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13 ABSTRACT

In this, the final report of Project STARDUST, a review is given of the results of analyses of filter and gas samples collected during the course of the program, 1961 to 1967, and a summary is given of the conclusions reached on the basis of these results concerning the influence of atmospheric processes on the transfer and fallout of radioactive materials injected into the stratosphere. Reference is made to results obtained during Project HASP also, for in many ways, Project STARDUST was a continuation of that program.

14 KEY WORDS	LINK A		LINK B		LINK C	
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STAR DUST						
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Stratospheric Aerosols						
High Altitude Sampling, Aircraft						
Upper Atmosphere Meteorology						
Mathematical Fallout Model						
Mathematical Upper Atmosphere Model						
Analysis Fission Products						
Analysis Neutron Activation Products						
Upper Atmosphere Meteorology						
SNAP-9A Reentry Burnup						

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FINAL REPORT ON PROJECT STARDUST

VOLUME II, Chapters 7 and 8

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VOLUME II

CONTENTS

CHAPTER 7. INFORMATION DERIVED FROM MEASUREMENTS OF RADIOACTIVITY FROM 1961 AND 1962 NUCLEAR WEAPON TESTS

During Project STARDUST it was possible to discern details of some of the atmospheric processes which had been described only in general terms during Project HASP. In addition, the more abundant data of Project STARDUST provided a firmer base for estimates of burdens and residence times of radioactive debris in the stratosphere than had been possible during Project HASP. Project STARDUST provided a quantitative documentation for much of the qualitative description of the transport processes in the stratosphere obtained during Project HASP.

The large scale testing of high yield nuclear devices in the atmosphere by the USSR and the U. S. during 1961 and 1962, produced a massive injection of radioactive debris into the stratosphere. The greatest effort expended during Project STARDUST was devoted to the measurement of this debris, and most of the information obtained during the project was derived from these measurements.

The STARDUST sampling program was begun in mid-1961. Project HASP had been terminated in mid-1960 because the moratorium on the testing of nuclear weapons, which had begun at the end of 1958, had resulted in a steady decline in the stratospheric burden of radioactive debris. When first begun, STARDUST sampling was quite limited in frequency and in geographic extent. Soon after the 1961 USSR test series ended the testing moratorium, however, the geographic coverage and frequency of STARDUST sampling were greatly increased. By early 1963 both the number of samples and the coverage exceeded those achieved during

Project HASP. The scope of the sampling program diminished slowly but steadily after 1964 as the stratospheric burden of radioactive debris rapidly dwindled. The program was terminated in 1967.

The initial interceptions of fresh debris from specific events during the 1961 and 1962 test series provided some information on the trajectories followed by the radioactive clouds and on their rates of movement around the earth. Interceptions of products of neutron activation, produced mainly by the very high yield events, provided evidence that little debris from even these events stabilized very far above 20 km height in the polar stratosphere. The failure of any significant amounts of the debris from the 1961 and 1962 USSR tests to penetrate into the southern hemisphere provided evidence that the tropical stratosphere is generally a region of slow mixing in the meridional direction. The sudden appearance of relatively large amounts of radioactive debris in the southern tropical stratosphere in late 1963 did indicate, however, that short periods of enhanced interhemispheric exchange do take place. In both early 1962 and early 1963 rapid changes in the circulation of the lower stratosphere were reflected by changes in the concentrations of radioactive debris intercepted in the STARDUST sampling corridor. Measurements of cadmium-109 provided information on the nature and rates of processes which produce the redistribution within the stratosphere of particulate material initially injected at great heights within the upper atmosphere. The bulk of the radioactive debris which was initially injected into the lower and middle stratosphere appeared to migrate fairly rapidly downward, probably because of gravitational settling, into the layer between the tropopause and 20 km. The stratospheric debris exhibited a residence half-time of about 10 months. It had been expected that this residence half-time would lengthen gradually with the passage of time as the lower stratosphere became depleted by fallout into the troposphere, but this did not occur. The peak in the vertical distribution of radioactive debris continued to be found near or below the 20 km level throughout 1963 to 1967, presumably because fallout into the troposphere was compensated by gravitational settling from above. This combination of processes appeared to maintain the residence half-time of the debris in the stratosphere at about 10 months. On the other hand, the residence half-time of carbon-14 in gaseous carbon dioxide did not remain constant during this period, but gradually lengthened as a result both of depletion of the lowest layers of the stratosphere and buildup of carbon-14 concentrations within the troposphere.

7.1 Interceptions of Fresh Debris from the 1961 USSR Weapon Tests

The first event in the 1961 series of nuclear weapon tests by the USSR occurred on 1 September 1961. Table 32 lists the events in this series which were identified as being of megaton yield[13], and which therefore might be expected to inject radioactivity into the stratosphere. The first of these occurred on 10 September 1961.

The appearance of radioactive debris from the USSR events in STARDUST filter samples was indicated by a sudden increase in the total beta activity of the filters. Table 33 lists the concentrations of total beta activity encountered at a height of about 20 km at about 45° N latitude during July 1961 to August 1962. The first interception at this location of radioactive debris from the 1961 USSR weapon tests occurred on 4 October 1961. Almost all samples collected subsequently at this location during 1961 and 1962 contained some debris from this test series. Clearly, however, the concentration of debris

TABLE 32. High Yield Events in the 1961 USSR Series of Nuclear Weapon Tests at Novaya Zemlya[13]

