

SEEDING SINGLE CLOUDS USING
PYROTECHNIC CARTRIDGES, 1973-74

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INTRODUCTION

Experiments conducted in 1968-69, which involved seeding single cumulus clouds using silver iodide burners mounted on an Air Force Dakota, indicated that the rainfall could be increased by seeding suitable cells at about 14,000 ft a.s.l., just below their centres (McNaughton, 1970). However, in an operation in which a large number of clouds are dosed, it is much easier if the seeding can be carried out from near cloud-top. This is because, firstly, the turbulence inside a growing cloud is much less near the top than it is lower down. Secondly, it is important to seed only those clouds which have attained sufficient height for the treatment to work, the height being best estimated by flying at cloud-top level. The top-seeding technique is different from that used lower down in the cloud, and separate confirmation of its effectiveness is therefore necessary; this was the prime objective of the 1973-74 experiments.

FACILITIES

1973-74 was the first season of a six-year cloud seeding research programme using an aircraft donated to Government through the University. The aircraft was a turbocharged Cessna 320, and was flown by a pilot from the Department of Civil Aviation.

Two Very pistols were locked in a panel on the starboard side of the aircraft. These fired specially manufactured pyrotechnic cartridges which burned for about 40 seconds, emitting a smoke containing silver iodide particles during a 4,000 ft fall through the cloud. Two types of cartridge were available, with chemical compositions similar to the TB1 (LW83) and TB2 (EW20 or 2AL2) formulations described by St.-Amand *et al.* (1970). A rain collector was mounted on top of the aircraft about 200 mm above the skin of the fuselage. It was very similar to the collector used in earlier experiments in Rhodesia (McNaughton, 1970). A standard 5-inch (127 mm) rain gauge rim was fitted to a forward-pointing funnel to form the rain-collecting aperture. This led via a 25 mm bore tap into a separating chamber in the aircraft, from which the air escaped upwards and out of the back of the collecting funnel; the rainwater could then be collected and measured from the bottom of the separating chamber.

Radiosondes were sent up at dawn from Salisbury every day. These gave the temperature, stability and water content of all levels of the

atmosphere where cloud development is possible. This information enabled suitable experimental days to be selected, and provided an estimate of cloud-top temperature, when used in conjunction with the aircraft altimeter. Standard aviation "alticor" procedures were followed for converting the altimeter readings to true heights above sea level, in order to relate them to the heights calculated from the radiosonde data using the hydrostatic equation.

EXPERIMENTAL DESIGN

The experimental unit was the isolated cumulus cloud. This was considered better than the fixed area experiment in which any increase in rainfall due to seeding is diluted by large and variable quantities of natural rain, because the aircraft is never able to seed all clouds affecting the area during the 24 hours prior to the reading of the riangauges.

Even single clouds which outwardly appear similar often give very different quantities of natural rain, and these differences are much greater than any increment in rainfall due to seeding. Evidence of any effect of seeding can therefore be obtained only after a long series of trials on clouds selected according to strict criteria, designed to make the sample as homogeneous as is practical. Approximately half the clouds are seeded, and the other half are deliberately left alone on a randomized bases. The total rainfall given by each cloud is measured, and a comparison is made between the rain obtained from seeded and non-seeded clouds. Even then, sensitive statistical tests are required to establish an overall difference between the rainfalls of the two categories, because there is a considerable overlap between them.

EXPERIMENTAL PROCEDURE

Cloud selection

Clouds were selected for experiment if they met the following specifications:

- (1) Only solid-looking cumuliform clouds were accepted which had not yet glaciated but were still growing, this being indicated by a sharp and well-defined cloud-top outline.
- (2) The temperature at cloud-top had to be -10°C or colder, because of indications both in Rhodesia (McNaughton, 1972) and in Australia (Bethwaite *et al.*, 1966) that successful seeding is usually achieved within this temperature range. When there were no clouds available reaching -10°C , supplementary experiments were carried out on warmer clouds; these were all seeded occasions without a randomizing procedure.
- (3) A cloud system was never chosen unless it seemed likely

that its rain would not become indistinguishable from that of an extraneous system. In practice this meant selecting clouds at least 8 km from the nearest rain. Multicell systems were accepted, provided their top heights and temperatures had been measured. The reason for this was that American experiments have indicated that if seeding can bring about an amalgamation of adjacent cells, then the effect on increased rainfall is particularly great (Simpson and Woodley, 1970).

