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Mr. Robert Benzon
Office of Aviation Safety
Major Investigations Division
Washington, D.C. 20594

Dear Bob,

Enclosed is my report to your group which summarizes my remarks at the Flight 800 hearing in Baltimore. I'm also sending it on two discs. I wrote the report on a Powermac, using Microsoft Word 5.1 for the text and Excel Version 4.0 for the tables, so one disc has that. On the other, I have tried to format it for Windows, on the assumption that you probably have better access to an IBM PC. Hopefully, both have been successful, but let me know if you have a problem.

Sincerely,

Bill

William A. Cassidy
(Professor)

ESTIMATED FREQUENCY OF A METEORITE STRIKING AN AIRCRAFT

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Executive Summary

- Terms: *meteor* is a visual phenomenon, *"shooting star"* is a short-lived meteor, *fireball or bolide* is a longer-lived meteor, a *meteorite* is the cause of a fireball or bolide, and *asteroid zone* is the source region of meteorites.

- Classification of meteorites; *irons, stones, stony-irons.*

- Because of differences in composition and in entry velocities, meteorites have a much better chance to survive to lower altitudes than cometary particles.

- Most meteorites are stones, and stones tend to fragment during entry. The fragments quickly decelerate to around 150 m.p.h.

- The unexpected visual and sonic effects produced by a falling meteorite can cause unreliable reports by well-meaning observers.

- The expected frequency of damaging hits by meteorites to an aircraft can be calculated by comparison with the known frequency of damaging hits to dwellings and cars.
  1) The changing size of the dwellings and cars target over the past century must be normalized.
  2) Necessary assumptions are that the influx rate of meteorites is constant and evenly distributed over the earth, with any target receiving a share of the influx that is proportional to its area, and the aircraft target area is comparable to the dwellings and cars target area because aircraft are found in higher densities over population centers.

- The expected frequency of hull-penetrating strikes to an aircraft over the U.S. is once in 59,000 - 77,000 years.

Introduction.

When I was first contacted by Robert Benzon, of the National Transportation Safety Board (NTSB), he and his colleagues were endeavoring to respond to what appears to be an intense degree of public interest and concern over whether or not a meteorite might have brought down TWA Flight 800. Their inquiry to me was a challenge, because meteoritics and aircraft accidents are fields with very little in common.

My first reaction was to conclude that there was no way to evaluate the possibility of a meteorite hitting an airplane because there was no body of data from which to start: there was not even one such incident in the record. There is, however, a record of meteorites striking houses and cars, so perhaps the relative target areas could be compared, and perhaps such a comparison could lead to a quantitative result.

In this report I introduce the reader to some common knowledge about meteorites; I describe our current understanding of the interactions between meteorites and the earth; and I describe the method by which I arrived at an estimate for the expected frequency of aircraft-damaging hits by meteorites. My result suggests that if the numbers in, and degree of utilization of, our aircraft fleet remained the same, there will be one such event over the U.S. every 59,000 - 77,000 years.

Terms.

Meteor: The visual phenomenon generated by a body plunging through the atmosphere at hypersonic velocity.

"Shooting star:" A very short-lived meteor generated by a dust particle or a bit of cometary ice.

Fireball or bolide: A longer-lived meteor generated by a larger body such as a meteorite.

Meteorite: A chunk of silicate rock or nickel-iron alloy believed to originate as a fragment of an asteroid.

Asteroid zone: A region of space between the orbits of Mars and Jupiter occupied by thousands of small bodies (asteroids), all less than about 550 miles in diameter. Most asteroids are much smaller than this -- of the order of a few tens of miles, or less, in greatest dimension.

It is with these definitions in mind that the terms above are used in this report.

Classification of meteorites.

A simple classification is used here:

IRONS - STONY IRONS - STONES

Iron: A meteorite composed of nickel-iron alloy. Irons represent about 7% of all meteorites that fall.

