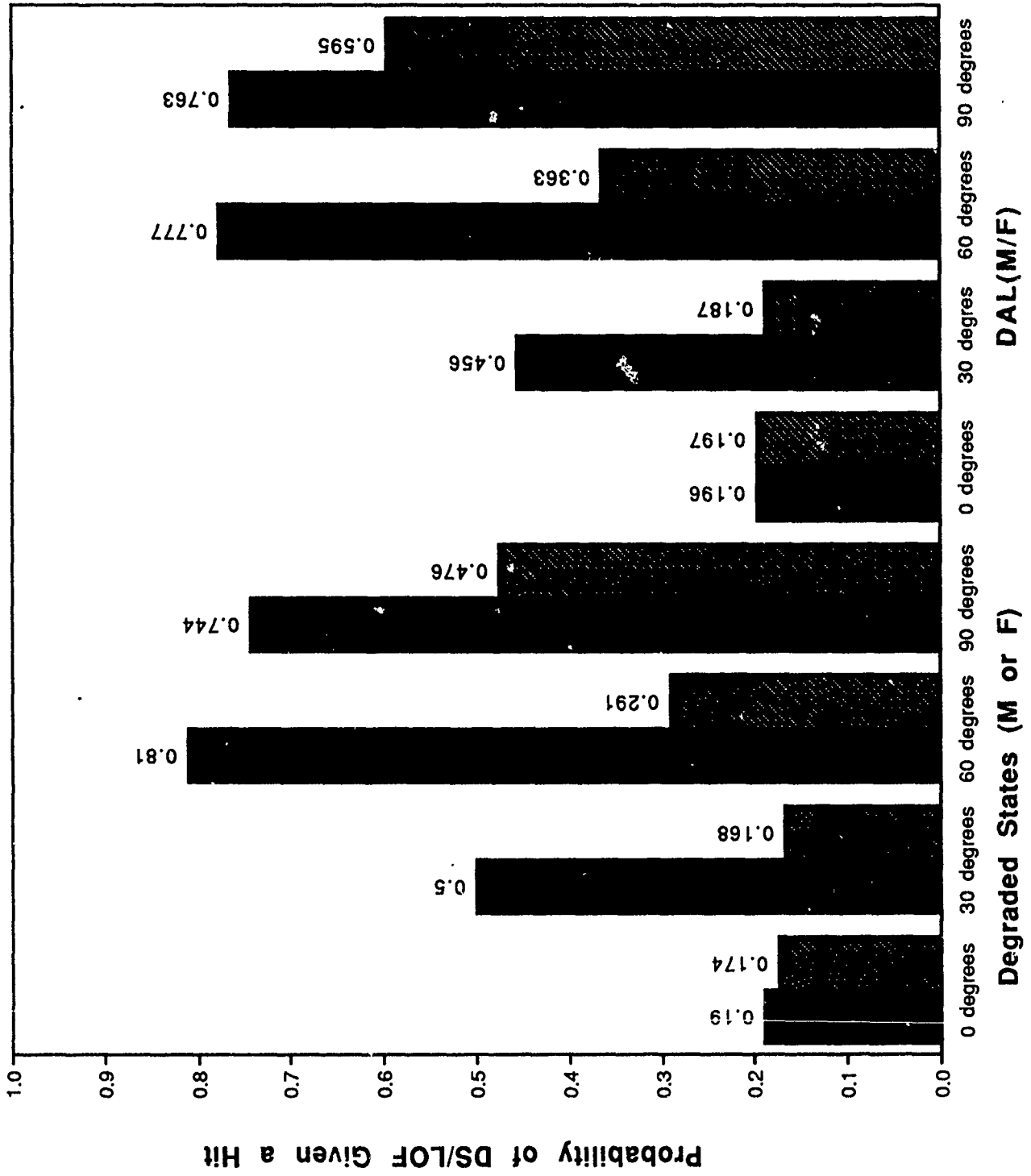


Figure C-23. Degraded States and DAL Exposure Sensitivity

Threat: P2  
 Range: 3km  
 Dispersion: 10ft  
 Exposure

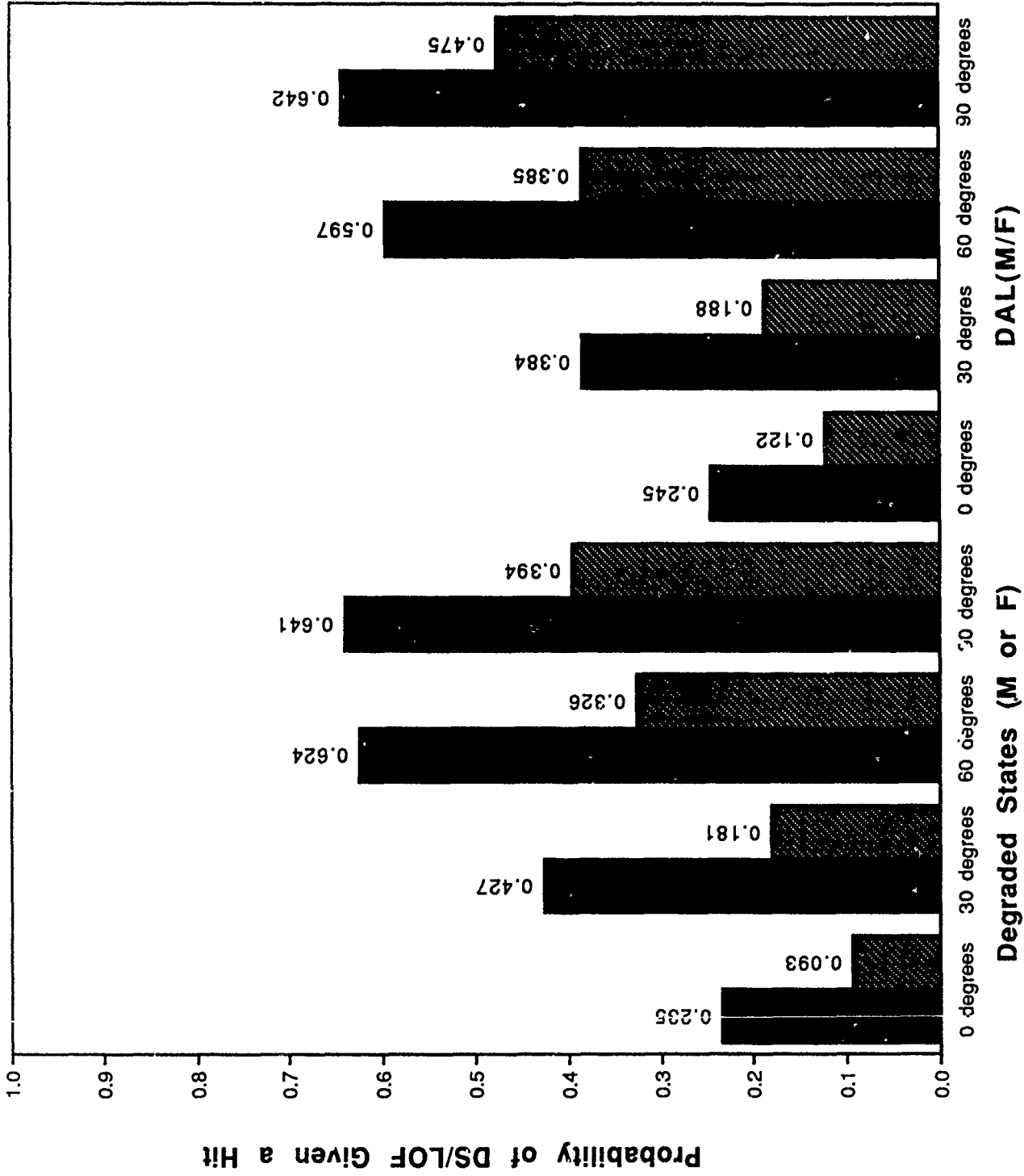
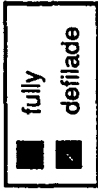
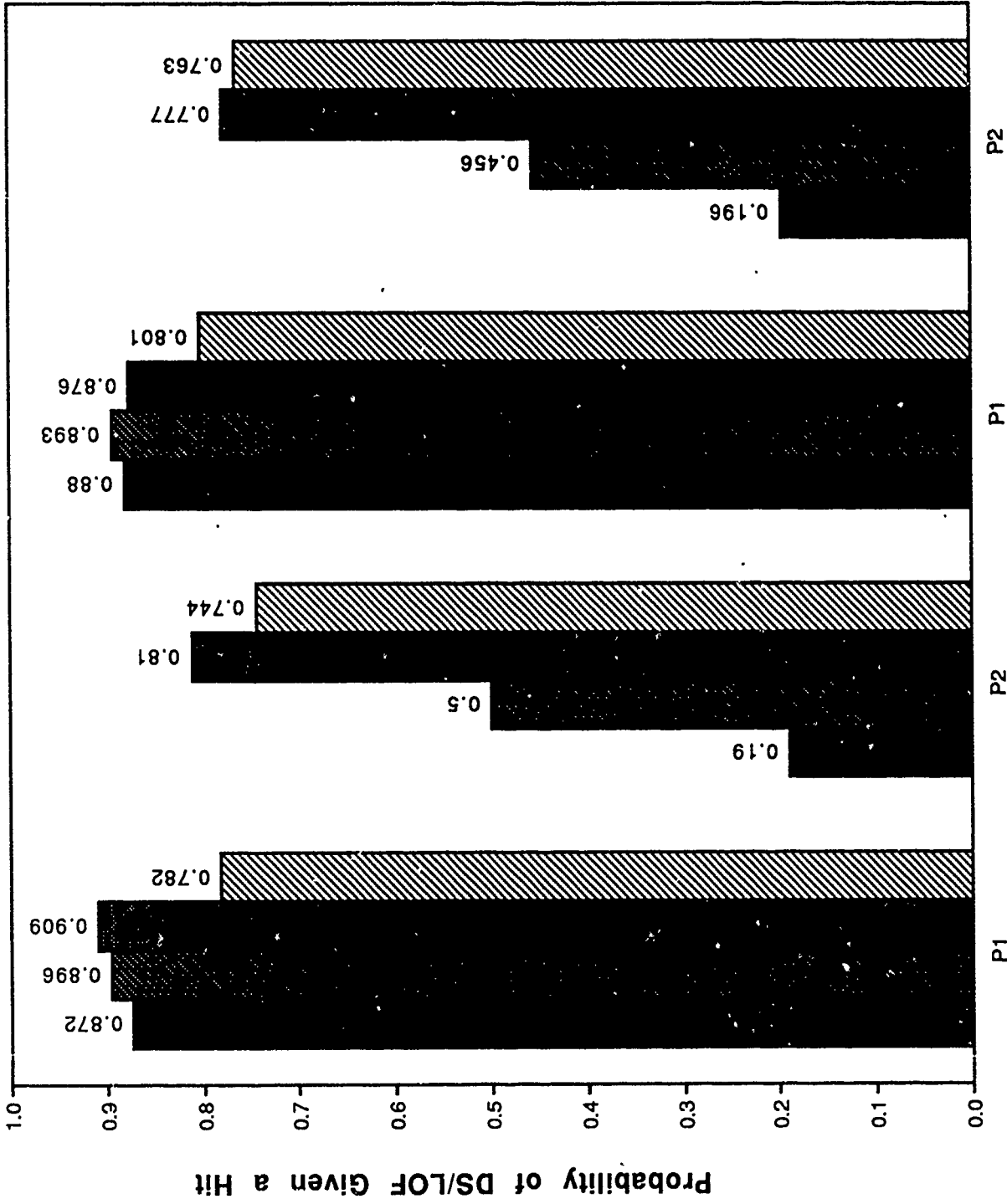
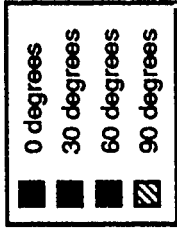