When isolated cloud systems could not be found, supplementary experimental trials were conducted on whatever was available, with the idea of investigating the effects of seeding under very wet conditions.

Seeding

After a cloud had been declared as selected for experiment, it was photographed, and its top height and temperature were measured or estimated. An envelope was then opened containing an instruction either to seed the cloud or to leave it alone. The seeding penetration was usually carried out 1-2,000 ft below cloud top, and the cartridges were fired as soon as strong updraughts were encountered. If the cloud system contained more than one growing cell, then one cartridge was fired into each cell. Whenever the cloud-top temperature was colder than -10°C , a TB2 cartridge was used. If peripheral cells were dosed whose temperatures were warmer than -10°C , then TB1 cartridges were used, because at warmer temperatures the more expensive TB1 formulation is superior (St.-Amand & Elliot, 1972).

Rain measurement

After seeding, the aircraft descended quickly to 1-2,000 ft below cloud base in order to measure the rain. As far as possible measuring flights were made through the heaviest part of the shower in two fixed orthogonal directions alternately. Successive runs were usually three to five minutes apart, and for each one the duration of the flight through rain, the altimeter flight level, the outside air temperature and the indicated airspeed were noted. These parameters enabled the true airspeed to be computed, giving the dimension of the shower at that instant in that particular direction. Also, after every run through rain the volume of water scooped up by the collector was measured and recorded. Whenever possible, this procedure continued until the cloud had stopped raining, on non-seeded as well as seeded occasions.

Although clouds were not selected unless further than 8 km from the nearest rain, sometimes during the course of the experiment extraneous rain broke out alongside the shower being measured, and occasionally the experimental cloud was absorbed completely by a large adjacent storm. Because no cloud-top measurements had been taken of this second system, such experiments had to be abandoned. In practice whenever foreign rain came within 2 km of the selected experimental cloud, it became impossible to take accurate measurements without collecting some water belonging to the other cloud.

The rain measuring procedure was very similar to that used in Australia by Bethwaite *et al.* (1966) using a raindrop impactor. The 1968-69 Rhodesian experiments used an impactor and collector simultaneously, and showed that either instrument could be used successfully to distinguish different rainfall intensities.

ESTIMATE OF TOTAL RAINFALL

Graphs were plotted of the variation in time of the north-south and of the east-west dimensions of the shower, or of whichever orthogonal directions were used for the rain measurements. The calculations were exactly as used in the 1968-69 program (McNaughton, 1970). In this paper it was shown that the rate of rainfall, at any given instant, can be regarded as proportional to a product Vb , where V is the volume of rain collected during a run, and b is the width of the shower perpendicular to that run. Thus another graph was drawn of the variation in time of the rate of rainfall, and the area under this graph gave the total rain yield from the cloud.

Allowance for time-lag between seeding and rain

The probable lag between seeding a cloud and the production at cloud-base of the associated rain can only be estimated approximately. In the raindrop impactor records from the 1968-69 cloud-seeding experiments in Rhodesia, nearly all raindrops had a diameter of between 1 mm and 3 mm. According to Gunn and Kinzer (1949) this would give them a terminal velocity in still air of 750 to 1,500 ft/minute. Upcurrents in the cloud, and collisions with cloud droplets would of course slow these speeds down. It must also be remembered that most raindrops start their lives as ice crystals, whose terminal velocities vary greatly with type, but are probably less than a quarter of those of raindrops of comparable size (Nakaya and Terada, 1934). It is not possible to make accurate realistic calculations of hydrometeor fall-times under our conditions, but it seems perfectly reasonable that for clouds with depths of about 15,000 ft these times could be anything up to 20 minutes, and quite possibly more. Added to this is the time lag between cartridge ignition and the glaciation of the cloud top, which might be 3-5 minutes, depending on the height through which the chemicals have to be carried upwards.

It is therefore obvious that any positive effect of seeding will stand out more clearly if we subtract, from each cloud's total, any rain measured so soon after seeding that it is likely to be purely natural rainfall. Thus it was decided to take four different "starting points" for the calculations of rainfall, these being 10, 15, 20 and 25 minutes after the first seeding; or the time that seeding would have taken place in the clouds that were not dosed. It was never possible to bring the aircraft down to cloud base for rain measurements earlier than 10 minutes after seeding.

