FRAGMENTATION HAZARD

COMPUTER MODEL

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This model provides a method for establishing the fragment hazard produced by the mass-detonation of ammunition stacks stored in the open. Fragmentation characteristics used as input to the model are derived from small-scale arena tests. In the case of 155mm projectiles, for example, the small-scale test may consist of one or more pallets positioned and detonated to yield a representative sample of an entire stack.

Hazardous fragmentation is defined by the Explosive Safety Board as follows:

1. Fragment kinetic energy of at least 58 ft-lbs.

2. Hazardous fragment density of at least one fragment per 600 square feet.

The hazardous fragment density criterion is equivalent to a hit probability of .01 given that the presented area of a man is six square feet.

The unique feature of the model lies in the fact that a complete trajectory is calculated for each fragment recovered in the small-scale arena tests. This procedure requires a great amount of calculations which are made practical by modern high speed computers.

Past tests have demonstrated that virtually all the fragmentation going down-range is produced by the ordnance (projectiles, bombs, etc.) on the face of the stack pointing toward the target area. Fragmentation from the ordnance in the interior of the stack is, for the most part, contained within the stack. When a stack is detonated, fragment jets are produced between adjacent items on the face of the stack. The width of the jet is dependent on the method of stack initiation. When all units are detonated simultaneously, the jet is typically 10 degrees wide. If only one or two donor units are initially detonated, the jet width is more typically 20 degrees. Stack detonation by donor units is called natural communication and all current testing uses this technique.

The jets produced between adjacent units are called interaction areas. The greatest fragment densities and highest velocities are produced within the interaction areas. For safety purposes, the fragmentation characteristics of the interaction areas are used for input to the computer model. The interaction areas overlap at relatively short distances down-range and their effects can therefore be added to represent the cumulative effect of large ammunition stacks.

Figure 1 shows the essential elements of the model. Since interaction areas overlap at relatively short distances down-range, all fragments are assumed to emanate from a vertical line at the center of the stack. The height of the vertical line is made consistent with the typical stack height of the ordnance under consideration. The height at which an individual fragment originates is randomly selected within the program. A pie-shaped sector is used to simulate the down-range hazard volume. A hazardous fragment is only of concern when its trajectory lies within this pie-shaped hazard volume. The height of the sector is equal to the height of the man selected. The angular width of the sector is 10 degrees. This value has been selected to match the 10 degree sector width used in the fragment pickup from full-scale tests. In this way, one can compare the program predictions with actual test data to gauge the validity of the simulation model. The sector is divided into 100 feet segments from 0 to 4800 feet. All calculations of fragment numbers, fragment density, etc. are made in terms of these 100-feet segments. Later in the simulation, the results in each 100-feet segment may be combined to yield results for 200, 300 and 400 feet increments. This helps to produce smooth curves for final plotting. If results are plotted every 100 feet, a pronounced saw-toothed plot is usually produced.

Figure 2 shows a more detailed picture of a fragment trajectory. Wind is included as a two dimensional velocity vector having both a range and cross-range component. There is no vertical component to the wind vector. The wind, therfore, is always contained in a horizontal plane. The vertical position for the origin of the fragment trajectory is selected randomly from a range of heights typical of the stack heights for the ordnance under consideration. The trajectory is calculated using a fourth-order Runge-Kutta routine. Calculations are made in three dimensions with the effects of wind included. The Runge-Kutta routine requires initial conditions for fragment velocity and elevation angle which are obtained from fragment arena tests. Each point in the trajectory is calculated from the conditions existing at the previous point. The calculations continue until impact; at which time, the impact velocity and angle are determined. The impact velocity, together with the known fragment mass, are used to determine the kinetic energy. The impact kinetic energy is compared with a kinetic energy criterion to determine whether the fragment is hazardous. The impact angle is used in subsequent density and probability of hit calculations. Range, cross-range and distance are computed for hazard distance calculations. Currently, the initial fragment velocity vector is constrained to the vertical XY plane. However, since the model uses a true three dimensinal routine, there is complete three dimensional freedom for establishing initial conditions. Trajectory calculations are made for each fragment recovered in the small-scale test.

A tailwind has three effects on hazard conditions--all bad. First, a tailwind will increase the range of the fragments. Second, it will increase the impact velocity of the fragments thereby increasing their lethality. Third, a tailwind will decrease the angle of impact thereby increasing the presented area of the man which increases the probability of hit. The increased range due to a tailwind is approximately equal to the time of flight multiplied by the wind speed. In the far range where the time of flight is approximately 10 seconds, a tailwind speed of 50 feet per second will result in a range increase of about 500 feet.