Figure C-24. Degraded States and DAL Exposure Sensitivity

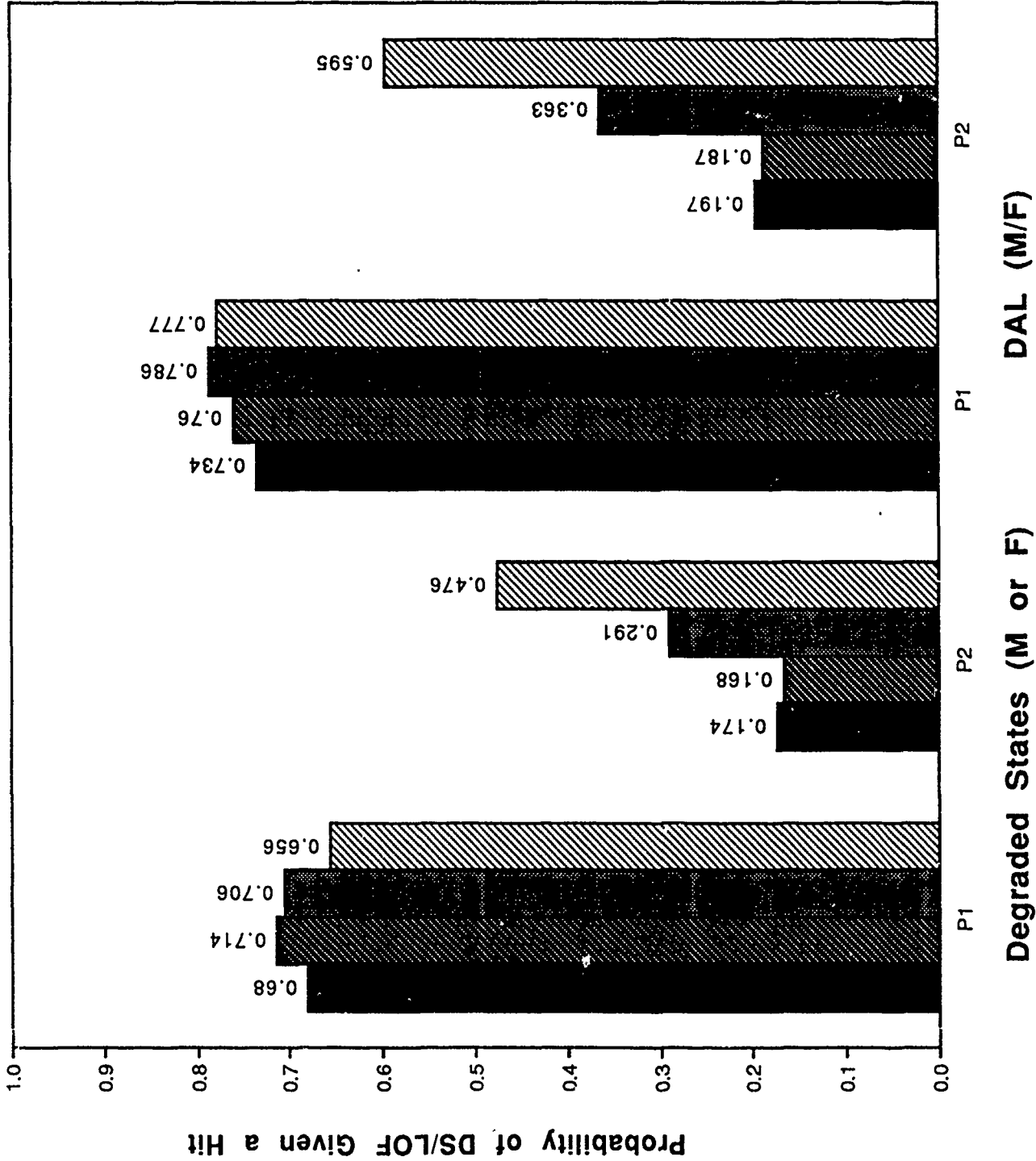
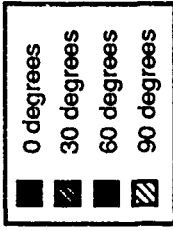
Range: 1km  
 Dispersion: 2ft  
 Exposure: fully  
 Azimuth



Degraded States (M or F) DAL (M/F)

Figure C-25. Degraded States and DAL Azimuth Sensitivity

Range: 1km  
 Dispersion: 2ft  
 Exposure: defilade  
 Azimuth



Degraded States (M or F) DAL (M/F)

Figure C-26. Degraded States and DAL Azimuth Sensitivity

Range: 3km  
 Dispersion: 10ft  
 Exposure: fully  
 Azimuth

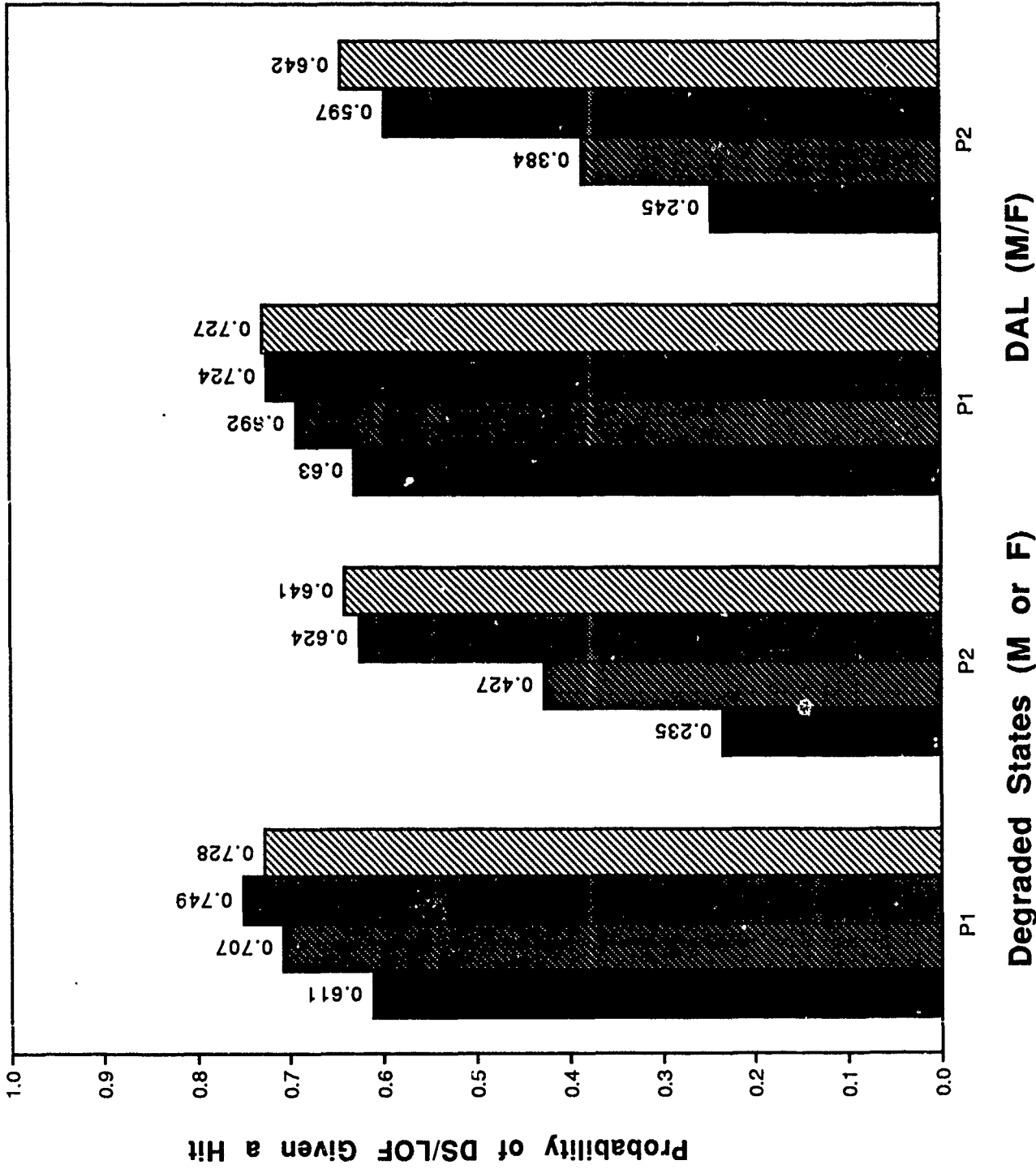
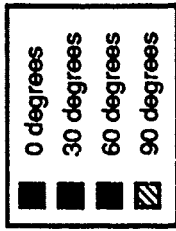
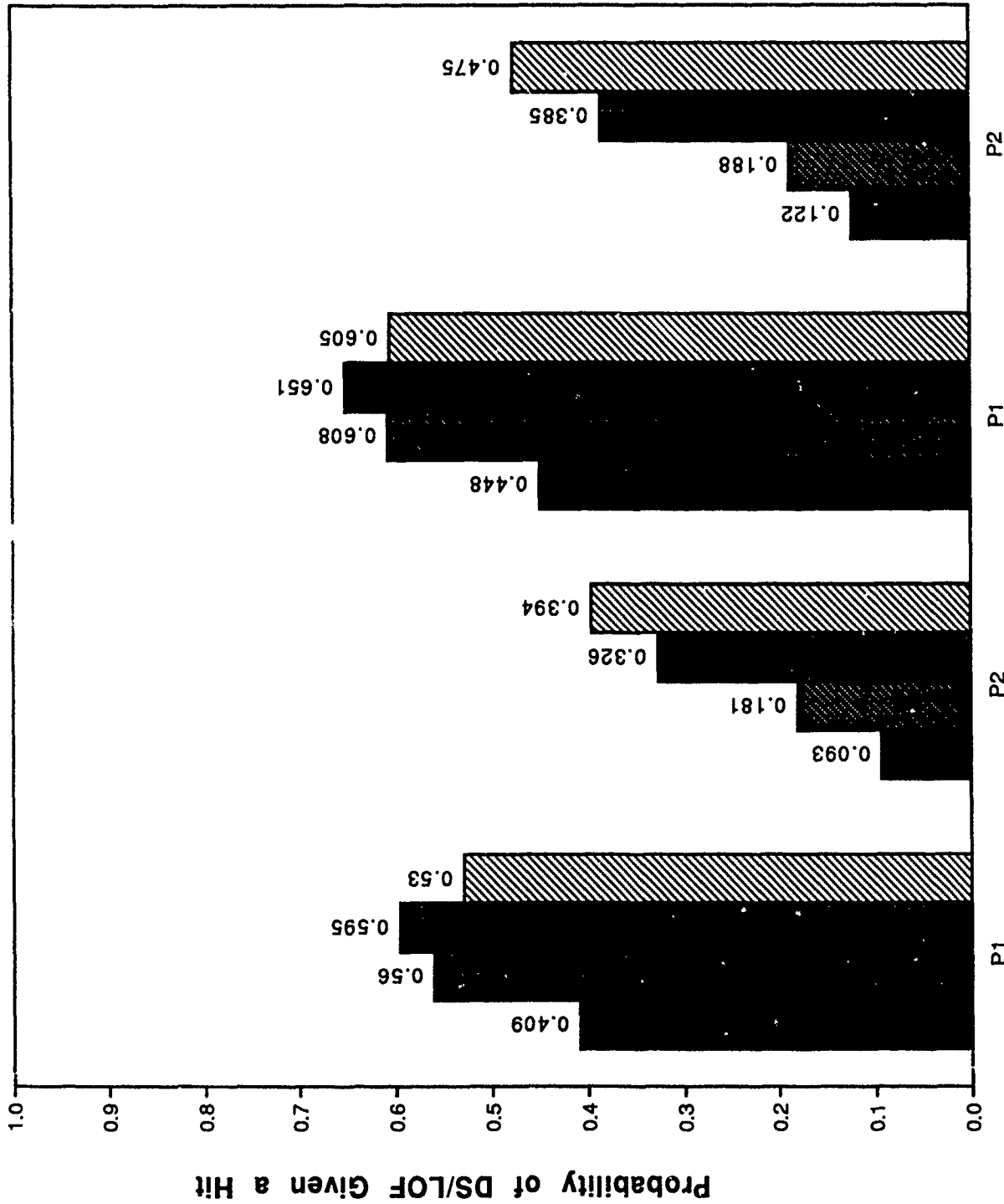
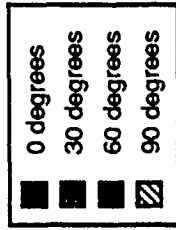