Stony iron: A meteorite that is about 50% nickel-iron alloy and 50% silicates. Stony irons are quite rare, representing only about 1% of all meteorites that fall.

Stone: A meteorite composed of silicates, usually with minor amounts of nickel-iron alloy scattered through its volume as tiny inclusions. 92% of the meteorites that fall are stony meteorites.

There are subdivisions of the three major types of meteorite, but the complete classification is not relevant to this inquiry.

Orbital dynamics.

Please refer to figure 1, which illustrates the earth in its orbit about the sun and some possible directions from which meteorites may approach collision with the earth. The direction of approach is relevant to the possible degree of damage to dwellings and, by inference, to aircraft. Flight 800 was just inside the night zone, on the P.M. side.

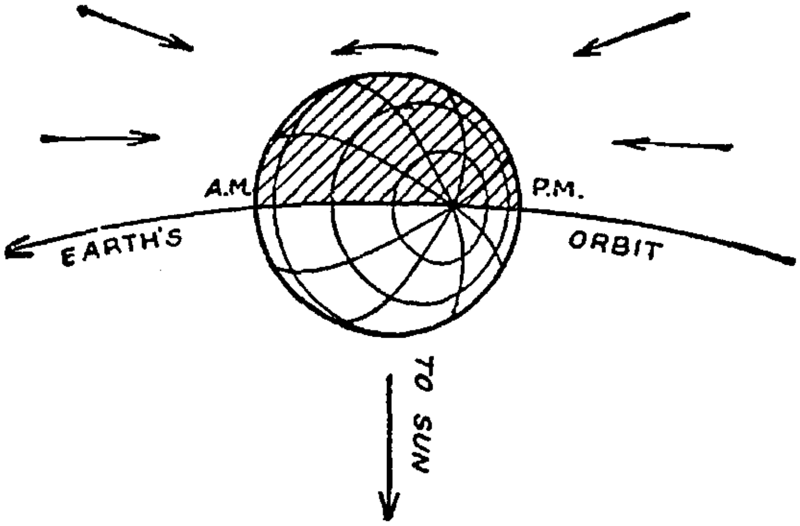


FIGURE 1

In figure 1 it can be seen that objects colliding with the earth "head on," as it were, will have their own orbital velocity added to the orbital velocity of the earth, while objects overtaking the earth will have the earth's orbital velocity subtracted from their own orbital velocity. The orbital velocity of the earth is 18.5 mi./sec and the maximum orbital velocity for any solar system object is 26 mi./sec. Thus, for a direct head-on collision between an object and the earth, in which the two velocities are directly additive, the *maximum possible* velocity of collision is 44.5 mi./sec, while for a directly overtaking collision, the *maximum possible* collision velocity will be 7.5 mi./sec. These are first approximations, and the actual numbers will be affected slightly by the gravitational attraction of the earth and the relative motion of the surface of the earth (and its atmosphere) as the earth rotates on its axis. For each case, the actual velocities of collision will be less than these maxima because the collision paths will be at some angle to the earth's orbit and the effective approach velocity will be some component of the total orbital velocity of the object. Also, most solar system objects whose orbit intersects that of the earth will have lower velocities than 26 mi./sec.

Cometary orbits have an isotropic distribution in space, relative to the earth, and the cometary particles that produce "shooting stars" apparently approach the earth from completely random directions. Asteroids (the parent bodies of meteorites), on the other hand, revolve about the sun in the same direction as the earth, so that when a meteorite in the asteroid belt suffers orbital perturbation and eventually becomes an earth-crossing meteorite, its approach to the earth will generally have a large component of velocity in the direction of the earth's motion about the sun. This suggests that meteorite collisions with the earth will, in general, be lower velocity collisions than those involving cometary particles, with the meteorite overtaking the earth, or the earth overtaking the meteorite.

Because of composition differences, but also because the entry dynamics are extremely sensitive to velocity, a meteorite will have a much better chance to survive to a lower altitude than a cometary particle.

Entry dynamics.