RESULTS OF EXPERIMENTS

Table I shows in chronological order the list of clouds belonging to

TABLE I

Randomised Clouds from which an estimate of rain yield is possible, 1973-74

Date	Seeded or not	Seeding flight level	When selected			RAIN (10^3 m^3) from x mins. after 'seeding'				Mins. after seeding rain ceased	Rain Duration (mins)	Other notes (e.g., subsequent growth)
			Cloud Top FL	Temp. of top °C	Cloud Depth ft	x=10	x=15	x=20	x=25			
22/11/73	N	-	218	-16	10 300	Nil	Nil	Nil	Nil	Nil	Nil	Top flight level: 209, 30 minutes after selection.
23/11/73	S	198	207	-13	12 000	Nil	Nil	Nil	Nil	Nil	Nil	Top neither grew nor dispersed in the hour after seeding.
26/11/73	N	-	218	-14,5	10 800	Nil	Nil	Nil	Nil	Nil	Nil	
26/11/73	S	190	197	-10	8 700	Nil	Nil	Nil	Nil	Nil	Nil	Top flight level unchanged: 40 minutes after seeding.
27/11/73	S	215/205	215	-14,5	11 800	>438	>438	>438	>438	(>74)	>43	Multicell cluster. Two shower cells observed.
29/11/73	S	225/205	230	-16	14 500	>1 211	>1 210	>1 194	>1 172	(>61)	>48	Double-cell structure. Grew into a cumulonimbus.
30/11/73	N	-	193	-8	12 300	239	215	166	121	49		At the end of a line, but did not actually merge with other rain.
06/12/73	S	215	225	-14,5	13 900	>640	>639	>597	>500	(>48)	>35	Lightning was observed 40 minutes after seeding.
11/12/73	S	207	217	-14	14 700	63	53	26	5	29		
12/12/73	N	-	205	-13,5	12 900	6	6	5	3	(33)	20	
13/12/73	N	-	235	-17	16 000	19	14	10	5	36		Double cell.
17/12/73	S	206/180	210	-13	11 500	10	1	Trace	Nil	22		Base broken. Starting to fade, when selected. (Top -8°C after 5 mins.)
03/01/74	N	-	202	-10,5	12 200	12	3	Trace	Nil	21		
10/01/74	S	210	218	-14	11 800	Trace	Nil	Nil	Nil	13		Top dispersed and collapsed within five minutes of seeding.
11/01/74	S	198	215	-13,5	13 500	45	29	16	6	34		
14/01/74	N	-	219	-12,5	13 900	2	Trace	Nil	Nil	18		
14/01/74	N	-	226	-14	14 600	122	74	30	9	30		Multicell structure.
17/01/74	S	220	228	-16	13 800	Trace	Trace	Nil	Nil	(20)	2	

TABLE I (Contd.)

Randomised Clouds from which an estimate of rain yield is possible, 1973-74

Date	Seeded or not	Seeding flight level	When selected			RAIN (10^3 m ³) from x mins. after seeding				Mins. after seeding rain ceased.	Rain Duration (mins.)	Other notes (e.g., subsequent growth)
			Cloud Top FL	Temp. of top °C	Cloud Depth ft	x=10	x=15	x=20	x=25			
18/ 1/74	S	195	218	-14	13 100	1 792	1 679	1 595	1 554	88		Double-cell structure.
21/ 1/74	S	183	225	-13	13 500	157	116	87	49	47		Double-cell structure.
28/ 1/74	N	-	217	-13	13 700	74	44	14	3	31		
29/ 1/74	N	-	210	-12,5	12 600	6	3	Trace	Nil	(25)	18	
29/ 1/74	S	178	208	-12	12 400	1	1	1	1	(32)	18	
1/ 2/74	S	186	223	-14	14 300	314	209	125	67	50		
5/ 2/74	S	220/210	223	-14	14 400	77	53	25	7	38		Top flight level only 205 when first observed. Cloud leaning quite badly.
7/ 2/74	N	-	220	-10,5	11 500	29	8	1	Nil	25		Double-cell structure.
11/ 2/74	S	204	208	-10,5	12 800	204	147	92	42	47		
22/ 2/74	N	-	221	-14,5	15 300	127	101	85	61	45		Top collapsed slowly. Merged with a line in its dying moments.
28/ 2/74	S	217/200	225	-13	14 500	27	21	15	12	44		No further growth by 10 minutes after seeding.
1/ 3/74	N	-	218	-12,5	14 600	100	68	36	11	34		Double-cell structure.
18/ 3/74	N	-	218	-13,5	14 600	630	616	574	366	45		Double-cell structure. Grew about 1 000 ft during the 3 minutes after selection.
19/ 3/74	S	208/200	225	-15,5	15 300	60	33	11	2	30		Multi-cell structure. Top collapsed slowly after seeding.
21/ 3/74	S	193	200	-10,5	12 500	142	74	38	16	37		
27/ 3/74	N	-	230	-16	15 000	79	45	17	4	31		Double-cell structure.
28/ 3/74	S	202/187	210	-12	13 000	1	1	1	1	(30)	7	Adjacent cell also seeded, but with top only at flight level 193.
29/ 3/74	N	-	235	-20,5	15 600	Nil	Nil	Nil	Nil	Nil	Nil	Top collapsed slowly after selection.

