ARTICLE NO. 79-0539R

C80-081

Rain and Hail Extremes at Altitude

30005

Glen J. Kissel*
Massachusetts Institute of Technology, Cambridge, Mass.

A study of the literature was conducted to find the latest data on the rainfall and hail extreme ambient conditions at altitude for the purpose of reviewing the environmental operating conditions of aircraft turbine engines. A 0.1% probability of exceeding 20.96 g/m³ of water between 4 and 6 km was found for the rainiest month in the tropics, which gives a maximum water/air ratio of 3.18% at 6 km. There is a 0.1% probability of encountering a 2.4-in. (6.1-cm) or greater size hailstone along a 200-mile (320-km) route during the most severe month in the most severe area.

Introduction

A STUDY of the literature was conducted to find the latest data on the rainfall and hail extreme ambient conditions at altitude for the purpose of reviewing the environmental operating conditions of aircraft turbine engines. The request for this study came about in part because of the unfortunate crash of a passenger jetliner, a DC-9, in New Hope, Ga. on April 4, 1977, resulting in 72 deaths. The fact that both engines failed as the aircraft descended through a thunderstorm made the FAA Propulsion Branch aware that they were in need of more information on hydrometeor extremes at altitude.

A press release by the National Transportation Safety Board summarizing its findings on the accident illustrates the apparent consequences of ingesting large amounts of rain and hail to aircraft turbine engines:

> "In its report, the Board concluded that the jetliner flew in heavy rain and hail for about 2½ minutes immediately before it lost complete engine thrust. The thrust was lost as the engines ingested large amounts of precipitation causing their rotational speed to decrease. About the same time, the crew apparently had retarded the engine thrust levers to low settings—probably flight idle—to descend from 17,000 to 14,000 feet. The exact intensity of the rain and hail was not known, but the Board said tests showed that engine rotational speed will be lost at low thrust settings—if water is ingested at a rate greater than 14 percent water-to-air ratio.
>
> "With the loss of rotational speed, high pressure compressors on both engines began to surge and stall severely as a result of both water ingested and the pilot's attempt now to advance the engine thrust levers—a normal reaction to counteract a reduction in the engine's rotational speed. The Board concluded that these events led to deflections of rotating compressor components and their contact with stationary vanes causing extreme damage and subsequent failures of the high pressure compressors."

Ideally one would want to obtain the probabilities of exceeding certain rainfall rates (or liquid water contents) and hailstone sizes at a range of altitudes in the worst places of the world during the worst months. Physical data for such circumstances, particularly at altitude, are not readily available; however, studies done by the Air Force Cambridge Research Laboratories (AFCRL, renamed the Air Force Geophysics Laboratory, AFGL, in 1976) addressing these questions were helpful in the preparation of this paper.

Presented as Paper 79-0539 at the AIAA 15th Annual Meeting and Technical Display, Washington D.C., Feb. 6-8, 1979; submitted April 13, 1979; revision received Dec. 18, 1979.

Index category: Atmospheric and Space Sciences.

*Student, Department of Aeronautics and Astronautics. Student Member AIAA.

Rain

In 1971 a report by Samela, et al.,[1] of the AFCRL (now AFGL) determined the rainfall rate at the surface which is exceeded 0.1% of the time during the rainiest month in the rainiest part of the world—Cherrapunji, India, in the tropics—to be 3.13 mm/min. The 0.1% probability of exceedence was chosen arbitrarily as a very low risk value.

The problem now is to determine the ratio of rainfall intensities at altitude to the intensities at the surface for very severe rainstorms. Briggs[2] and others[3,4] have presented data that are helpful in this respect. In a 1972 AFCRL report Sissenwine[5] concludes from available studies such as Briggs', that an increase of intensity from the surface to the 4-6 km level (the altitude range of greatest rainfall intensity) of about 35% is reasonable. Sissenwine describes Briggs as using "hourly and 2 minute surface point rain rates, probabilities of radar echoes aloft, and a sophisticated statistical treatment to relate point rain intensities to severest 'instantaneous' intensity applicable in aircraft design, taking aircraft speed" and two tropopause heights into account to obtain the extreme intensity likely in 10^5 h of flying by altitude in an area of the tropics. The precipitation ratios by altitude and corresponding rainfall rates shown in Table 1 are for 1 min averages, while 10 s extremes will be 110% of those values.