Please refer to figure 2, which describes conditions during entry of a meteorite into the earth's atmosphere.

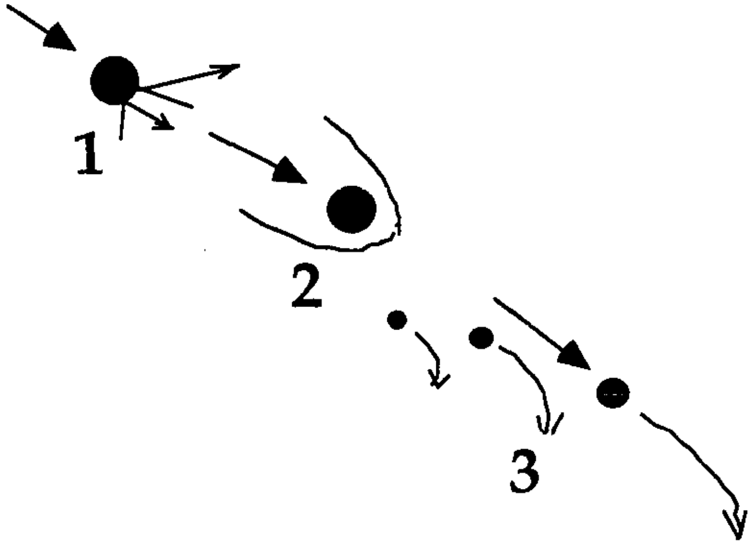


FIGURE 2

Stage 1. The first air molecules the meteorite encounters rebound from the leading face with no effect.

Stage 2. As the meteorite penetrates deeper into the atmosphere, rebounding air molecules collide with other molecules and can be driven back to strike the leading face of the meteorite again. This happens with greater and greater frequency as the meteorite encounters denser and denser air until the leading face is enveloped in a cap of increasingly compressed air, which becomes very hot because of increasing compression. At this stage, the compressed air is glowing brightly and is hot enough to melt the leading face of the meteorite, vaporizing some of the melt and brushing the rest off the meteorite, leaving a trail of droplets behind. The cap of incandescent gas is surrounded by a shock front, which produces sonic booms.

Stage 3. In the most frequent case (92% of the falls), the meteorite is a stone. Often the stony material cannot withstand the pressure on its leading face, and breaks into fragments which decelerate very rapidly and continue as freely falling bodies. Terminal velocity does not exceed 150 mph. The altitude at which the meteorite or its fragments become freely falling bodies can vary with the size of the original meteorite, its entry velocity and its angle of entry. The Peekskill, N.Y. meteorite, which fell on Oct. 9, 1992, began fragmenting at an altitude of around 25 miles. Fragmentation ended at an altitude around 20 miles, and the largest surviving fragment, weighing 27 lb., probably reached terminal velocity soon thereafter. Smaller meteorites will generally decelerate at higher altitudes. After the meteorite has reached terminal velocity, the glow disappears.

Virtually all meteorites will be traveling only at 150 m.p.h. by the time they reach altitudes at which aircraft fly.

Observed effects.

Sonic booms. The observer will hear sonic booms, some time after the meteor has disappeared. These will seem to die away in the distance, as those generated farther away sweep through. If the observer has not seen the path of the meteor, he will often indicate a travel direction exactly opposite to the true path, based on the sound phenomena.

Retinal images. Meteors caused by meteorites are an intense source of light. At night, they often create a short-lived "daylight effect," lighting up the surroundings and casting shadows. An observer following the path of such a meteor will generate a retinal image, which can be intense enough so that he will not sense the disappearance of the glow as the meteorite reaches terminal velocity. His eyes are already moving, and he will often "follow" his retinal image down to the ground. In such a case, the meteorite will always seem to land nearby, sometimes seeming to start a small fire in the grass, which attests to the persistence of the retinal effects. The typical report is, "The meteorite landed over there (indicating a nearby area) and started a fire in the grass, but when I walked over, I couldn't see any burned patch."