the random sequence. Columns 4, 5 and 6 give the cloud-top height and temperature and the cloud depth at the moment of selection. It was not always possible to observe subsequent changes in cloud-top heights, but if it was, then notes have been inserted in the right-hand section of Table I.

Table II shows that, on average, there was no built-in bias in favor of the seeded clouds, when they were selected. If anything the non-seeded clouds seemed slightly better endowed, being deeper, and also having colder tops.

Columns 7-10 inclusive of Table I give the total rain in kilocumes measured after the four different threshold times, varying between 10 and 25 times after seeding, or the equivalent for non-seeded clouds. A kilocume is 1,000 cubic meters, so that one kilocume of water weighs 1000 metric tons.

Column 11 of Table I gives the time between seeding (or the equivalent) and the termination of rain. If the start of rain was observed, then the actual rain duration has been entered in column 12, and the figure in column 11 appears in brackets, because it can be misleadingly high if the rain was late in starting. (See for example the 17th January 1974: the actual rain duration was only 2 minutes, but the termination time was 20 minutes after seeding). If the start of rain was not known, then column 12 is left blank.

TABLE II

Average Top Temperatures and Cloud Depths at the Moment of Selection

	Depth ft.	Top Temperature °C
Seeded clouds	13,100	-13.3
Non-seeded clouds	13,500	-13.7

Indicated increase in rainfall

Table III shows the average rain produced both by the 20 seeded and by the 16 non-seeded clouds measured after the four different starting times. These averages include all occasions of nil rainfall. It is significant that there is a consistent and steady improvement in the uplift in rainfall as the starting time for measurements is made later; from 10 minutes onwards the uplift was approximately threefold, and after 25 minutes it was just over fivefold. It is also important to notice that the differences of seeded minus non-seeded rainfalls were, to a first approximation, constant and independent of the starting time of measurements: this difference was in every case about 160 kilocumes. This fact supports the hypothesis that most if not all of the additional rain due to seeding was produced comparatively late in the cloud's lifetime.

It is worth noting that experiments conducted in Florida in 1968 and

1970 also showed an improvement in results with increasing time after seeding (Simpson et al., 1971).

TABLE III
Indicated Increase in Rainfall
 (Averages include all nil rainfall occasions)

	Rain measurement from x minutes after "seeding"			
	x = 10	x = 15	x = 20	x = 25
Average rain, Seeded clouds (10 ³ m ³)	259	235	213	194
Average rain, Non-seeded clouds (10 ³ m ³)	90	75	59	36
Rainfall ratio, seeded/non-seeded clouds	2.87	3.14	3.63	5.32
Rainfall difference seeded minus non- seeded clouds (10 ³ m ³)	169	160	154	158
Significance level (one-tailed)	0.22	0.23	0.14	0.09

The likelihood of the results being pure chance

The clouds were arranged in descending order of rainfall, and labeled according to whether they were seeded or not. Using the rainfalls measured from the 25-minute starting time, the ranking reads

SSSSNSNSSSSNNSSNNNNSSS (SSSSS)
 (NNNNNNN)

(The five S's and seven N's enclosed in brackets are all nil-rainfall occasions tying for bottom rank).

It will be seen that the four clouds with the heaviest rain were all seeds, and also that nine clouds out of the top 12 were seeded ones. A Mann and Whitney permutation significance test shows that there is only a 0.09 probability of an equally or more favorable arrangement occurring by

chance. In other words, this is a nine to one indication that the silver iodide treatment increased the rainfall measured after 25 minutes from seeding.