To obtain a useful answer for analysis, the liquid water content (grams of water/m³ of air) equivalent to a given rainfall rate must be known. To find these liquid water contents, Sissenwine chooses an equation presented by Atlas[6] which originated in Illinois and is specifically applicable to intense thunderstorms:

$$M = 0.052\ (60R)^{0.97} \tag{1}$$

where M is liquid water content in g/m³ and R is rainfall rate in mm/min. Liquid water contents equivalent to a range of rainfall rates according to Eq. (1) are given in Fig. 1.

From this equation the precipitation liquid water contents which are exceeded 0.1% of the time during the rainiest month in the rainiest spot of the world can be computed and are shown in Table 1. Further meteorological research at altitude is needed to refine the equation converting rainfall rate to liquid water content for very intense storms, but Sissenwine concludes that Eq. (1) is "...that available for providing liquid water content during extreme convective precipitation which is supported best in the scientific literature." The study of the literature supports Sissenwine's conclusion.

The water content which is intended above is that of precipitation-size drops to which storm radar is sensitive, i.e., particles greater than 100 μm. In addition to rain at altitude, cloud particles will be encountered and these are considered to

Table 1 0.1% exceedence values for rain aloft

	Ratios		Rate,	0.1% worst month, tropics			
				Water, g/m³			
Altitude, km	Precip.	Cloud	− mm/min	Precip.	Cloud	Total	Water/air ratio, %
Surface	1.00	0	3.13	8.35	0	8.35	0.68
1.5	1.12	0.83	3.50	9.30	8.12	17.42	1.65
3.0	1.24	0.92	3.88	10.28	9.00	19.28	2.12
4.5	1.35	1.00	4.23	11.18	9.78	20.96	2.70
6.0	1.35	1.00	4.23	11.18	9.78	20.96	3.18
9.0	0.75	0.56	2.35	6.32	5.53	11.85	2.54
12.0	0.44	0.32	1.38	3.77	3.18	6.95	2.23
15.0	0.19	0.14	0.59	1.65	1.38	3.03	1.56
18.0	0.03	0.02	0.09	0.27	0.21	0.48	0.39

Note: Intensities are 1 min averages, 10 s extremes will be 110% of these values.

Table 2 Record rainfalls extrapolated to altitude

	42 min record					1 min record				
		Water, g/m³					Water, g/m³			
Altitude, km	Rate, mm/min	Precip.	Cloud	Total	Water/air ratio, %	Rate, mm/min	Precip.	Cloud	Total	Water/air ratio, %
Surface	7.26	18.88	0	18.88	1.54	31.20	77.65	0	77.65	6.34
1.5	8.15	21.12	8.12	29.24	2.76	34.90	86.57	8.12	94.69	8.95
3.0	9.02	23.30	9.00	32.30	3.55	38.70	95.70	9.00	104.70	11.51
4.0	9.82	9.78	9.78	35.08	4.51	42.10	103.80	9.78	113.58	14.62
6.0	9.82	25.30	9.78	35.08	5.31	42.10	103.80	9.78	113.58	17.21
9.0	5.44	14.27	5.53	19.80	4.24	23.50	58.98	5.53	64.51	13.81
12.0	3.19	8.50	3.18	11.68	3.74	13.80	35.20	3.18	38.38	12.30
15.0	1.38	2.77	1.38	5.15	2.64	5.94	15.54	1.38	16.92	8.69
18.0	0.22	0.66	0.21	0.87	0.72	0.94	2.59	0.21	2.80	2.30

Notes: 1) Intensities are 1 min averages; 10 s extremes will be 110% of these values. 2) Cloud density is not increased as rain intensity increases beyond the 0.1% model.