Figure C-27. Degraded States and DAL Azimuth Sensitivity

Range: 3km  
 Dispersion: 10ft  
 Exposure: deflade  
 Azimuth



**Degraded States (M or F) DAL (M/F)**  
 Figure C-28. Degraded States and DAL Azimuth Sensitivity

**APPENDIX D**

**Degraded States vs. DAL Comparisons**

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This appendix contains the numerical comparisons of the two methodologies' results. At the range of 1 kilometer and with a 2 foot dispersion value, the DS probabilities and DAL LOF values are compared for both threats and exposures. The DS values are probabilities given a hit extracted from the probability distribution output for each set of initial conditions. The DAL values are LOF given a hit from the basic and modified DALs.

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Threat: P1  
 Range: 1 km  
 Azimuth: 0 degrees  
 Exposure: fully  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		<u>DAL</u>	
		<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, slight	0.005	
	Reduced speed, significant	0.038	
	Total immobilization	<u>0.615</u>	
		0.658	0.725      0.645
<b>FIREPOWER</b>	Loss of main armament	0.487	
	Increased time to fire		
	Reduced delivery accuracy	0.021	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.229	
	Loss of main armament		
	Loss of secondary armament	<u>0.090</u>	
	0.827	0.810      0.783	
<b>ACQUISITION</b>	Reduced acquisition capability	0.020	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.773</u>	
		0.793	?
<b>CREW</b>	One crew casualty	0.387	
	Two crew casualties	0.133	
	Three crew casualties	0.052	
	Four crew casualties	<u>0.090</u>	
		0.662	?
<b>COMMO</b>	No internal communications		
	No external communications	<u>0.479</u>	
		0.479	?
<b>AMMUNITION</b>	Bustle ammo lost	<u>0.006</u>	
		0.006	?      ?
<b>K-kill</b>		0.090	0.090      0.090

Figure D-1. DAL vs. DS numerical comparison

Threat: P1  
 Range: 1 km  
 Azimuth: 30 degrees  
 Exposure: fully  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		<u>DAL</u>	
		<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, slight	0.021	
	Reduced speed, significant	0.119	
	Total immobilization	<u>0.587</u>	
		0.727	0.768      0.679
<b>FIREPOWER</b>	Loss of main armament	0.512	
	Increased time to fire		
	Reduced delivery accuracy	0.036	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.165	
	Loss of main armament		
	<u>0.093</u>		
	0.806	0.779      0.756	
<b>ACQUISITION</b>	Reduced acquisition capability	0.026	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.770</u>	
		0.796	?
<b>CREW</b>	One crew casualty	0.254	
	Two crew casualties	0.122	
	Three crew casualties	0.038	
	Four crew casualties	<u>0.091</u>	
		0.505	?
<b>COMMO</b>	No internal communications		
	No external communications	<u>0.561</u>	
		0.561	?
<b>AMMUNITION</b>	Bustle ammo lost	0.004	
	Hull ammo lost	<u>0.004</u>	
		0.008	?
<b>K-kill</b>		0.090	0.090      0.090

Figure D-2. DAL vs. DS numerical comparison

Threat: P1  
 Range: 1 km  
 Azimuth: 60 degrees  
 Exposure: fully  
 Dispersion: 2 ft

		DEGRADED STATES	DAL	
			Basic	No crew or commo or acquisition
<b>MOBILITY</b>	Reduced speed, slight	0.063		
	Reduced speed, significant	0.268		
	Total immobilization	<u>0.417</u>		
		0.748	0.731	0.606
<b>FIREPOWER</b>	Loss of main armament	0.528		
	Increased time to fire			
	Reduced delivery accuracy	0.045		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.198		
	Loss of main armament			
	Loss of secondary armament	<u>0.046</u>		
	0.817	0.790	0.753	
<b>ACQUISITION</b>	Reduced acquisition capability	0.026		
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.789</u>		
		0.815	?	
<b>CREW</b>	One crew casualty	0.256		
	Two crew casualties	0.155		
	Three crew casualties	0.032		
	Four crew casualties	<u>0.045</u>		
		0.488	?	
<b>COMMO</b>	No internal communications			
	No external communications	<u>0.600</u>		
		0.600	?	
<b>AMMUNITION</b>	Bustle ammo lost	<u>0.005</u>		
		0.005	?	?
<b>K-kill</b>		0.045	0.045	0.045

Figure D-3. DAL vs. DS numerical comparison

Threat: P1  
 Range: 1 km  
 Azimuth: 90 degrees  
 Exposure: fully  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		DAL	
		<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, slight	0.035	
	Reduced speed, significant	0.307	
	Total immobilization	<u>0.278</u>	
		0.620	0.652      0.487
<b>FIREPOWER</b>	Loss of main armament	0.383	
	Increased time to fire		
	Reduced delivery accuracy	0.057	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.252	
	Loss of main armament	<u>0.028</u>	
	Loss of secondary armament	0.720	0.711      0.638
<b>ACQUISITION</b>	Reduced acquisition capability	0.036	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.713</u>	
		0.749	?
<b>CREW</b>	One crew casualty	0.194	
	Two crew casualties	0.140	
	Three crew casualties	0.116	
	Four crew casualties	<u>0.028</u>	
		0.478	?
<b>COMMO</b>	No internal communications		
	No external communications	<u>0.497</u>	
		0.497	?
<b>AMMUNITION</b>	Bustle ammo lost	<u>0.001</u>	
		0.001	?      ?
<b>K-kill</b>		0.028	0.027      0.027

Figure D-4. DAL vs. DS numerical comparison

Threat: P1  
 Range: 1 km  
 Azimuth: 0 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

		DEGRADED STATES	DAL	
			Basic	No crew or commo or acquisition
MOBILITY	Reduced speed, significant	0.022	0.324	0.197
	Total immobilization	<u>0.183</u>		
		0.205		
FIREPOWER	Loss of main armament	0.529	0.730	0.674
	Increased time to fire			
	Reduced delivery accuracy	0.007		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.050		
	Loss of main armament			
	Loss of secondary armament	<u>0.094</u>		
		0.680		
ACQUISITION	Reduced acquisition capability	0.066	?	
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.498</u>		
		0.564		
CREW	One crew casualty	0.212	?	
	Two crew casualties	0.129		
	Three crew casualties	0.027		
	Four crew casualties	<u>0.094</u>		
		0.462		
COMMO	No internal communications		?	
	No external communications	<u>0.233</u>		
		0.233		
AMMUNITION	Bustle ammo lost	<u>0.009</u>	?	?
		0.009		
K-kill		0.094	0.093	0.093

Figure D-5. DAL vs. DS numerical comparison

Threat: P1  
 Range: 1 km  
 Azimuth: 30 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>			<u>DAL</u>	
			<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, significant	0.088		
	Total immobilization	<u>0.148</u>		
		0.236	0.374	0.206
<b>FIREPOWER</b>	Loss of main armament	0.526		
	Increased time to fire			
	Reduced delivery accuracy	0.005		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.085		
	Loss of main armament			
	Loss of secondary armament	<u>0.098</u>		
		0.714	0.757	0.707
<b>ACQUISITION</b>	Reduced acquisition capability	0.122		
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.535</u>		
		0.657	?	
<b>CREW</b>	One crew casualty	0.271		
	Two crew casualties	0.120		
	Three crew casualties	0.023		
	Four crew casualties	<u>0.098</u>		
		0.512	?	
<b>COMMO</b>	No internal communications			
	No external communications	<u>0.386</u>		
		0.386	?	
<b>AMMUNITION</b>	Bustle ammo lost	0.008		
	Hull ammo lost	<u>0.004</u>	?	?
		0.012		
<b>K-kill</b>		0.098	0.097	0.097

Figure D-6. DAL vs. DS numerical comparison

Threat: P1  
 Range: 1 km  
 Azimuth: 60 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		DAL	
		<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, significant	0.167	
	Total immobilization	<u>0.099</u>	
		0.266	0.437      0.208
<b>FIREPOWER</b>	Loss of main armament	0.490	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.159	
	Loss of main armament		
	Loss of secondary armament	<u>0.056</u>	
		0.705	0.784      0.697
<b>ACQUISITION</b>	Reduced acquisition capability	0.125	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.530</u>	
		0.655	?
<b>CREW</b>	One crew casualty	0.255	
	Two crew casualties	0.213	
	Three crew casualties	0.034	
	Four crew casualties	<u>0.056</u>	
		0.558	?
<b>COMMO</b>	No internal communications		
	No external communications	<u>0.467</u>	
		0.467	?
<b>AMMUNITION</b>	Bustle ammo lost	<u>0.009</u>	
		0.009	?      ?
<b>K-kill</b>		0.056	0.056      0.056

Figure D-7. DAL vs. DS numerical comparison

Threat: P1  
 Range: 1 km  
 Azimuth: 90 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		DAL	
		<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, significant	0.287	
	Total immobilization	<u>0.044</u>	
		0.331	0.543      0.230
<b>FIREPOWER</b>	Loss of main armament	0.429	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.214	
	Loss of main armament		
	Loss of secondary armament	<u>0.013</u>	
		0.656	0.775      0.642
<b>ACQUISITION</b>	Reduced acquisition capability	0.105	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.576</u>	
		0.681	?
<b>CREW</b>	One crew casualty	0.141	
	Two crew casualties	0.298	
	Three crew casualties	0.174	
	Four crew casualties	<u>0.013</u>	
		0.626	?
<b>COMMO</b>	No internal communications	0.609	
	No external communications	<u>0.609</u>	
		0.609	?
<b>AMMUNITION</b>	Bustle ammo lost		?
			?
<b>K-kill</b>		0.013	0.014      0.014

Figure D-8. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 0 degrees  
 Exposure: fully  
 Dispersion: 2 ft