Similar rankings and significance tests were also carried out for the 10, 15 and 20-minute starting times, and the results are included in Table III. Like the seed/non-seed ratios, the significance levels mostly improve as the starting time becomes later. It should be mentioned that on many occasions the rain measurements did not start much before 15 minutes after seeding, making it necessary to extrapolate the graphs to calculate the 10-minute totals, which are therefore less accurate than the others. For this reason the lack of improvement in the significance level between 10 and 15 minutes is not important.

In the Appendix there is an explanation of the Mann-Whitney procedure used in the calculations, including the correction necessary when tied ranks occur.

The effect of a very wet season on the results

The 1968-69 Rhodesian experiments suggested that seeding tended to be less effective on days of fairly general rain, than on days when showers were isolated (McNaughton, 1970). This is consistent with experience overseas (Bethwaite et al., 1966, Simpson et al., 1971).

1973-74 was one of the wettest rainy seasons on record in Rhodesia. In Table III the average rainfall per non-seeded cloud, measured from the 10-minute starting point, is 90 kilocumes, and measured from 25 minutes it is 36 kilocumes. Both these quantities are greater than the 1968-69 non-seeded average rainfall of 16 kilocumes, and this is why the three to fivefold uplift achieved in 1973-74 is less than the ninefold increase produced by seeding in 1968-69.

Table IV includes the results of rainfall measurements taken on clouds which belonged to a much larger system; very often they were part of an almost continuous line of storms or showers, as noted in the right-hand section of the table. As has been explained above, these measurements cannot be regarded as accurate, because of the difficulty of excluding foreign rain; however, an approximate estimate of rainfall has been made. There are too few of these experiments to justify any separate statistical treatment, but it is noteworthy that on 6th February the rainfall from a non-seeded section of a storm-line appeared to be substantially heavier than that from any of the isolated seeded clouds in Table I. The rain from the two other non-seeded members of a large storm system on 7th December and 11th January was also high, exceeded by only six or seven of the randomized single clouds of Table I.

In other words, in conditions of copious natural rainfall it appears that the benefits of cloud seeding are reduced, and this is probably why the positive effect of seeding was not as clear-cut in 1973-74 as it was in 1968-69.

TABLE IV

Supplementary Experiments 1973-74

Date	Seeded or not	Seeding flight level	When selected			RAIN (10^3 m^3) from x mins. after "seeding"				Mins. after seeding rain ceased	Rain Duration (mins)	Other notes (e.g., subsequent growth)
			Cloud Top FL	Temp. of top °C	Cloud Depth ft	x=10	x=15	x=20	x=25			
5/11/73	S	216	223	-13	13 600	217	174	141	119	44		Substantial growth after seeding, and heavier rain than similar clouds nearby.
6/11/73	S	226	230	-14,5	15 300	290	240	220	28	236		Merged with storm line; measurements inaccurate. Collector leaking.
14/11/73	S	183	183	-9	10 300	Mod/heavy				Not known		Very close to other rain. Collector still leaking.
15/11/73	S	180	190	-11,5	10 400	Nil	Nil	Nil	Nil	Nil	Nil	Double-cell structure.
15/11/73	S	200	210	-15,5	12 300	>1 134	>1 134	>1 115	>1 052	(>59)	23	Multicell. Gave much heavier rain than similar clouds around.
22/11/73	S	206	210	-14,5	9 300	Nil*	Nil*	Nil*	Nil*	Nil*	Nil*	Returned to base 25 mins. after seeding. *Rain seen in the area soon after.
23/11/73	S	190	205	-12,5	11 600	Approximately 10				(27)	20	Part of a system randomly seeded one hour earlier.
26/11/73	S	207	215	-14	10 200	Trace	Trace	Trace	Trace	(33)	22	
7/12/73	N	-	233	-18	15 500	2191	2183	2129	284	(239)	28	Absorbed by adjacent system; only 3 measuring runs possible.
31/12/73	S	210	218	-12	13 800	Heavy	Heavy	Heavy	?	?		Absorbed by an adjacent system.
2/ 1/74	S	237	240	-17	16 000	>428	>368	>245	>144	>38		Grew to 28 000 ft. Comparable clouds around gave only light rain.
3/ 1/74	S	200	210	-12	12 800	30	28	23	2	29		Multicell structure.
11/ 1/74	N	-	235	-18	16 000	>196	>181	>164	>151	>39		Merged with other rain in a continuous line of showers.
17/ 1/74	S	185/192	197	-10,5	10 300	13	13	13	12	(45)	26	Top flight level estimated at least 210, 10 minutes after seeding.
5/ 2/74	S	180/190	205	-11	12 500	Nil	Nil	Nil	Nil	Nil	Nil	Leaning very badly. Had already begun collapsing, (top $-7\frac{1}{2}^{\circ}\text{C}$ after 5 minutes).
6/ 2/74	N	-	225	-15	14 500	>2 362	>2 212	>2 129	>2 047	>76		Multicell structure in a storm-line.
11/ 2/74	S	181	215	-12	13 500	Nil	Nil	Nil	Nil	Nil	Nil	This experiment simultaneous with a random one.
21/ 2/74	S	200/181	200	-9	12 000	>426	>422	>407	>384	>64		Multicell. Comparable clouds around gave only light rain.
28/ 2/74	S	185	193	-6	11 400	8	1	Trace	Nil	21		No further growth observed : top remained too warm for seeding.
1/ 3/74	S	185	191	-6,5	11 100	Nil	Nil	Nil	Nil	Nil	Nil	Broken base and bad lean. Top probably too warm for seeding.