Scaling problems. We are used to estimating distances and speeds of known objects such as automobiles and people. We can do this because we know the relative sizes of these familiar objects. In spite of the fact that we know neither the size nor the distance of a meteor, we often will attempt to estimate its speed or its size, or both. Such reports are completely unreliable.

In the case of an unfamiliar phenomenon, an observer has not always seen exactly that which he honestly believes he saw.

Estimating the frequency of damaging meteorite impacts to an aircraft.

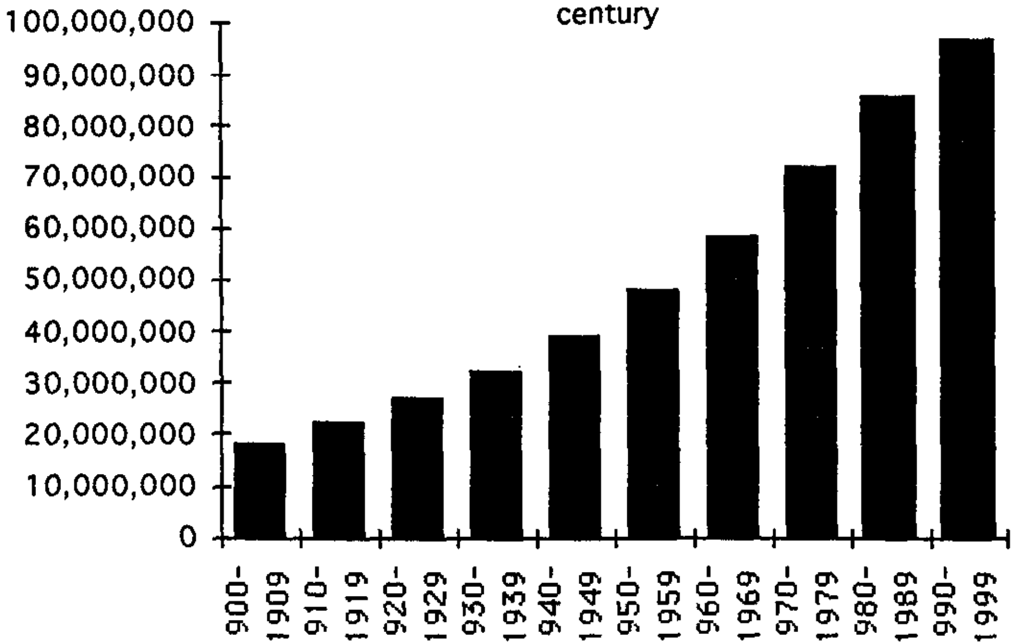
The following points are relevant to this discussion:

- No data exist on hits to aircraft by meteorites.
- There *is* a body of data on meteorites that have damaged houses and cars.
- The frequency of damaging impacts to houses and cars *can* be calculated.
- If the target area represented by houses and cars, and the target area represented by aircraft are both known, the expected frequency of damaging hits to aircraft can be calculated.

In the following discussion, I consider those meteorites that have penetrated the roofs of houses and cars in the coterminous United States (*i.e.*, the U.S. without Alaska and Hawaii) during this century. The reason for excluding Alaska and Hawaii is that before 1960, the U.S. census data do not include numbers of dwellings in those states-to-be. I also limit my calculation to the United States because the census data for this country, as well as data on the air-traffic density above it, are very reliable. Table 1 is a list of meteorites that penetrated the roofs of houses and cars during this century.

Census data indicate that the number of dwellings has changed significantly over this period of time, so the actual target area for infalling meteorites has been getting larger. Figure 3 illustrates this trend, tabulated as average number of dwellings per decade.

Figure 3. Changes in numbers of dwellings during this century



The total area of the target was calculated for two assumptions: that the average area of one house plus one automobile during the century was (1) 800 ft^2 and (2) 1000 ft^2. Applying these assumptions to the total average number of dwellings per decade allowed an estimate of the average target size per decade, in ft^2. These results are shown in Table 2, in which the bottom line gives the total hits on dwellings and cars by falling meteorites/ft^2/yr over the last century, calculated for the two assumptions about target size.