Figure 3 shows the two types of trajectories considered in the model. The normal, or non-ricochet, trajectory has been considered above. The ricochet trajectory is a more recent addition to the model. It is based on experiments conducted by BRL, Aberdeen in the late 1960's (reference 1). In both types of trajectories, the points at which the fragment enters and leaves the hazard volume are accurately calculated. This permits the hazard to be definitely associated with the proper distance increment. When a fragment impacts the ground, its impact angle is compared with a critical ricochet angle to determine whether the fragment will ricochet. The critical ricochet angle is dependent on the type of soil. Once it is determined that the fragment will ricochet, the ricochet angle and velocity are determined from the incident angle and velocity together with the effect of the soil type. Since all the dynamic characteristics of the fragment are known at each point calculated in the Runge-Kutta routine, all fragment hazard characteristics can be calculated at each point. When more than one point is contained in a distance increment, averages are used to determine the hazard characteristics for the distance increment.

Figure 4 shows how hazard density and hazard probability of hit are calculated. Since the trajectories are calculated point by point, the distance increment of the hazard volume through which the fragment passes can be determined. The fragment mass and velocity are known at each point and, therefore, it can be determined whether the fragment possesses sufficient kinetic energy to exceed the hazardous kinetic energy criterion. After the fragment has been determined to be hazardous, the presented areas of the man and of the total volume of the distance increment can be calculated in the plane perpendicular to the fragment trajectory. This can be done because the trajectory angle with respects to the horizontal plane is calculated at each point along the trajectory. Once the presented areas of the man and of the total volume of the distance increment are known, the density and probability of hit can be calculated using the formulas shown on Figure 4. The number of hazardous fragments (N_f) is based on the data from arena tests using appropriate scaling techniques. Note that the man is depicted as a rectangular parallelepiped.

The model is run as a Monte Carlo program. Simply stated, this means that the values for certain variables are randomly selected for each trajectory calculation. The five variables which are randomly selected are:

1. Height of the trajectory origin
2. Initial fragment velocity
3. Initial fragment elevation angle
4. Drag coefficient
5. Soil constant for ricochet

The random values are selected within the known or assumed ranges of uncertainty for each variable. Once the appropriate values have been selected for the variables, trajectories are calculated for the entire set of fragments recovered from the small-scale arena test. The entire procedure is repeated (replicated) using different random values for the variables. In effect, each replication is a simulation of a full-scale test. The values of the output variables vary from replication to replication because of the random values used for the input variables for each replication. During each replication, data are saved for hazard calculations as a function of distance increments. In the program, 100 feet distance increments are used. Sufficient replications are made to permit density and probability of hit to settle near stable averages. Once these near stable averages are obtained, the number of rounds needed to just exceed the density and probability of hit criteria are calculated as a function of distance increment. These are the final data to be used in establishing the fragment hazard posed by the ammunition under consideration. The model includes methods for presenting the data at 100, 200, 300 and 400 feet distance increments. One of these increments will usuually produce relatively smooth data for plotting. With a 100 feet increment, the final data are usually quite saw-toothed. Since the model includes the effects of wind, the program can be run at various wind speeds, and the effect of wind noted.

Table 1 shows typical fragmentation input data. Each fragment recovered from the arena test has its own set of data. Usually all fragments less than 300 grains are eliminated. The small fragments are of little concern for the far ranges which are of most importance in establishing fragment hazards. The recovery polar zone is listed for each fragment. In the program, an angle is randomly selected between the polar zone limits to establish a distinct elevation angle for the fragment. The fragment weight is an exact number for each fragment and is not randomized. The initial velocity is an average for the polar zone in question. A random velocity about the average is picked to account for the uncertainty in velocity measurement. The A/M (average presented area to mass ratio) is an exact number for each fragment. This quantity enters the drag calculations. The area ratio (maximum to minimum fragment presented area) is used to establish the subsonic drag coefficient. The use of this ratio eliminates about one quarter of the uncertainty associated with the subsonic drag coefficient. Transonic and supersonic drag coefficients are established form the subsonic drag coefficient.

There are two basic outputs: Number of Final Ground Impacts versus Distance Increment and Hazard Distance versus Number of Rounds.