The nil-rainfall seeded occasions

Table I includes a number of occasions when no rainfall fell from clouds, even after seeding. However, this has also been the case in experiments conducted overseas; see for example the Australian results given by Bethwaite *et al.* (1966), and also accounts of Russian work reported by Kornienko (1970).

The implication is that cloud seeding does not always succeed in producing extra rain; however, the occasions when it does work seem to be more than enough to compensate for the failures.

Attempts have been made overseas, with varying success, to discover a means of knowing in advance whether or not seeding is likely to be worthwhile, on any given day. So far, all of these have utilized the available radiosonde and upper wind data, usually in a computerized model.

The non-randomized seeding trials

Table IV includes the results of clouds which, for various reasons, were seeded without an envelope being opened.

On 28th February and 1st March, using Tbl cartridges, two clouds with tops at about -6°C were seeded, one of which had a very broken base and a pronounced lean. Neither gave any significant rain. However further experiments on clouds warmer than -10°C will be necessary before firm conclusions are made as to their seedability.

Four other occasions in the table are noteworthy: these are 5th November, 15th November, 2nd January and 21st February. On each of these days there was a wide choice of possible clouds, all fulfilling the selection criteria. However, the cloud selected and seeded produced heavy rain, whereas similar clouds around gave only light rain. Although measurements were not taken from the other showers, their rain-shafts were completely transparent, whereas the rain from the seeded clouds was opaque and therefore much more intense.

On 15th November Table IV shows that the first attempt at seeding produced nothing, but the second experiment resulted in very substantial rain. To begin with, this was the only rain visible from the aircraft, which commanded a view of at least 100 km in all directions. Later on a few light showers broke out about 15 km away.

CONCLUSIONS

Randomized trials carried out on 20 seeded and 16 non-seeded clouds resulted in heavier average rainfall on the seeded occasions. As the time of commencement of the rain calculations become later, so the indicated uplift from seeding increased progressively from threefold to fivefold. The difference between the average seeded and non-seeded rainfall yields was approximately 160 kilocumes. A ranking test showed a nine to one probability in support of the fivefold increase in rainfall, when measure-

ments started 25 minutes after seeding.

There is evidence that the effect of seeding is less under wet conditions. The experiments were carried out during one of the wettest seasons in Rhodesian history, and the results were not as spectacular as they were in 1968-69.

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Modifications to the aircraft were capably carried out by Field Aircraft Services (Pvt.) Ltd., who also maintained the aircraft during the 1973-74 season.

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APPENDIX

If there are n_1 seeded and n_2 non-seeded units, and T is the sum of the ranks of the seeded clouds, then the expected value of T

$$E(T) = \frac{1}{2} n_1 (N + 1) \quad \text{where } N = n_1 + n_2$$

If there are t_j observations tied for the j^{th} rank, then the variance, incorporating the correction for all ties, is given by

$$\sigma^2 = \frac{n_1 n_2}{12N(N-1)} \left\{ N(N^2 - 1) - \sum_j (t_j^3 - t_j) \right\}$$

The required probability is then determined by the position in the normal distribution of the value of

$$\frac{E(T) - T - \frac{1}{2}}{\sigma}$$