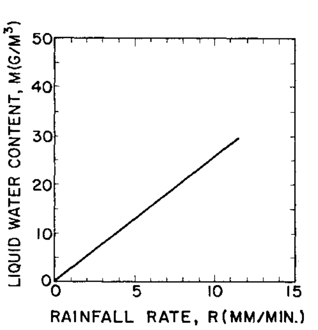

Fig. 1 Liquid water content for $M = 0.052(60R)^{0.97}$

be less than 100 μm. For cloud water mass Sissenwine adds a maximum of 9.78 g/m³ to the precipitation water mass. Table 1 shows the cloud ratios and water mass for this 0.1% exceedence case.

Sissenwine considers the precipitation to be all liquid below 4.5 km and a mixture of water and ice becoming ice with increasing altitude to all ice above 10 km. Hail will also be encountered in intense convective storms, but hail extremes are considered later.

Two factors could add to the liquid water content at aircraft turbine engine inlets above ambient conditions, but no attempt has been made to put a magnitude on these phenomena. During descent from cruise altitude to the terminal area at 10,000 ft, the aircraft engines are at low power settings while the aircraft is still flying at nearly cruise flight speed. Under these conditions, an engine is unable to swallow all of the air entering the engine inlet projected area. While the air will tend to flow around the engine nacelle, water droplets will tend to follow straight line trajectories and accumulate at the engine inlet during flight in rain. NASA has done research on this subject and has presented rather complex methods that could be applied to finding magnitudes for this phenomenon, known as "scoop factor."[7] Water running off a fuselage and wings into rear-mounted engines is another factor that could increase the liquid water content at the engine inlets.

Finally, the total liquid water content which is exceeded 0.1% of the time in the rainiest part of the world during the rainiest month is shown in Table 1. The maximum liquid water content with a 0.1% exceedence is that found between 4 and 6 km which includes 11.18 g/m³ for the rainfall and 9.78 g/m³ for cloud particles yielding a total of 20.96 g/m³.

Water/air ratios corresponding to these liquid water contents are computed by dividing the liquid water content by the appropriate density given by the U.S. Standard Atmosphere, 1976. This yields a maximum water/air ratio of 3.18% (3.18 g of water for every 100 g of air) at 6 km.

To give an idea of truly catastrophic rainfalls, Sissenwine's extrapolations to altitude for a Holt, Mo., 42 min record with an average of 7.26 mm/min and for the 1 min record at Unionville, Md., of 31.2 mm/min are shown in Table 2 along with the computed water/air ratios. Estimates of probabilities are not possible for these very unlikely events. Sissenwine notes, however, that the 7.26 mm/min rate of the 42 min record is "in fairly close agreement with recommendations by Briggs (1972) as a heavy rain likely to be encountered in 10^5 flying hours in the very rainy tropics."

The present water ingestion test specified by FAR 33.77 for aircraft turbine engine type certification is a 4% water/air ratio test. This test, which is not required to be conducted at altitude, is usually run at ground level at the engine manufacturer's facility.

Hail

Another hydrometeor encountered by the accident aircraft mentioned in the introduction was hail. While this study does not attempt to determine the combined effects of rain and hail on aircraft turbine engines or to what extent hail adds to the liquid water content, the report does address the very important question of the probability of encountering hailstones of maximum size in a storm. These hailstones of diameters greater than 0.75 in. (1.9 cm) are the ones that would cause any damage to aircraft.

The most severe location for hailstorms in the world is southeastern Wyoming and western Nebraska, and the most severe months are June and July. Gringorten[8] of the AFCRL considers two hailstorms per month during the worst month as representative for this area and that the average point duration for each of the two hailstorms is 10 min. This immediately gives a probability of 0.000448 (two hailstorms of 10 min duration each divided by $60 \times 24 \times 31$ min in a month) that a hailstorm will occur at some point in this worst place at a randomly selected instant during the worst month.