Table 2 shows the Number of Final Groud Impacts versus Distance Increment. Values for the minimum, average and maximum number of fragments are shown for each distance increment. The data apply to a 10 degree azimuth sector which is often used in the fragment pickup from full-scale tests. The data in Table 2 are used to compare the predicted and actual number of fragments picked up in the full-scale tests. This provides a check on the validity of the model. Each replication of the program will usually produce a different number of final ground impacts. After all replications are completed, the minimum, average and maximum numbers can be determined.

Table 3 shows the final output used to establish the hazard curves. The example shows a distance increment of 200 feet. The hazard distances are selected at the midpoints of the hazard increments so that the data are ready for plotting. Minimum, 90th percentile, average and maximum number of units required are shown. These numbers represent the required number of projectiles needed to just exceed a hazard density of one fragment per 600 square feet. The Explosive Safety Board currently specifies the use of 90th percentile quantities for hazard curves. The 999999 entries indicate that there were no hazardous fragments in the distance increment. The fewer the number of projectiles required, the more hazardous the condition. A similar table is also output for the hazardous probability of hit criterion.

Figure 5 shows an example plot of the final data for use in a safety manual. Note the steep rise and subsequent asymtotic behavior. Unlike hazardous blast radii, the fragmentation hazardous distance has an upper bound. This upper bound is equal to maximum fragment range obtained in the series of replications. No matter how many projectiles are on the face of the stack, the maximum range of the fragments constrains the upper bound.

The computer model provides a flexible tool for predicting the fragment hazards of open storage ammunition. Unlike analytical approaches, the Monte Carlo technique has the inherent capability of considering the multidimensional problem posed by fragmentation hazards. Future considerations are also more easily incorporated in a Monte Carlo model. In summary, the essential characterstics of the model are as follows:

- Individual 3-D fragment trajectories
- 2-D wind (horizontal plane)
- 4th order Runge-Kutta trajectory calculations
- Incorporates a 3-D man
- Can use different hazard criteria
- Air density and sound speed a function of altitude
- Drag coefficient a function of the maximum to minimum fragment area ratio
- Predicts distribution of final impacts in the ground plane
- Predicts hazard distance curves for:
    - Hazard density criterion
    - Hazard probability of hit criterion
- Includes fragment ricochet

Reference

1. Fragment Ricochet Off Homogeneous Soils and Its Effects on Weapon Lethality (U), Mark Reches, Army Material Systems Analysis Agency Technical Memorandum No. 79, August 1970, CONFIDENTIAL