		DEGRADED STATES	DAL	
			Basic	No crew or commo or acquisition
<b>MOBILITY</b>	Reduced speed, significant	0.004		
	Total immobilization	<u>0.075</u>		
		0.079	0.113	0.082
<b>FIREPOWER</b>	Loss of main armament	0.127		
	Increased time to fire			
	Reduced delivery accuracy	0.002		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.013		
	Loss of main armament			
	Loss of secondary armament	<u>0.005</u>		
		0.147	0.147	0.144
<b>ACQUISITION</b>	Reduced acquisition capability	0.018		
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.114</u>		
		0.132	?	
<b>CREW</b>	One crew casualty	0.031		
	Two crew casualties	0.023		
	Three crew casualties	0.027		
	Four crew casualties	<u>0.005</u>		
		0.086	?	
<b>COMMO</b>	No internal communications			
	No external communications	0.038		
		<u>0.038</u>	?	
<b>AMMUNITION</b>	Bustle ammo lost	0.003		
		<u>0.003</u>		
		0.003	?	?
<b>K-kill</b>		0.005	0.005	0.005

Figure D-9. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 30 degrees  
 Exposure: fully  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		DAL	
		Basic	No crew or commo or acquisition
<b>MOBILITY</b>	Reduced speed, significant	0.066	
	Reduced speed, slight	0.057	
	Total immobilization	<u>0.297</u>	
		0.420	0.377    0.356
<b>FIREPOWER</b>	Loss of main armament	0.135	
	Increased time to fire		
	Reduced delivery accuracy	0.021	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.081	
	Loss of main armament		
	<u>0.012</u>		
	0.249	0.225    0.218	
<b>ACQUISITION</b>	Reduced acquisition capability	0.012	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.236</u>	?
		0.248	
<b>CREW</b>	One crew casualty	0.052	
	Two crew casualties	0.016	
	Three crew casualties	0.006	
	Four crew casualties	<u>0.012</u>	?
		0.086	
<b>COMMO</b>	No internal communications		
	No external communications	<u>0.101</u>	?
		0.101	
<b>AMMUNITION</b>	Bustle ammo lost	<u>0.001</u>	?
		0.001	?
<b>K-kill</b>		0.012	0.011    0.011

Figure D-10. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 60 degrees  
 Exposure: fully  
 Dispersion: 2 ft

		DEGRADED STATES	DAL	
			Basic	No crew or commo or acquisition
<b>MOBILITY</b>	Reduced speed, slight	0.075		
	Reduced speed, significant	0.258		
	Total immobilization	<u>0.348</u>		
		0.681	0.646	0.533
<b>FIREPOWER</b>	Loss of main armament	0.447		
	Increased time to fire			
	Reduced delivery accuracy	0.044		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.194		
	Loss of main armament			
	Loss of secondary armament	<u>0.011</u>		
		0.696	0.676	0.632
<b>ACQUISITION</b>	Reduced acquisition capability	0.021		
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.689</u>		
		0.710	?	
<b>CREW</b>	One crew casualty	0.211		
	Two crew casualties	0.121		
	Three crew casualties	0.032		
	Four crew casualties	<u>0.011</u>		
		0.375	?	
<b>COMMO</b>	No internal communications			
	No external communications	<u>0.487</u>		
		0.487	?	
<b>AMMUNITION</b>	Bustle ammo lost	0.002		
	Hull ammo lost	<u>0.001</u>		
		0.003	?	?
<b>K-kill</b>		0.011	0.010	0.010

Figure D-11. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 90 degrees  
 Exposure: fully  
 Dispersion: 2 ft

DEGRADED STATES		DAL		
		Basic	No crew or commo or acquisition	
<b>MOBILITY</b>	Reduced speed, slight	0.036		
	Reduced speed, significant	0.284		
	Total immobilization	<u>0.250</u>		
		0.570	0.605	0.447
<b>FIREPOWER</b>	Loss of main armament	0.341		
	Increased time to fire			
	Reduced delivery accuracy	0.058		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.255		
	Loss of main armament	<u>0.025</u>		
Loss of secondary armament	0.679	0.667	0.594	
<b>ACQUISITION</b>	Reduced acquisition capability	0.036		
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.676</u>		
		0.712	?	
<b>CREW</b>	One crew casualty	0.173		
	Two crew casualties	0.128		
	Three crew casualties	0.104		
	Four crew casualties	<u>0.025</u>		
		0.430	?	
<b>COMMO</b>	No internal communications			
	No external communications	<u>0.454</u>		
		0.454	?	
<b>AMMUNITION</b>	Bustle ammo lost	0.002		
		<u>0.002</u>	?	?
<b>K-kill</b>		0.025	0.024	0.024

Figure D-12. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 0 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>			DAL	
			<u>Basic</u>	<u>No crew or commo or acquisition</u>
MOBILITY	Reduced speed, significant	0.002		
	Total immobilization	<u>0.021</u>		
		0.023	0.054	0.022
FIREPOWER	Loss of main armament	0.130		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.024		
	Loss of main armament			
	Loss of secondary armament	<u>0.020</u>		
		0.174	0.197	0.179
ACQUISITION	Reduced acquisition capability	0.026		
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.073</u>		
		0.099	?	
CREW	One crew casualty	0.039		
	Two crew casualties	0.019		
	Three crew casualties	0.012		
	Four crew casualties	<u>0.020</u>		
		0.090	?	
COMMO	No internal communications			
	No external communications	<u>0.025</u>		
		0.025	?	
AMMUNITION	Bustle ammo lost	<u>0.007</u>		
		0.007	?	?
K-kill		0.020	0.020	0.020

Figure D-13. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 30 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		DAL	
		<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, significant	0.020	
	Total immobilization	<u>0.005</u>	
		0.025	0.036      0.017
<b>FIREPOWER</b>	Loss of main armament	0.116	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.048	
	Loss of main armament		
	Loss of secondary armament	<u>0.005</u>	
		0.169	0.187      0.168
<b>ACQUISITION</b>	Reduced acquisition capability	0.042	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.078</u>	
		0.120	?
<b>CREW</b>	One crew casualty	0.045	
	Two crew casualties	0.011	
	Three crew casualties	0.002	
	Four crew casualties	<u>0.005</u>	
		0.063	?
<b>COMMO</b>	No internal communications		
	No external communications	<u>0.020</u>	
		0.020	?
<b>AMMUNITION</b>	Bustle ammo lost	<u>0.001</u>	
		0.001	?      ?
<b>K-kill</b>		0.005	0.005      0.005

Figure D 14. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 60 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

			DAL	
			Basic	No crew or commo or acquisition
<b>MOBILITY</b>	Reduced speed, significant	0.111		
	Total immobilization	<u>0.019</u>		
		0.130	0.241	0.093
<b>FIREPOWER</b>	Loss of main armament	0.168		
	Unable to fire on the move			
	Increased time to fire			
	Reduced delivery accuracy	0.115		
	Loss of main armament			
	Loss of secondary armament	<u>0.007</u>		
		0.290	0.361	0.285
<b>ACQUISITION</b>	Reduced acquisition capability	0.058		
	Reduced acquisition capability			
	Unable to acquire while moving	<u>0.247</u>		
		0.305	?	
<b>CREW</b>	One crew casualty	0.113		
	Two crew casualties	0.127		
	Three crew casualties	0.293		
	Four crew casualties	<u>0.007</u>		
		0.046	?	
<b>COMMO</b>	No internal communications			
	No external communications	<u>0.278</u>		
		0.278	?	
<b>AMMUNITION</b>	Bustle ammo lost	<u>0.004</u>		
		0.004	?	?
<b>K-kill</b>		0.007	0.007	0.007

Figure D-15. DAL vs. DS numerical comparison

Threat: P2  
 Range: 1 km  
 Azimuth: 90 degrees  
 Exposure: defilade  
 Dispersion: 2 ft

<u>DEGRADED STATES</u>		DAL	
		<u>Basic</u>	<u>No crew or commo or acquisition</u>
<b>MOBILITY</b>	Reduced speed, significant	0.247	
	Total immobilization	<u>0.018</u>	
		0.265	0.466      0.178
<b>FIREPOWER</b>	Loss of main armament	0.286	
	Unable to fire on the move		
	Increased time to fire		
	Reduced delivery accuracy	0.176	
	Loss of main armament		
	Loss of secondary armament	<u>0.012</u>	
		0.474	0.594      0.464
<b>ACQUISITION</b>	Reduced acquisition capability	0.088	
	Reduced acquisition capability		
	Unable to acquire while moving	<u>0.462</u>	
		0.550	?
<b>CREW</b>	One crew casualty	0.084	
	Two crew casualties	0.272	
	Three crew casualties	0.168	
	Four crew casualties	<u>0.011</u>	
		0.535	?
<b>COMMO</b>	No internal communications		
	No external communications	<u>0.541</u>	
		0.541	?
<b>AMMUNITION</b>			
<b>K-kill</b>		0.011	0.012      0.012

Figure D-16. DAL vs. DS numerical comparison

**APPENDIX E**

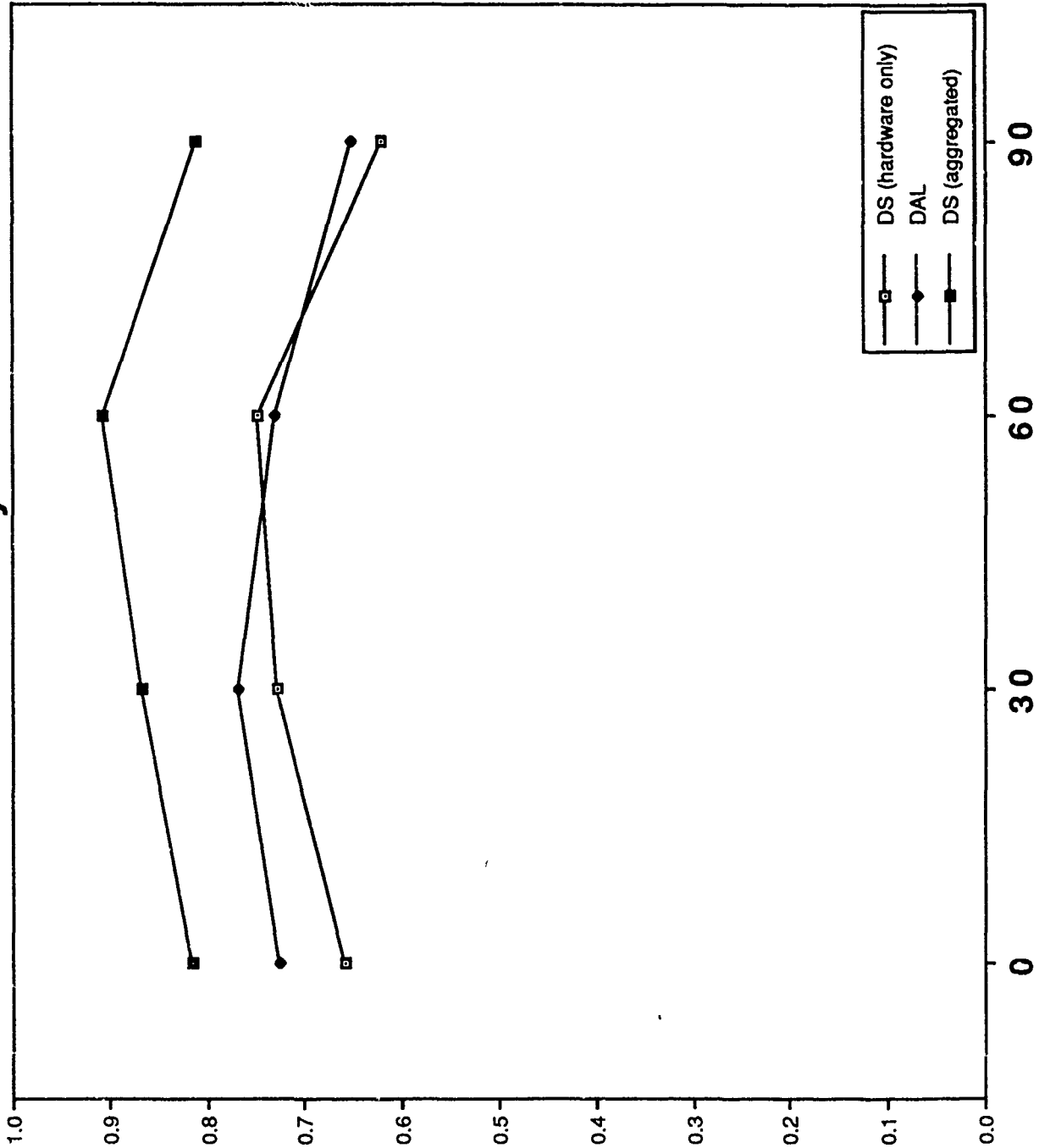
**Aggregated Degraded States vs. DAL Comparisons**

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This appendix contains line graphs which illustrate the numerical comparisons of the aggregated DS probabilities and the basic DAL LOF values. The values being compared are described as follows: DS "hardware only" probabilities give the probability of some damage to a particular kill category; DS aggregated probabilities give the probability of some damage to any of several kill categories; and, DAL LOF values are from the basic DAL.