If the size of the total target represented by aircraft in the air were known, the two areas could be compared. The ratio between them should allow us to calculate the expected frequency of hits/ft^2/yr. to the aircraft target. Table 3 contains data obtained by the NTSB from aircraft manufacturers and airline transportation companies that lead to a calculation of the total area occupied by airborne aircraft over the coterminous U.S. per year. Note that Column D lists the average fraction of a day that each plane in a given model category operates per day. Column B X Column D X Column E then gives Column F, which is the total target area for each model in the U.S. fleet every day. The total of all numbers in Column F is then the total aircraft target in ft^2 over the coterminous U.S. every day. Since this is the total target every day, it is also the total airborne aircraft target over the U.S./ft^2/yr. These units now are the same as those for the total dwellings in the U.S.

The calculation is subject to the following assumptions:

- There is a constant influx rate of meteorites falling to Earth.
- Any given area on Earth will receive a fraction of the total influx rate that is proportional to its size.
- Any hit by a meteorite that is capable of penetrating a roof will cause damage to an aircraft.
- The density of aircraft flying over an area is roughly proportional to the density of dwellings and cars below.

For the calculation, use the following values from the tabulated data:

- The total target area represented by houses and cars in the coterminous U.S. (HC ft^2/yr).
- The number of roof-penetrating meteorites per year (HC hits/yr).
- The total target area constantly covered by airplanes in flight (A ft^2/yr)

Solve for:

- The number of aircraft-damaging meteorite hits per year (A hits/yr)

$$\frac{\text{A hits/yr}}{\text{HC hits/yr}} = \frac{\text{A ft}^2\text{/yr}}{\text{HC ft}^2\text{/yr}}$$

In this calculation, depending on the assumed value for HC i.e., HC = 800 ft^2 or 1000 ft^2, A hits/yr will be 1.7 X 10^{-5} or 1.3 X 10^{-5}. The inverse of these numbers (years/hit) is the final estimate of how often a plane-damaging hit will occur. That number is: one such event in 59,000 - 77,000 years.

Concluding remarks.

Notice that the calculation above yields the estimated number of hits per year per ft^2 of aircraft in the air over the coterminous United States. Any such hit would have struck some aircraft somewhere within its crossectional area. A possible interpretation then would be that any hit to any square foot of an aircraft would be catastrophic. This may not be so, and if not, then that interpretation is a conservative one.

It is important also to note that this calculation does not give the estimated frequency of hits to any specific aircraft. Such an estimate would be very much smaller than the very small estimate of the frequency of hits to the total aircraft target. Hopefully, this will provide some degree of reassurance to passengers who might worry that the airplane they are flying in will be hit by a meteorite.

Appendix 1. Sources and Bibliography.

Data on roof-penetrating meteorites were culled from:

LaPaz, L and J. LaPaz (1961) "Space Nomads," Holiday House, N.Y., 187 pp.

"Scientific Event Alert Network (SEAN) Bulletin," a periodic bulletin issued by the Smithsoninan Institution, Wash., D.C.

Clarke, R. (1997) Personal communication, based on his and his colleagues' compilation, 1932-Present, of meteorites that fell near people. Embedded in this record is a subset of meteorites that struck houses and cars in the United States.

Figure 1 is from:
Baker, R. H. (1955) "Astronomy (6th Edition)," D. Van Nostrand, Princeton, 528 pp.

Dwellings data are from the U.S. Census Tables.

Aircraft data were furnished by the National Transportation Safety Board.

Appendix 2. The minimum meteorite size for penetration of an aircraft hull.