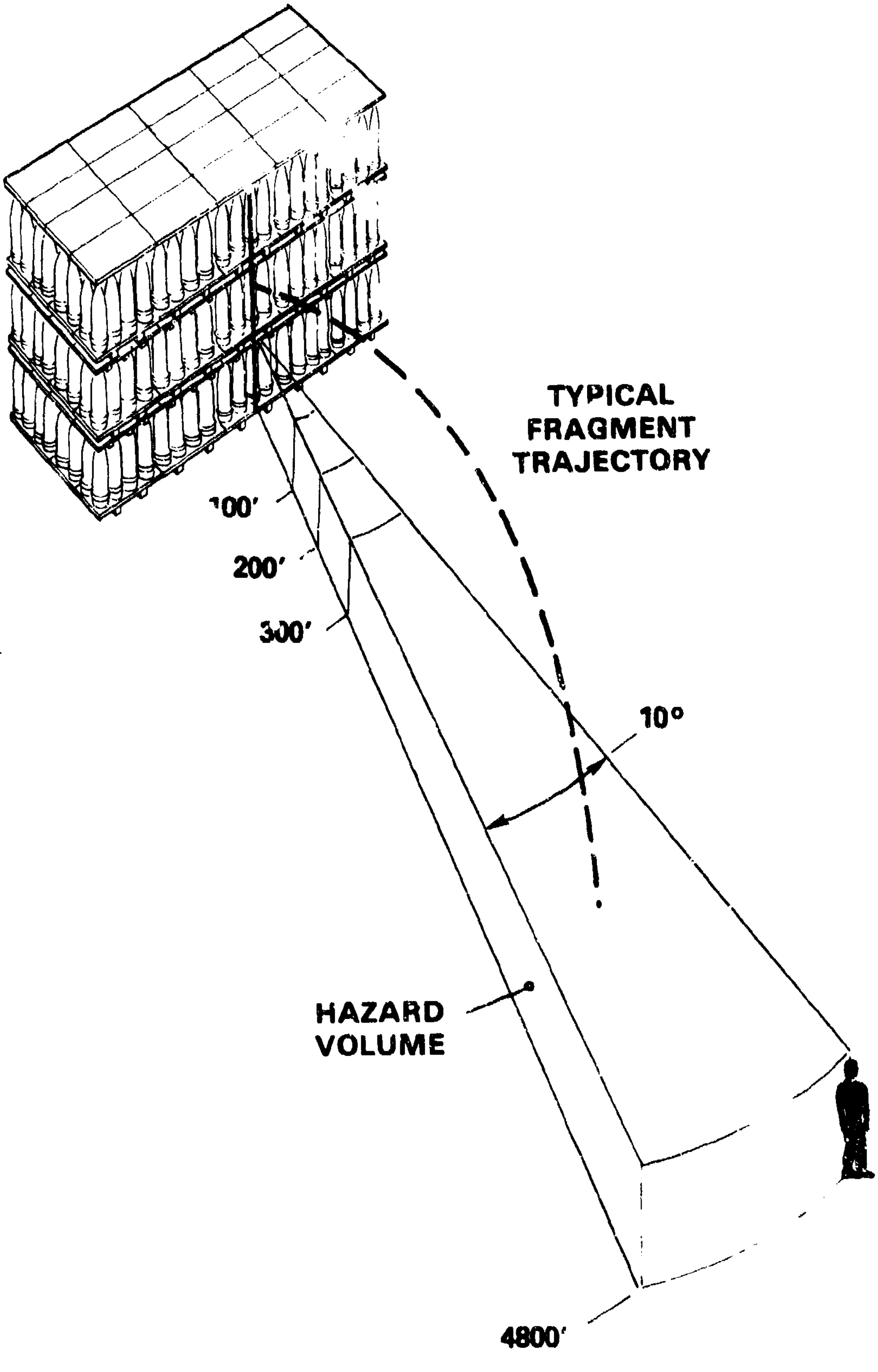

FIG 1 — STACK FRAGMENTATION SIMULATION

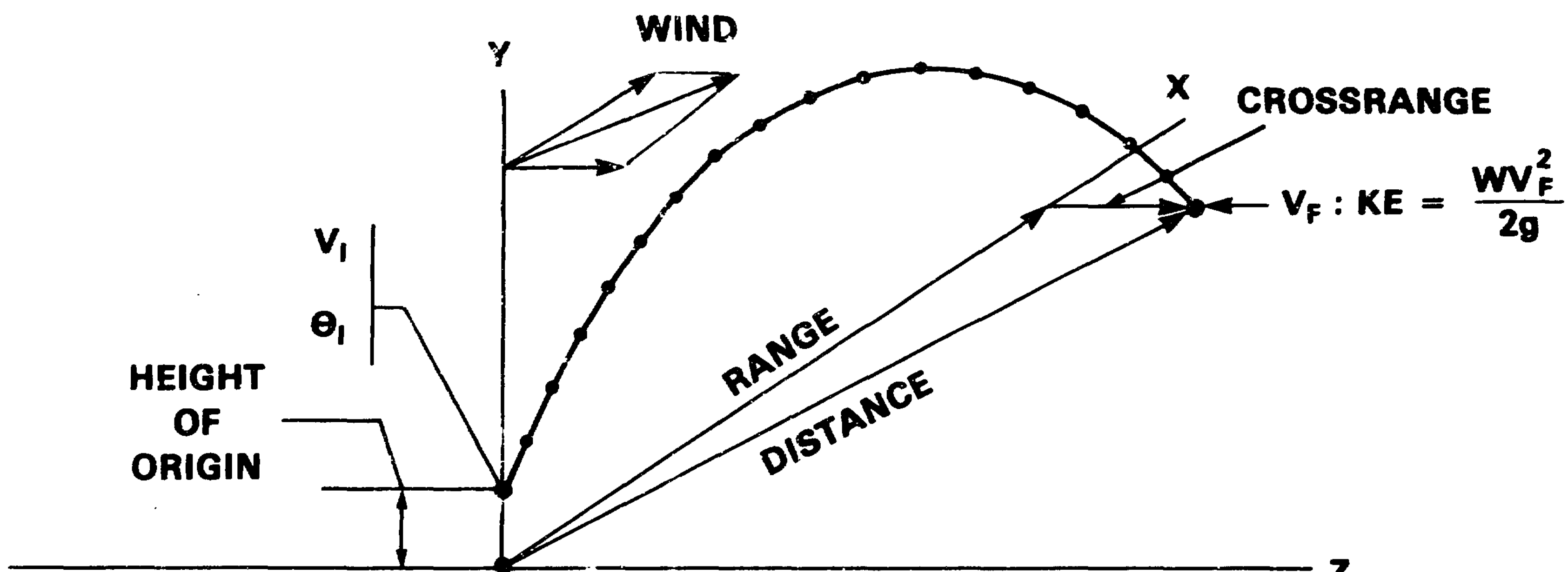

FIG 2 — FRAGMENT TRAJECTORY

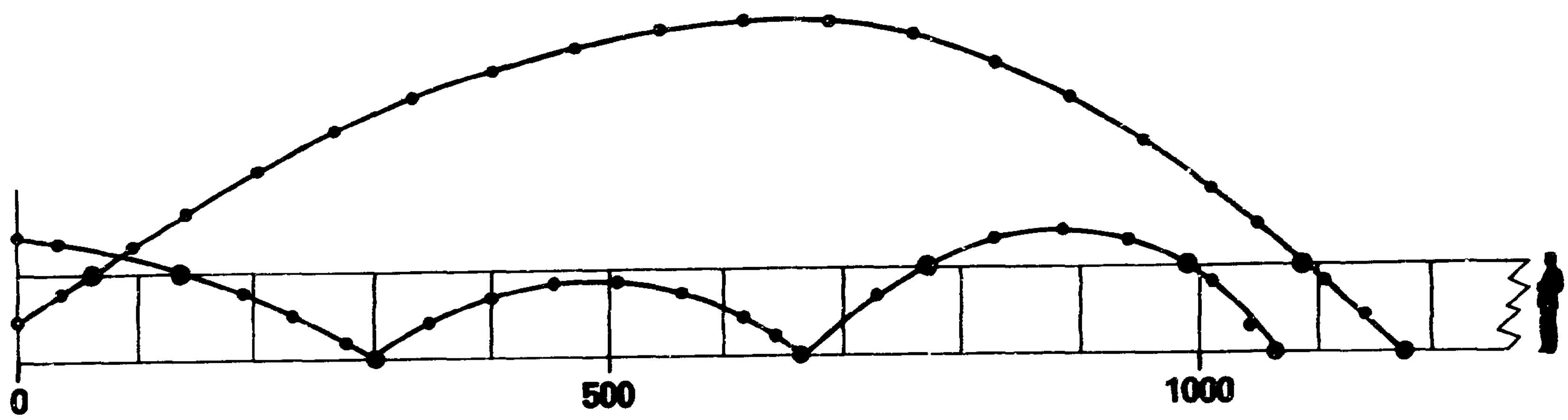

FIG 3 — TYPES OF TRAJECTORIES
1. RICOCHET
2. NON-RICOCHET

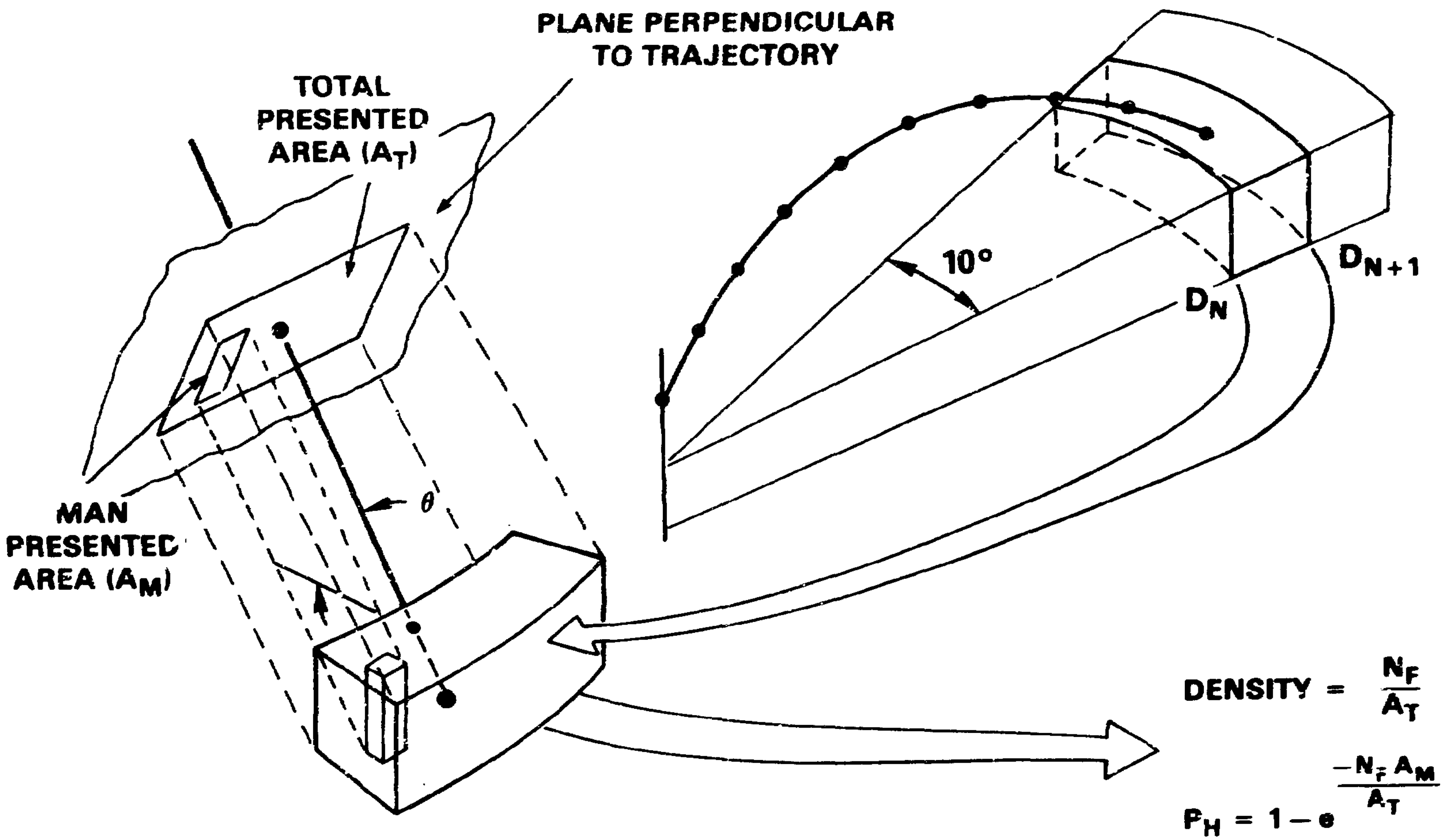

FIG 4 — HAZARD CALCULATIONS

TABLE 1

TYPICAL FRAGMENTATION INPUT DATA

FRAG NO.	POLAR ZONE	WEIGHT	INITIAL VELOCITY	$\bar{A}/M$	AREA RATIO
1	0-10	623	3246	10.2	6.2
2	0-10	891	3246	9.1	4.7