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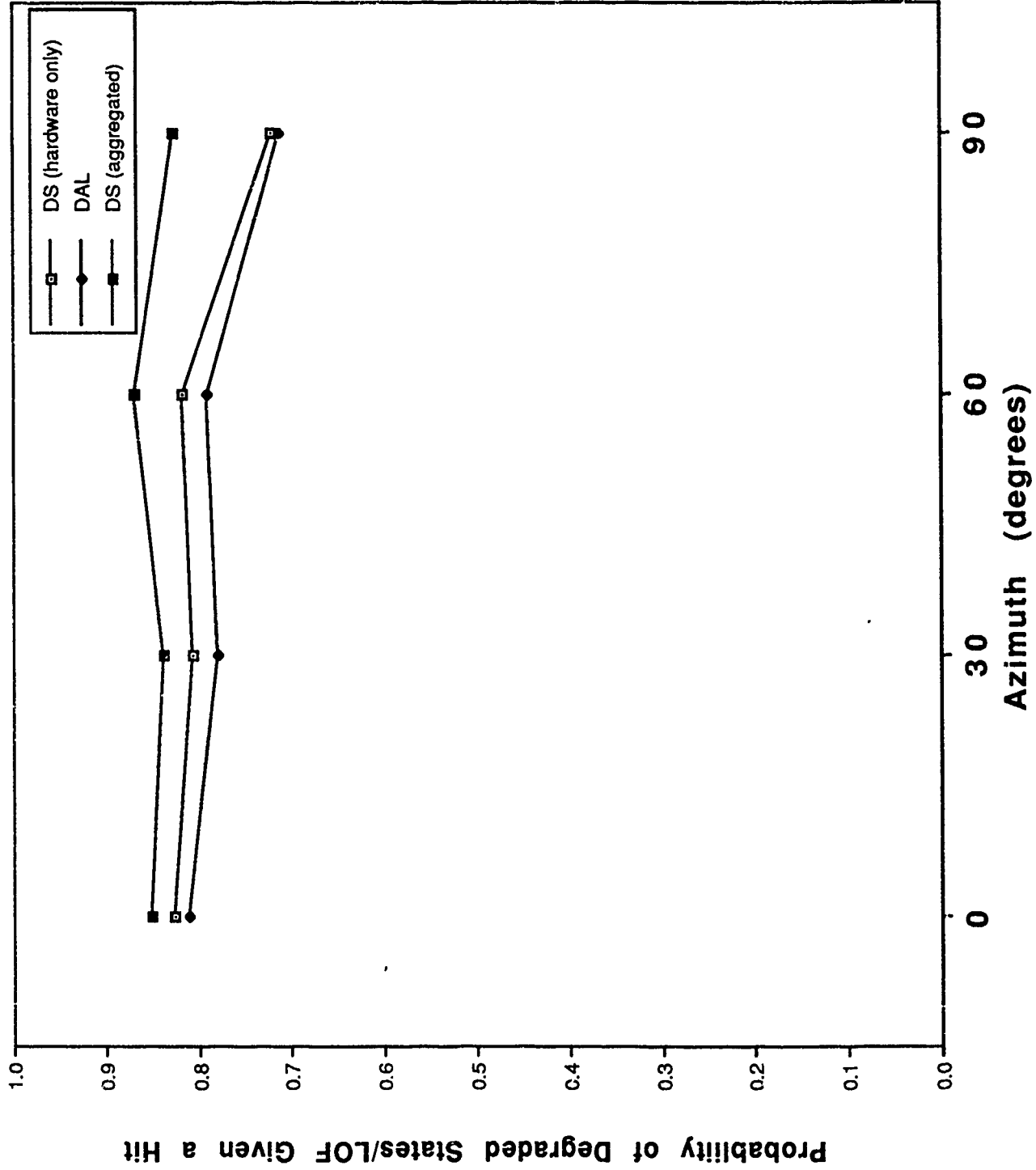
# Mobility