Using data gathered by Changnon[9] and Miller,[10] Gringorten presents a graph from which the probabilities of exceeding hailstone sizes when a hailstorm is in progress can be computed as shown in Fig. 2. This probability distribution multiplied by the 0.000448 probability of a hailstorm occurrence mentioned above gives the probability of encountering a hailstone of a given diameter at a single point location near the surface during the worst month in the worst location as shown in Table 3.

The AFCRL report used a model of spatial correlation based on Changnon data to determine the probability of encountering a hailstorm along a straight line segment for the worst month, worst place situation (Table 4). The probability of exceeding a given size hailstone at the surface, at some random instant along a 100- and 200-mile (160- and 320-km) route length, can thus be found for the most severe month of the most severe location (Table 5).

Risks of hailstones aloft must now be considered because there are "balance" levels[11] in the upper air where hailstones concentrate by suspension in thunderstorm updrafts. Gringorten[8] found that "the only available ratios of hail aloft to hail at a lower level are those given by the Thunderstorm Project, which are based on 1947 and 1948 data in Ohio and Florida thunderstorms." A computer assisted search of the literature indicates that this is still true. For this worst location, Gringorten considers the occurrence of hail during a hailstorm to be uniform between 10,000 and 20,000 ft (3 and 6 km) which is the maximum level of hail occurrence at seven times more hail occurrences than at the surface. Table 6 presents the probabilities of encountering hail at a point by altitude for the worst month in the worst location. Also for this location, the probability distribution of hailstone sizes greater than 0.65 cm is not significantly changed by melting during fall, so the distribution is virtually the same at altitude as that originally determined for the surface in Fig. 2.

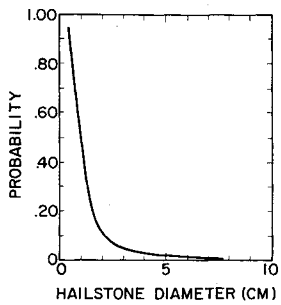

Fig. 2 Probability of exceeding a hailstone diameter given that hailstorm occurs.

Table 3 Probability of encountering hailstone of given diameter at single point location near surface during worst month in worst location

Hail diameter in.	cm	Single point probability
Any size		0.000448
1/4	0.64	0.000354
1/2	1.27	0.000161
3/4	1.90	0.0000605
1	2.54	0.0000314
2	5.08	0.00000851
3	7.62	0.00000170
4	10.16	0.00000025

Table 4 Model estimates of probability of hailstorm in the most severe month of most severe area

Line length S mile	km	Probability
0	0	0.000448
1	1.6	0.000460
2	3.2	0.000520
4	6.4	0.000710
8	12.9	0.00120
16	25.7	0.0020
32	51.5	0.0035
64	103.0	0.0063
128	206.0	0.0128
265	426.4	0.028

Table 5 Estimates of probability of encountering hailstones, enroute near Earth's surface during most severe month of most severe location

Hail diameter		Route length	
		100 miles	200 miles
in.	cm	(160.9 km)	(321.8 km)
Any size		0.010	0.021
1/4	0.64	0.00790	0.0166
1/2	1.27	0.00360	0.00756
1	2.54	0.00070	0.00147
2	5.08	0.000190	0.000399
3	7.62	0.000038	0.000080
4	10.16	0.0000055	0.0000116

Table 6 Estimates of probability of encountering hail, of any size, at single point location, by altitude

Altitude ft	km	Probability
Ground level		0.000448
5,000	1.52	0.000448
10,000	3.05	0.00314
15,000	4.57	0.00314
20,000	6.10	0.00314
25,000	7.62	0.00134
30,000	9.14	0.00100
35,000	10.67	0.00067
40,000	12.19	0.00034
45,000	13.72	0.000

Table 7 Estimate of hailstone size equalled or exceeded with 0.1% probability of encounter while enroute aloft, during most severe month in most severe area