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
89	30-40	1021	4831	8.6	5.6
90	30-40	819	4831	12.2	8.2
91	40-50	2162	5814	7.7	5.7
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
231	110-120	813	4831	9.1	4.9
232	120-130	1421	5772	11.3	13.2
233	120-130	667	5772	7.2	10.6

TABLE 2

NUMBER OF FINAL GROUND IMPACTS 10 deg AZIMUTH SECTOR

DISTANCE	MIN	AVG	MAX
0-200	12	16	21
200-400	5	8	11
400-600	20	25	37
600-800	40	52	67
800-1000	57	71	85
1000-1200	82	97	115
1200-1400	112	127	142
1400-1600	91	104	117
•	•	•	•
•	•	•	•
•	•	•	•
•	•	•	•
4600-4800	0	0	0

TABLE 3

HAZARD DISTANCE vs. NUMBER OF PROJECTILES DISTANCE INCREMENT = 200 ft

HAZARD DISTANCE	NUMBER OF PROJECTILES NEEDED TO JUST EXCEED DENSITY CRITERION			
	MIN	90%	AVG	MAX
100	1	1	1	1
300	2	2	3	4
500	4	5	7	11
700	11	12	15	21
900	22	25	31	47
•	•	•	•	•
•	•	•	•	•
•	•	•	•	•
•	•	•	•	•
•	•	•	•	•
4700	999999	999999	999999	999999

FIGURE 5

HAZARD DISTANCE vs. NUMBER OF PROJECTILES PROJECTILE XXX