For the specific case of TWA Flight 800, it seems to be the conviction of those who examined the wreckage that no penetration hole larger than about one inch in diameter exists in the reconstructed hull of the plane. If true, this finding limits the size of the postulated meteorite fragment that might have brought the plane down. Could a meteorite only an inch or two in greatest dimension even have damaged the aircraft? The answer is yes, possibly, but not necessarily. Two of the roof-penetrating meteorites listed in Table 1, the San Juan Capistrano fall and the 1971 Wethersfield fall, were suitably small. Table 4 is a list of relatively small meteorite falls, some of which may have been energetic enough to penetrate the hull of an aircraft, and some of which definitely were not. The Stratford, CT fall was not reported in Table 1 because it did not penetrate a roof, but it did strike an asphalt street, leaving a dent one inch deep in the pavement. The Denver, CO fall penetrated the roof of a warehouse, not a dwelling.

Among the falls listed in Table 4, all of which may have been small enough so that a penetration hole would not have been detected in the hull of Flight 800, three apparently were not energetic enough, and four probably were.

Table 1

METEORITES THAT PENETRATED HOUSES AND CARS DURING THIS CENTURY					
DATE	LOCATION	TIME OF DAY	MASS (gm)	WT. (lb.)	NATURE OF DAMAGE
1911	KILBOURN, WI		772	1.7	PENETRATED THREE THICKNESSES OF SHINGLES, A ONE-INCH HEMLOCK ROOF BOARD AND A 7/8-INCH HEMLOCK FLOORBOARD
1916	BAXTER, MO		611	1.3	PENETRATED ROOF AND BOUNCED OFF A LOG JOIST
29 SEP., 1938	BENLD, IL	0900	1770.5	3.9	PENETRATED GARAGE ROOF, TOP OF CAR, AND SEAT CUSHION. IT BOUNCED OFF MUFFLER, LEAVING . ONE-INCH DENT AND LODGED IN SEAT CUSHION ABOVE
20 SEP., 1950	MURRAY, KY	0135 (ESTIMATED)	450	1.0	PENETRATED ROOF OF BACK PORCH: 3/4 INCH PINE WOOD AND TAR PAPER, MAKING A HOLE 4 1/2 INCHES IN DIAM.
10 DEC., 1950	ST. LOUIS, MO	2307	1000	2.2	PENETRATED THE SOFT ROOF OF AN AUTOMOBILE
30 NOV., 1954	SYLACAUGA, GA	1300	3860	8.5	PENETRATED THE COMPOSITION ROOFING MATERIAL, THE 3/4 INCH WOODEN DECKING AND THE 3/4 INCH WOODEN CEILING
13 OCT., 1959	HAMLET, IN	0900	2045	4.5	STRUCK HOUSE, RIPPING OFF RAIN GUTTER
8 APR., 1971	WETHERSFIELD, CT	0200-0500	350	0.8	PENETRATED ROOF OF A HOUSE AND PARTIALLY PENETRATED PLASTER CEILING.
15 MAR., 1973	SAN JUAN CAPISTRANO, CA	2400-0400	50.5	0.1	PENETRATED ALUMINUM ROOF OF A CARPORT
27 OCT., 1973	CANON CITY, CO	1800-1815	1400	3.1	PENETRATED ROOF OF A GARAGE
8 NOV., 1982	WETHERSFIELD, CT	2114	2754	6.1	PENETRATED ROOF OF HOUSE, CEILING IN HALLWAY, DENTED WOOD FLOORING, BOUNCED UP TO CEILING AND ROLLED INTO DINING ROOM
9 OCT., 1992	PEEKSKILL, NY	1850	12400	27.3	CRUSHED BACK END OF CAR
20 OCT., 1994	COLEMAN, MI	0152	469	1.0	PENETRATED ROOF, CONSISTING OF TWO LAYERS OF ROLLED ROOFING MATERIAL, A PIECE OF SHEET METAL AND 1/4 INCH OF PLYWOOD