Threat: P1  
Range: 1km  
Exposure: fully  
Dispersion: 2ft

Figure E-1. Aggregated DS vs. DAL Comparison

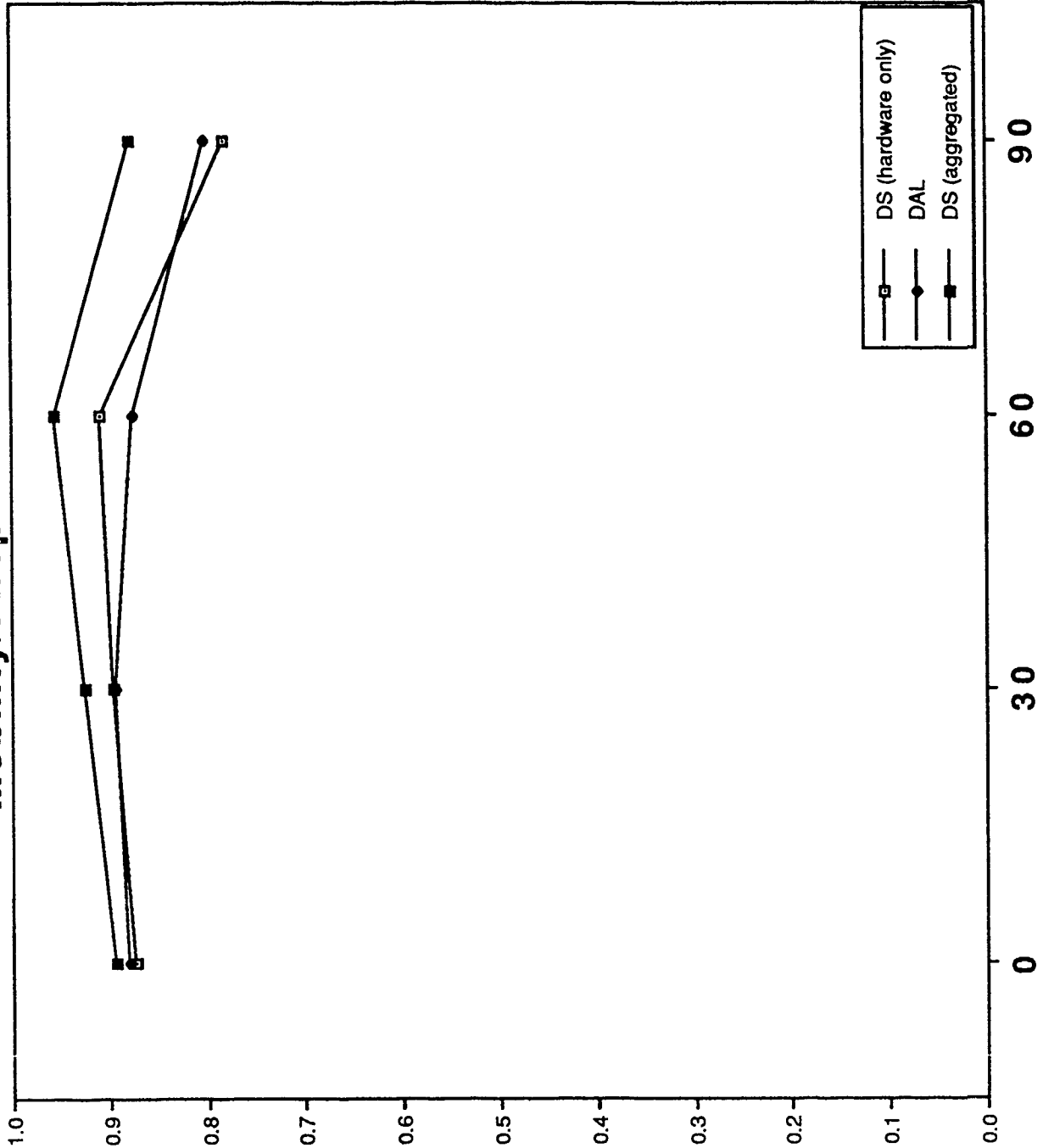
# Firepower



Threat: P1  
Range: 1km  
Exposure: fully  
Dispersion: 2ft

Figure E-2. Aggregated DS vs. DAL Comparison

# Mobility/Firepower



Threat: P1  
 Range: 1km  
 Exposure: fully  
 Dispersion: 2ft

# Azimuth (degrees)

Figure E-3. Aggregated DS vs. DAL Comparison

# Mobility

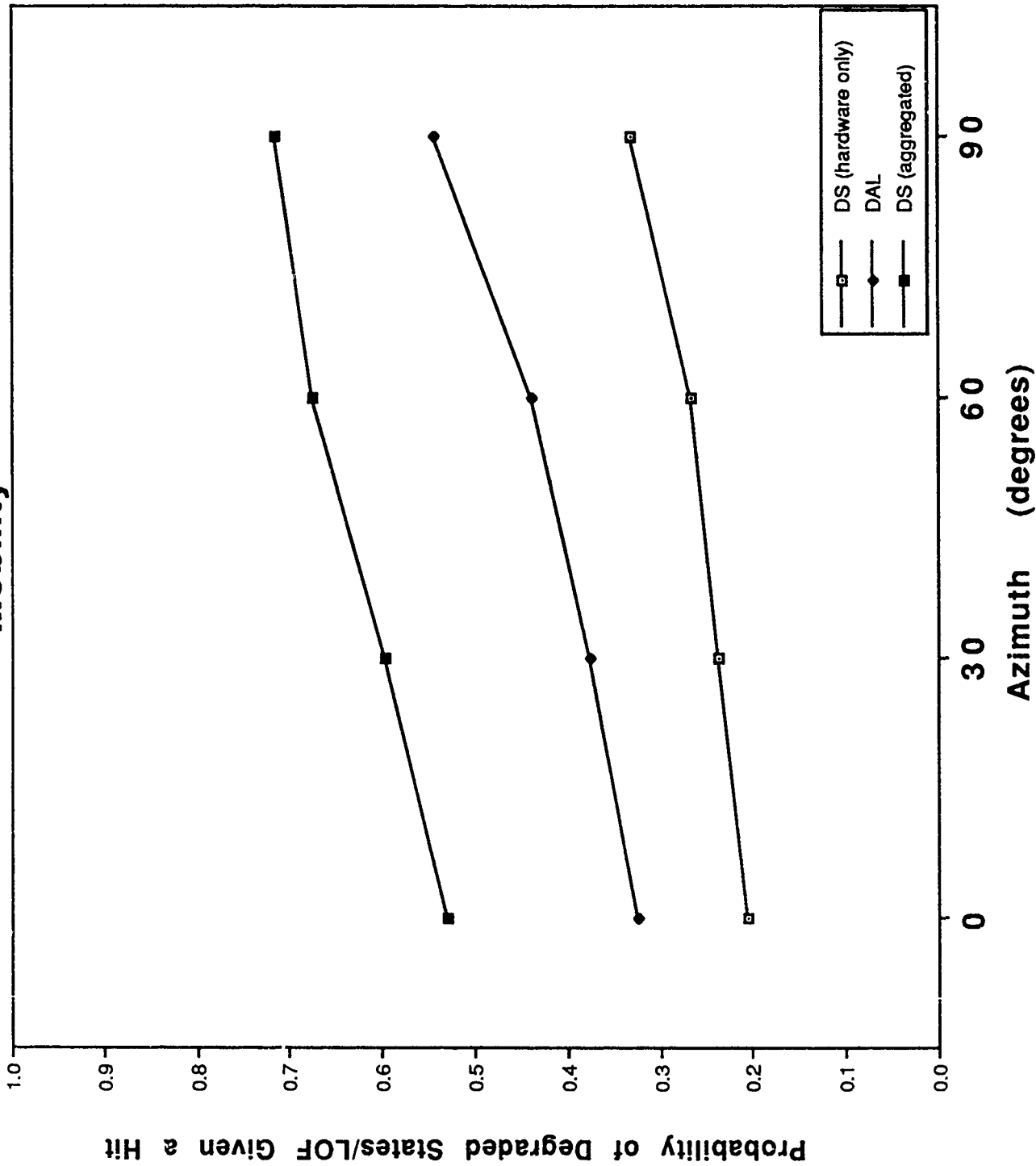
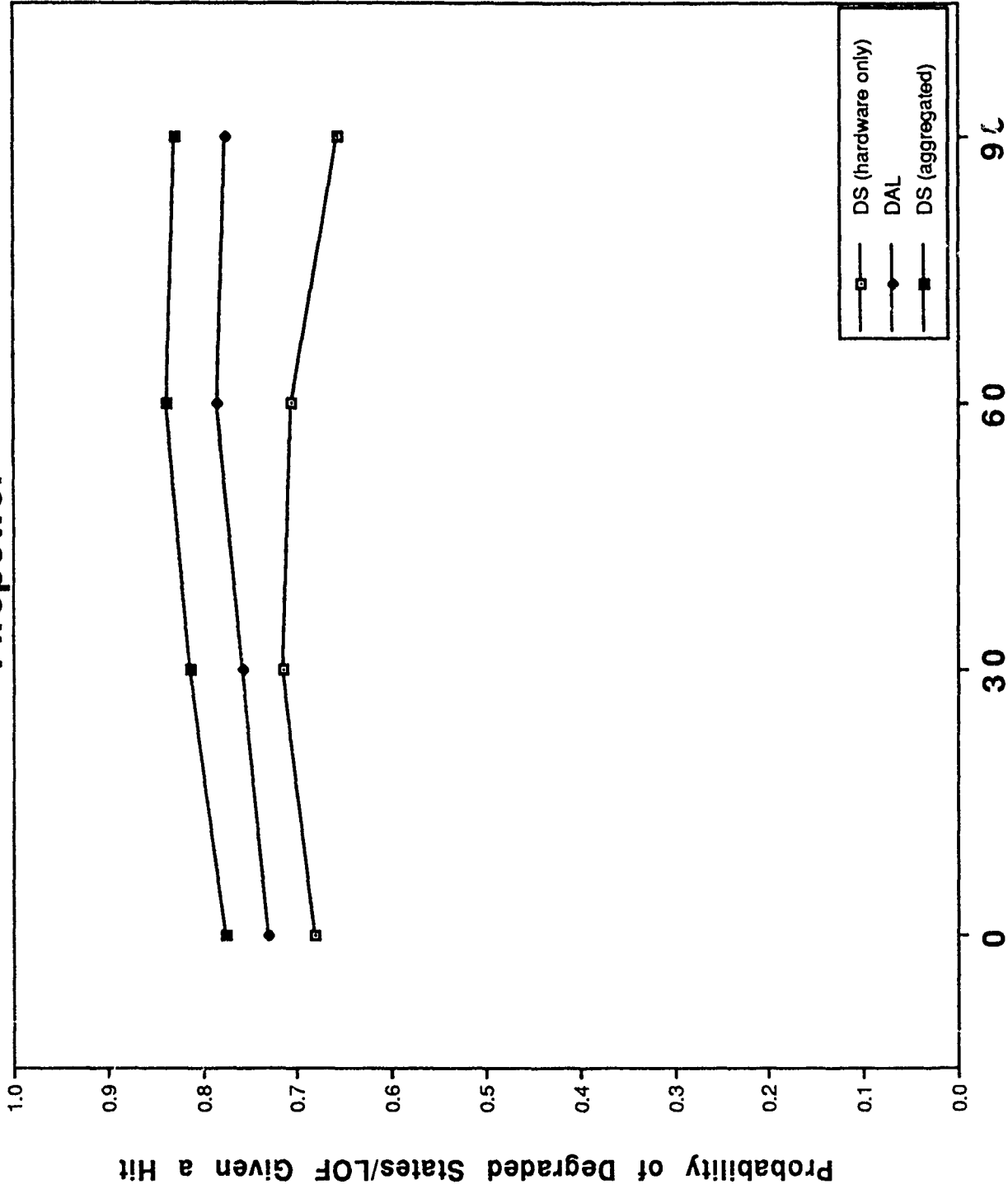