Altitude		100 mile route (160.9 km)		200 mile route (321.8 km)	
ft	km	in.	cm	in.	cm
5,000	1.52	0.9	2.29	1.2	3.05
10-20,000	3.05-6.10	1.9	4.83	2.4	6.10
25,000	7.62	1.3	3.30	1.9	4.83
30,000	9.14	1.2	3.05	1.7	4.32
35,000	10.67	1.0	2.54	1.5	3.81
40,000	12.19	0.8	2.03	1.1	2.79
45,000	13.72	0	0	0	0

Using spatial correlation models, Gringorten calculated the probabilities of exceeding 0.1% of the time certain size hailstones at altitude along a 100 and 200 mile (160 and 320 km) route during the most severe month in the most severe area (Table 7). Again the 0.1% probability was arbitrarily chosen as a low risk value. The largest diameter hailstone with a 0.1% exceedence is a 2.4 in. (6.1 cm) hailstone between 10,000 and 20,000 ft (3 and 6 km) along a 200-mile (320-km) route.

The present hail ingestion test for aircraft turbine engine type certification specified by FAR 33.77 includes 1- and 2-in. (2.5- and 5.1-cm) hailstones, where the number of hailstones to be ingested is a function of the inlet area of the particular engine undergoing test.

Conclusions

The study of the literature has found the extreme ambient conditions at altitude for rain and hail during the most severe month in the most severe area for the respective hydrometeor. The maximum liquid water content which is exceeded 0.1% of the time, was found to be 20.96 g/m^3 between 4 and 6 km which gives a maximum water/air ratio of 3.18% at 6 km. A 0.1% probability of encountering a 2.4 in. (6.1 cm) or greater size hailstone was found for a 200-mile (320-km) route between 10,000 and 20,000 ft (3 and 6 km).

It should not be assumed that the 0.1% probability of exceeding any given rainfall rate or hailstone size has any significance relative to aircraft engine airworthiness. It is not intended to imply the loss of an aircraft encountering the exceeding conditions is an acceptable risk. The 0.1% probability of exceedence is used as a mathematically reasonable number for analysis.

Acknowledgments

This research was performed in 1977 during a Federal Summer Internship in the Propulsion Branch of the Federal Aviation Administration. The author is grateful to A.K. Forney of FAA and to L.R. Ebbesen of Oklahoma State University for their guidance and encouragement.

References

[1] Salmela, H.A., Sissenwine, N., and Lenhard, R.W., "Preliminary Atlas of 1.0, 0.5, and 0.1 Percent Precipitation Intensities for Eurasia," AFCRL-71-0527, 1971.

[2] Briggs, J., "Probabilities of Aircraft Encounters with Heavy Rain," *Meterological Magazine*, Vol. 101, Jan. 1972, pp. 8-13.

[3] Cole, A.E., Donaldson, R.J., Dyer, R., Kantor, A.J., and Skrivanek, R.A., "Precipitation and Clouds," AFCRL-69-0487, 1969.

[4] Granthan, D.D. and Kantor, A.J., "Distribution of Radar Echoes Over the United States," AFCRL-67-0232, 1967.

[5] Sissenwine, N., "Extremes of Hydrometeors at Altitude for MIL-STD 210B," AFCRL-72-0369, 1972.

[6] Atlas, D., "Advances in Radar Meteorology," *Advances in Geophysics*, Vol. 10, Academic Press, New York, 1964, pp. 317-478.

[7] Bowden, D.T., Gensemer, A.E., and Skeen, C.A., "Engineering Summary of Airframe Icing Technical Data," FAA ADS-4, 1963.

[8] Gringorten, I.I., "Hailstone Extremes for Design," AFCRL-72-0081, 1972.

[9] Changnon, Jr., S.A., "Note on Hailstone Size Distributions," *Journal of Applied Meteorology*, Vol. 10, Feb. 1971, pp. 168-170.

[10] Miller, R.C., "Notes on Analysis and Severe-Storm Forecasting Procedures of the Military Weather Warning Center," AWS-TR-200, July 1967.

[11] Atlas, D., "The Balance Level in Convective Storms," *Journal of the Atmospheric Sciences*, Vol. 23, Nov. 1966, pp. 635-651.