Table 2

THE NUMBER OF ROOF-PENETRATING HITS / SQ. FT. / YEAR ON DWELLINGS

DECADE	HITS PER DECADE	AV. NO. OF DWELLINGS	AV. TARGET AREA (SQ.FT.E+10/DECADE)		HITS(E-11)/SQ.FT. PER DECADE	
			800 SQ.FT.	1000 SQ.FT.	800 SQ.FT.	1000 SQ.FT.
1900-1909	0	18,110,000	1.45	1.81	0	0
1910-1919	2	22,304,500	1.78	2.23	1.1	0.9
1920-1929	0	27,129,000	2.17	2.71	0	0
1930-1939	1	32,380,000	2.59	3.24	0.4	0.3
1940-1949	0	38,840,500	3.11	3.88	0	0
1950-1959	4	47,769,500	3.82	4.78	1.1	0.8
1960-1969	0	58,025,500	4.64	5.8	0	0
1970-1979	3	71,600,500	5.73	7.16	0.5	0.4
1980-1989	1	85,683,000	6.85	8.57	0.1	0.1
1990-1999	2	97,121,000	7.77	9.71	0.3	0.2
TOTAL HITS/SQ.FT./DECADE ON DWELLINGS					3.50E-11	2.70E-11
TOTAL HITS/SQ.FT./YEAR ON DWELLINGS					3.50E-12	2.70E-12

Table 3

A	B	C	D	E	F
THE TOTAL AIRCRAFT TARGET / YEAR OVER THE U.S.					
AIRCRAFT DATA	NO. OPERATING	HOURS/DAY	FR. OF DAY	CROSSECTION	AREA/PLANE/YR
DC-8	52	4.21	0.18	6640	60568
DC-8 STRETCH	181	4.21	0.18	7263	230603
DC-9	598	5.38	0.22	3612	484195
MD-80	638	8.48	0.35	4307	970913
MD-90	20	8.09	0.34	4362	29407
DC-10	288	6.82	0.28	10344	846553
MD-11	60	10.95	0.46	10540	288533
A-300	35	9	0.38	5000	65625
A-320	97	9	0.38	5000	181875
L-1011	70	9.5	0.40	8800	243833
707	115	2.35	0.10	5000	56302
720	5	1.77	0.07	5000	1844
727	975	1.4	0.06	3870	220106
737	1123	1.17	0.05	2570	140698
747	235	4.48	0.19	11610	509292
757	490	2.29	0.10	5000	233771
767	234	3.73	0.16	6440	234207
777	27	4.63	0.19	9880	51462
		THE AIRCRAFT TARGET:		TOTAL AREA/YR	4849786
NOTES:	COLUMN B: NO. OPERATING PER DAY				
	COLUMN E: HORIZONTAL CROSSECTIONAL AREA IN SQ. FT.				

Table 4

HOW LARGE MUST A METEORITE BE TO CAUSE DAMAGE?

LOCATION	MASS (gm)		SPHERE DIAMETER	EFFECTS	DAMAGE?
SALEM, OR	92		3.6 cm = 1.4 in.	STRUCK HOUSE	NO DAMAGE
BLOOMINGTON, IL	67.8		3.4 cm = 1.3 in.	FELL ONTO BACK PORCH OF A HOUSE	NO DAMAGE
BELLS, TX	28-56		3.4 cm = 1.3 in.	HIT ROOF OF A HOUSE	NO DAMAGE
STRATFORD, CT	50		3 cm = 1.2 in.	DENT, ONE INCH DEEP, IN ASPHALT STREET	DAMAGE?
SAN JUAN CAPISTRANO, CA	50.5		3 cm = 1.2 in.	PENETRATED ALUMINUM ROOF OF A CARPORT	DAMAGE
DENVER, CO	230		5 cm = 2 in.	PENETRATED ROOF OF A WAREHOUSE: GALVANIZED STEEL SHEET WITH TARRED SURFACE	DAMAGE
WETHERSFIELD, CT	350		5.7 cm = 2.2 in.	PENETRATED ROOF OF A HOUSE AND PARTIALLY PENETRATED PLASTER CEILING	DAMAGE