Figure E-4. Aggregated DS vs. DAL Comparison

# Firepower

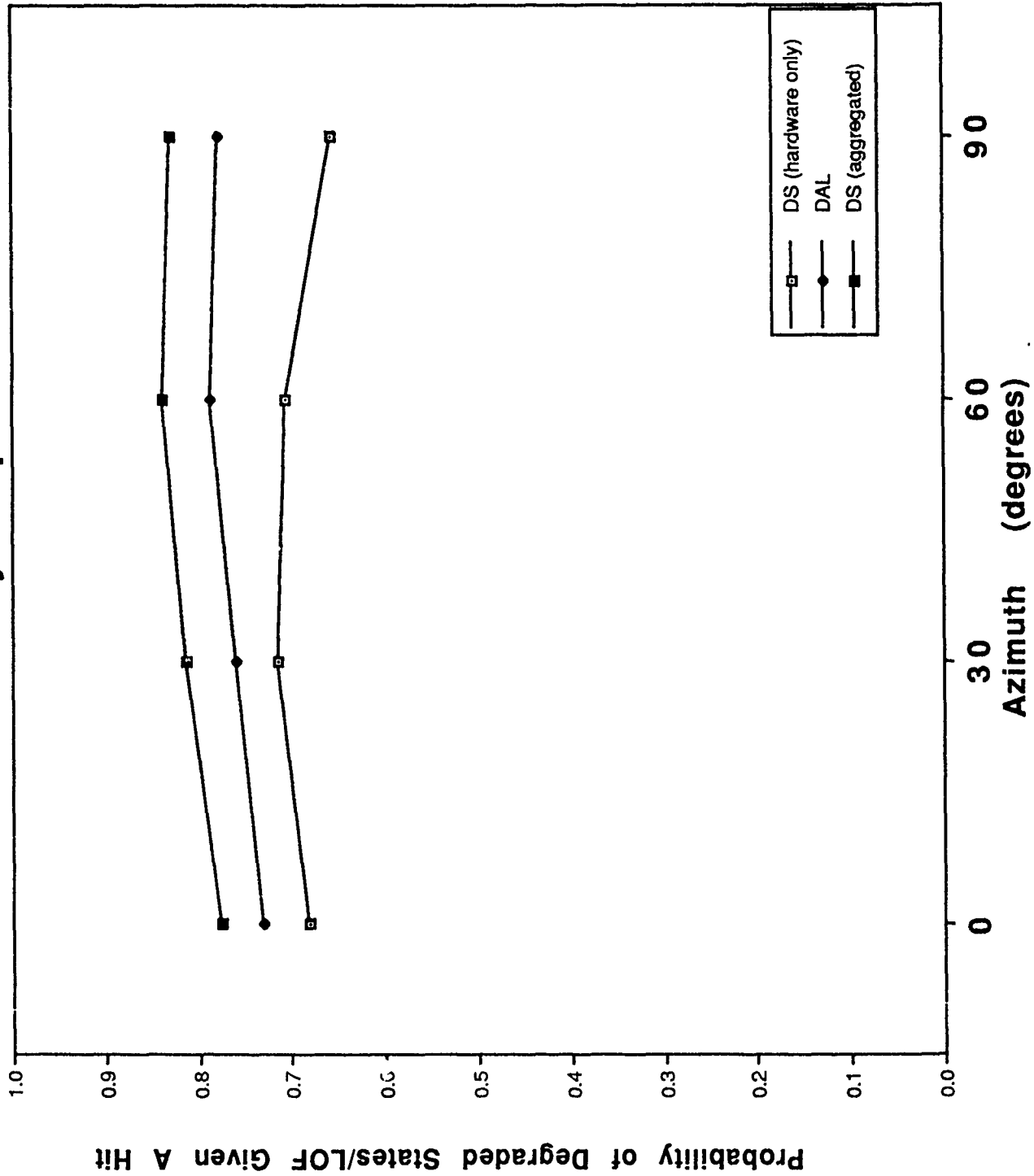


Threat: P1  
Range: 1km  
Exposure: defilade  
Dispersion: 2ft

# Azimuth (degrees)

Figure E-5. Aggregated DS vs. DAL Comparison

# Mobility/Firepower



Threat: P1  
 Range: 1km  
 Exposure: defilade  
 Dispersion: 2ft

Figure E-6. Aggregated DS vs. DAL Comparison

# Mobility

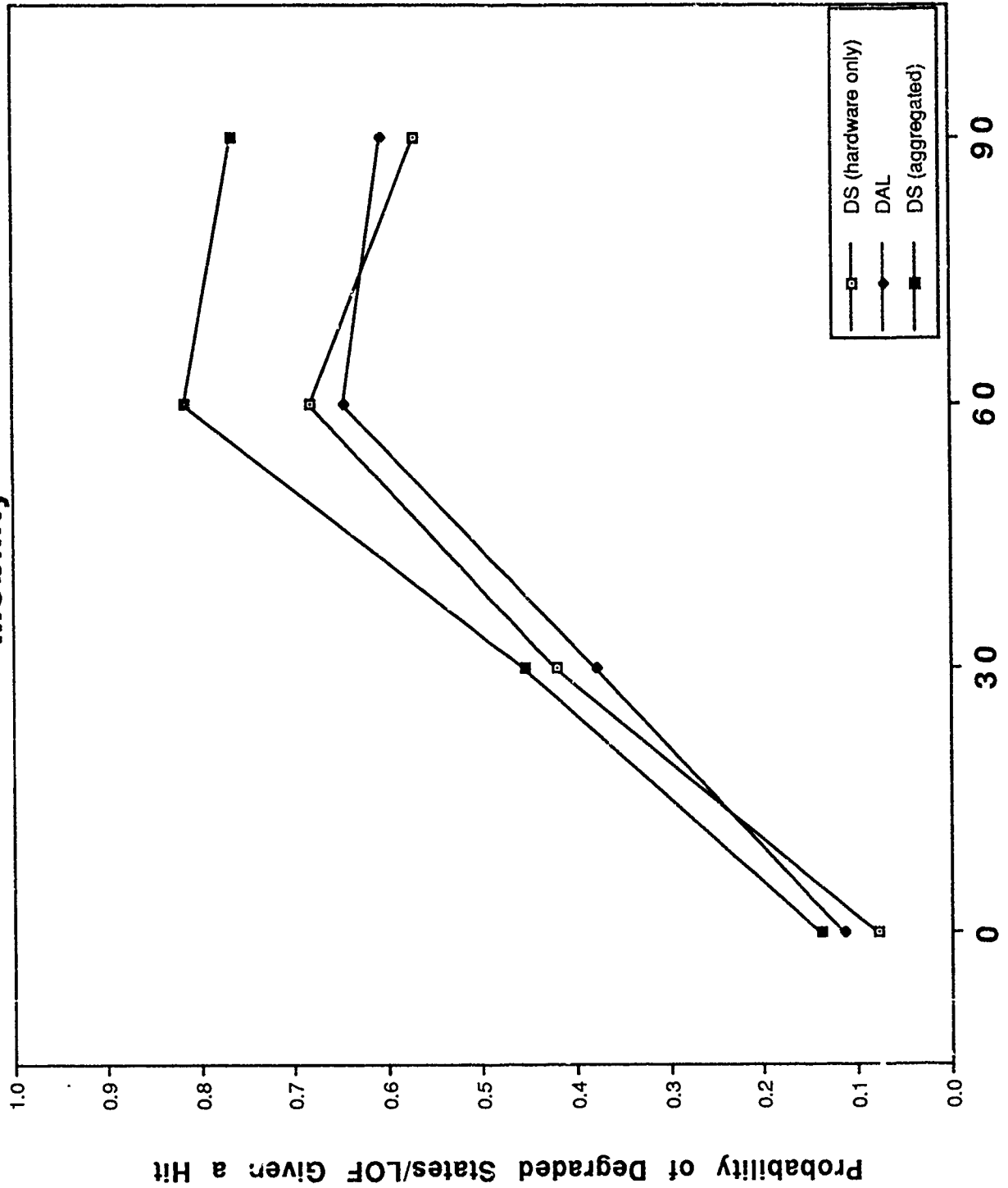


Figure E-7. Aggregated DS vs. DAL Comparison

# Firepower

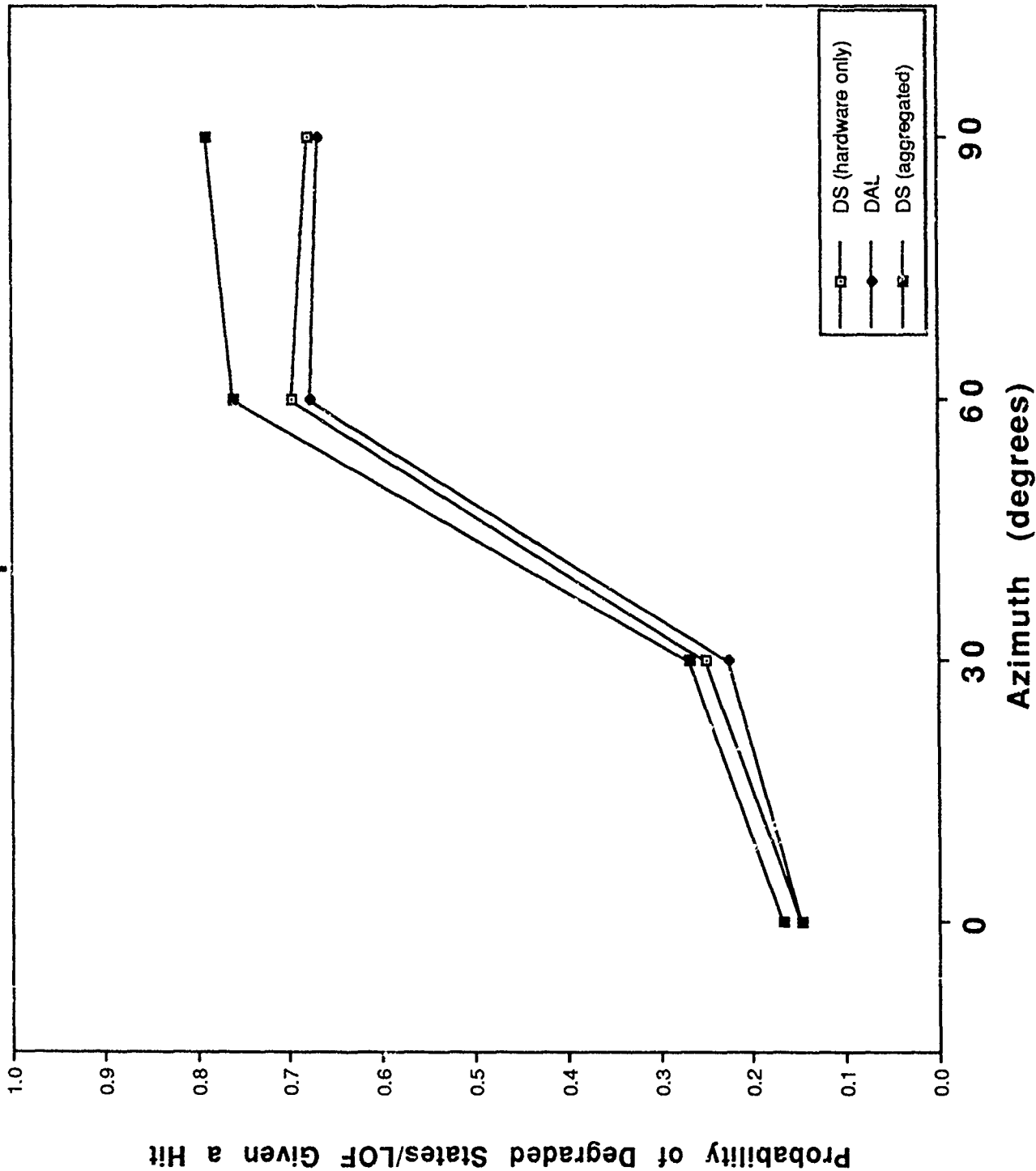
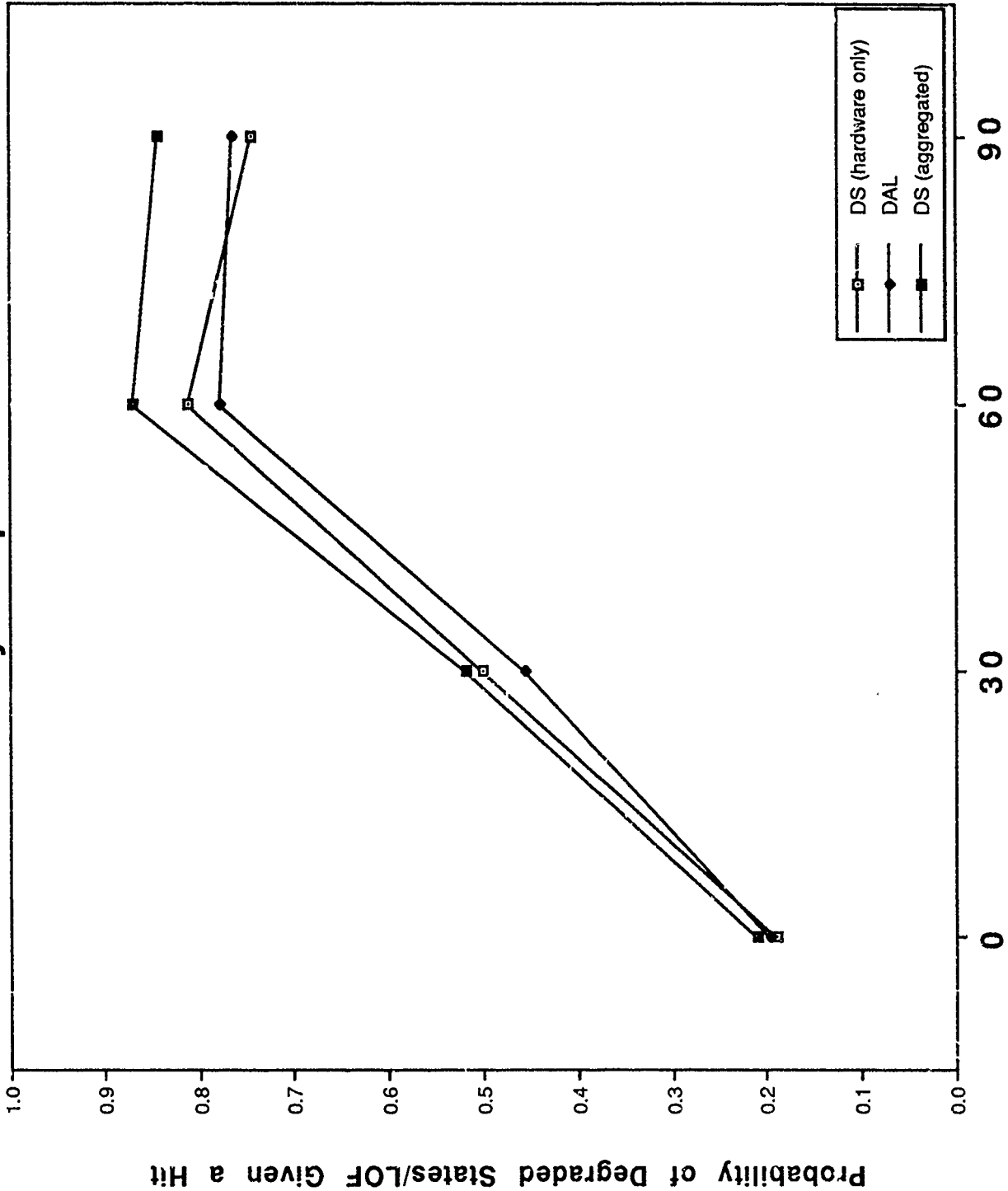


Figure E-8. Aggregated DS vs. DAL Comparison

# Mobility/Firepower



Threat: P2  
Range: 1km  
Exposure: fully  
Dispersion: 2ft

Figure E-9. Aggregated DS vs. DAL Comparison

# Mobility

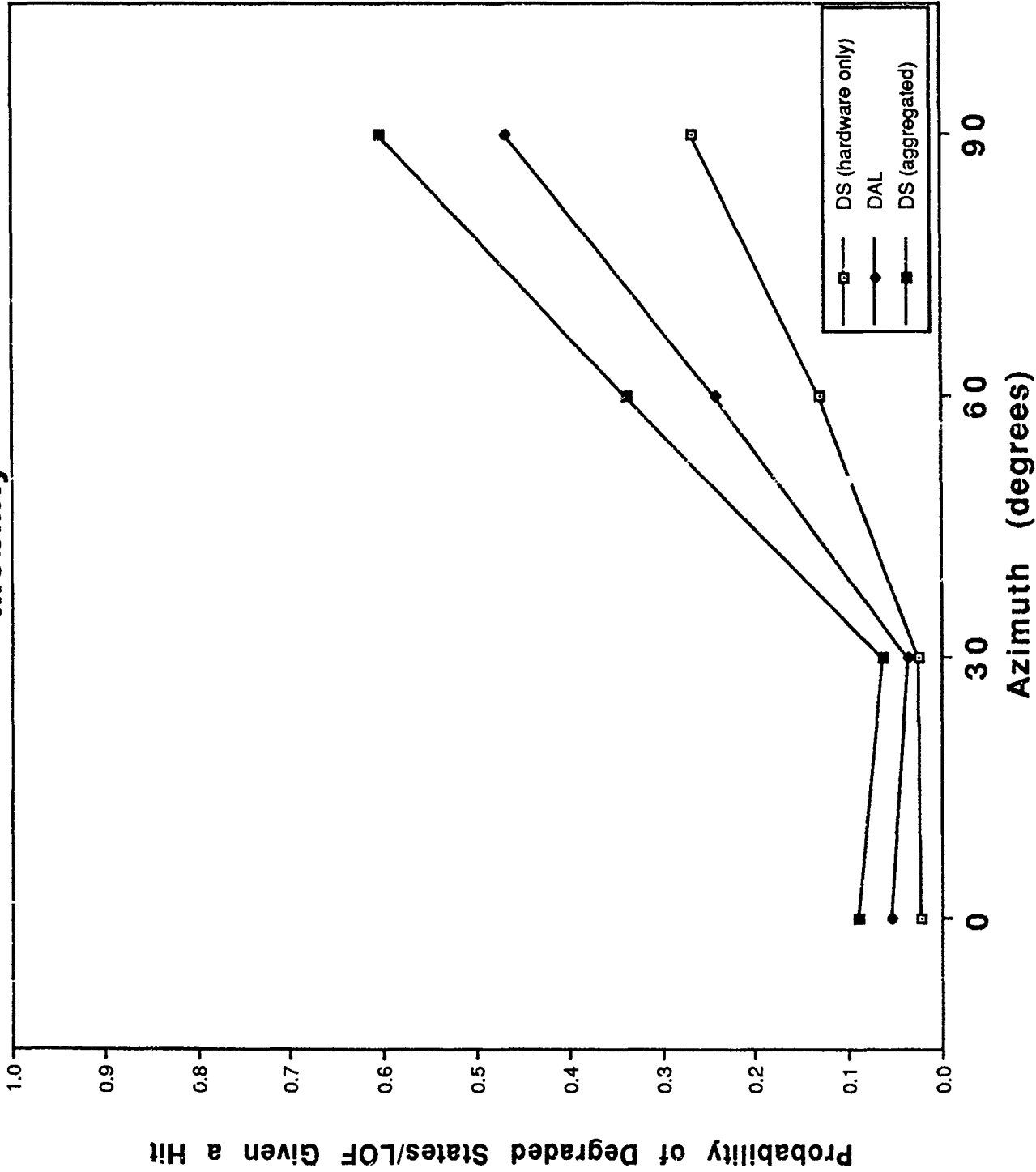


Figure E-10. Aggregated DS vs. DAL Comparison

# Firepower

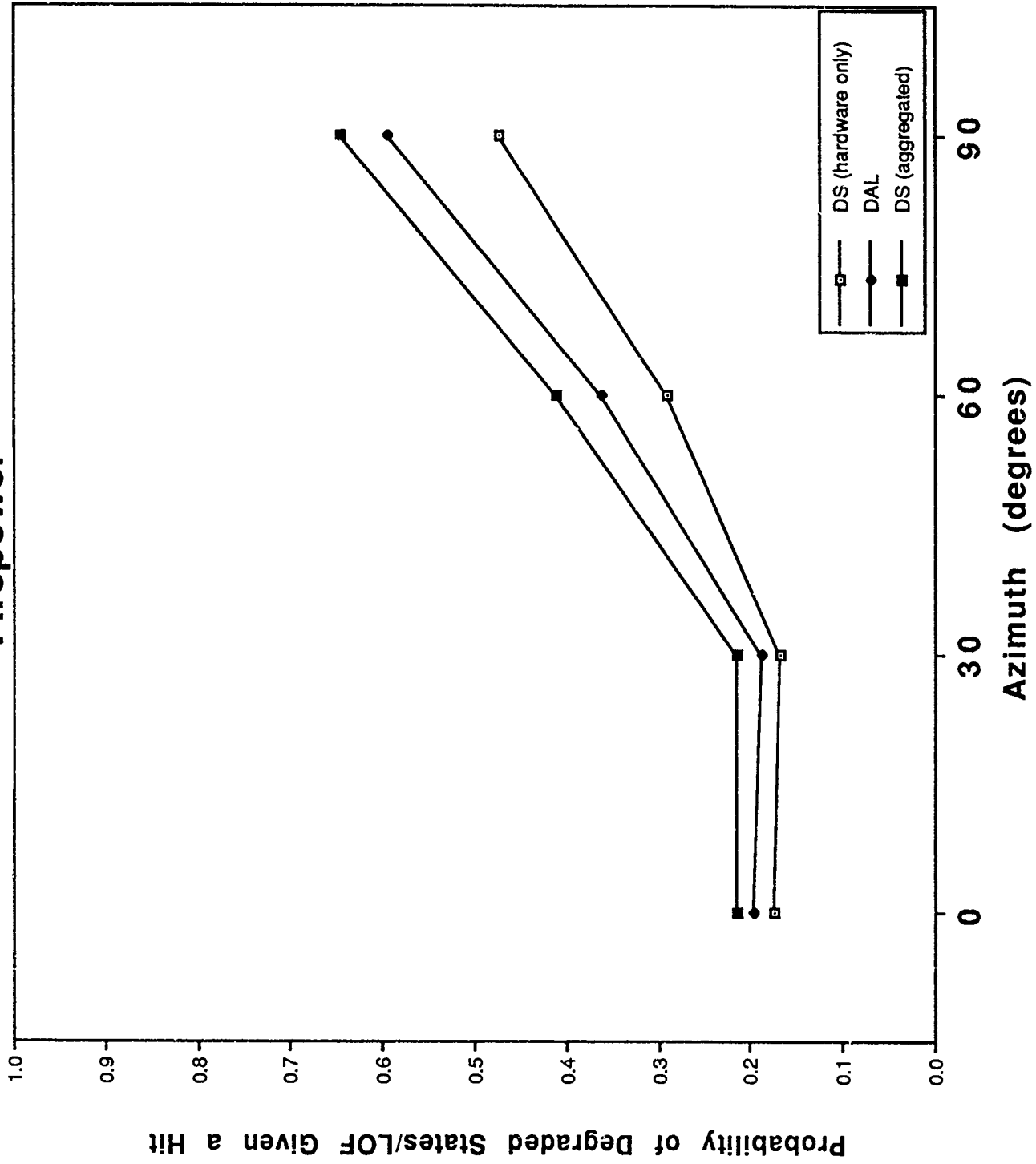
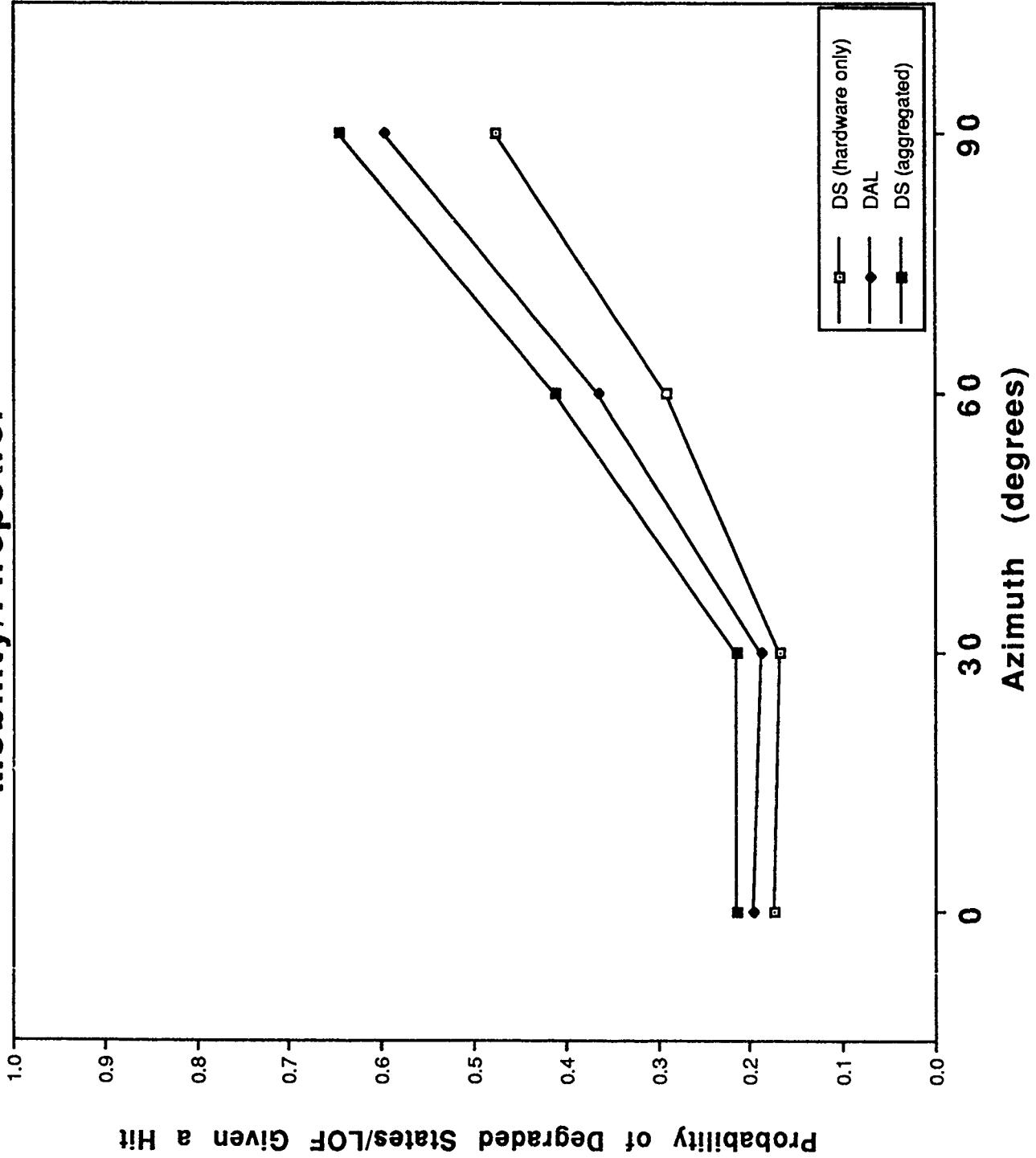


Figure E-11. Aggregated DS vs. DAL Comparison

# Mobility/Firepower



Threat: P2  
Range: 1km  
Exposure: defilade  
Dispersion: 2ft

Figure E-12. Aggregated DS vs. DAL Comparison

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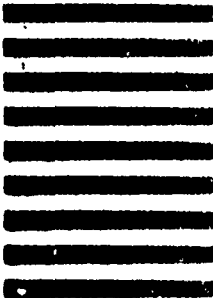


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