Date	Yield	Remarks
10 Sep 1961	Several Megatons	
12 Sep 1961	Several Megatons	
14 Sep 1961	Several Megatons	
16 Sep 1961	Order of a Megaton	
18 Sep 1961	Order of a Megaton	
20 Sep 1961	Order of a Megaton	
22 Sep 1961	Order of a Megaton	
2 Oct 1961	Order of a Megaton	
4 Oct 1961	Several Megatons	
6 Oct 1961	Several Megatons	
20 Oct 1961	Several Megatons	
23 Oct 1961	About 25 Megatons	Detonated at about 12,000 feet.
25 Oct 1961	Intermediate - high	Yield probably less than a megaton.
30 Oct 1961	55 to 60 Megatons	Small fission yield.
31 Oct 1961	Several Megatons	
31 Oct 1961	Intermediate - high	Yield probably less than a megaton.
4 Nov 1961	Several Megatons	

TABLE 33. Total Beta Activities of Samples Collected at about 20 km Altitude at 45°N during the Second Half of 1961 and Early 1962

Collection Date	Latitude Range	Altitude (km)	Activity (pCi/SCM)
6 Jul 1961	48° - 43°N	20	38
7 Jul 1961	48° - 43°N	20	44
25 Jul 1961	48° - 43°N	20	43
2 Aug 1961	48° - 43°N	20	36
15 Aug 1961	48° - 43°N	20	58
22 Aug 1961	48° - 43°N	20	60
6 Sep 1961	48° - 40°N	20	35
7 Sep 1961	48° - 43°N	20	43
8 Sep 1961	48° - 43°N	20	37
28 Sep 1961	48° - 43°N	20	36
30 Sep 1961	47° - 43°N	21	54
4 Oct 1961	48° - 43°N	20	260,000
24 Oct 1961	48° - 43°N	20	570
25 Oct 1961	48° - 43°N	20	6,220
31 Oct 1961	48° - 43°N	20	590
15 Nov 1961	48° - 43°N	20	12,700
16 Nov 1961	48° - 43°N	20	18,500
6 Dec 1961	48° - 43°N	20	1,130
7 Dec 1961	48° - 43°N	20	990
19 Dec 1961	48° - 43°N	20	1,530
21 Dec 1961	48° - 43°N	20	1,860
11 Jan 1962	48° - 43°N	20	1,150
15 Jan 1962	48° - 41°N	20	510
23 Jan 1962	49° - 44°N	20	530
30 Jan 1962	49° - 44°N	20	350
6 Feb 1962	49° - 44°N	20	149
13 Feb 1962	49° - 44°N	20	48
19 Feb 1962	49° - 44°N	20	200
27 Feb 1962	49° - 44°N	20	250
6 Mar 1962	49° - 44°N	20	4,260
13 Mar 1962	49° - 44°N	21	94
30 Mar 1962	49° - 43°N	20	430
31 Mar 1962	51° - 42°N	20	370
19 Apr 1962	50° - 42°N	21	280
26 Apr 1962	49° - 43°N	20	400
1 May 1962	48° - 43°N	20	380
8 May 1962	49° - 43°N	20	1,150
15 May 1962	49° - 43°N	20	1,220
16 May 1962	49° - 41°N	20	800
22 May 1962	49° - 43°N	20	410
28 May 1962	49° - 41°N	20	620
29 May 1962	49° - 43°N	20	770

TABLE 33. (continued)

Collection Date	Latitude Range	Altitude (km)	Activity (pCi/SCM)
5 Jun 1962	49° - 43°N	19	700
12 Jun 1962	49° - 43°N	20	2,700
19 Jun 1962	49° - 44°N	20	1,230
26 Jun 1962	48° - 44°N	20	1,230
6 Jul 1962	49° - 44°N	20	930
13 Jul 1962	49° - 44°N	20	920
20 Jul 1962	49° - 44°N	20	1,650
27 Jul 1962	48° - 44°N	20	1,550
3 Aug 1962	49° - 43°N	20	710

intercepted was strongly dependent upon the configuration of the stratospheric circulation, as has been discussed for early 1963 by Telegadas[36]. Thus, the development of the winter night circulation in the polar stratosphere apparently inhibited the southward movement of debris sufficiently to prevent concentrations of fresh debris as high as those encountered on 4 October 1961 from again reaching this site on any subsequent sampling date. In addition, the displacement of the polar vortex circulation toward Eurasia during late January 1962 permitted air which was relatively uncontaminated by the USSR debris to move into the vicinity of this site, where it was sampled on 6 and 13 February and 13 March 1962. The breakdown of the polar night circulation in the early spring of 1962 allowed larger quantities of the USSR debris to enter the vicinity of the sampling site during May 1962 and subsequent months. As a result, the concentrations of total beta activity intercepted at this site during May to August 1962 were considerably higher than most of those intercepted during January to April 1962 in spite of the steady decrease in the total activity of stratospheric air as a result of radioactive decay and fallout.

An attempt was made to identify the specific event which had produced each pulse of fresh debris which reached the STARDUST sampling corridor. Two techniques were used. The first, which was discussed in Chapter 6, depended upon monitoring the rate of decay of the total beta activity of a sample and then comparing the shape of the decay curve with the shape of the curve given by Dolan[14] to estimate the age of the debris. The second technique involved analyzing the sample radiochemically for two or more short-lived fission products, and then comparing the fission product ratios with those expected in debris from typical megaton yield events[35]. Actually neither method was sufficiently accurate to distinguish clearly between events which occurred only one or two days apart. Besides the inevitable analytical errors, the variable fractionation of the debris from the different events rendered the precise dating of samples of debris very difficult, and the continuously growing background of debris from earlier events in the series made the dating of later samples only approximate at best.

Table 34 lists flight data and analytical data for some samples which contained fresh radioactive debris from the 1961 USSR test series. The beta decay curves for some of these samples are plotted in Figure 49. The decay curves distinguish debris which originated in the mid-September events (samples 4306N and 4312H) from that which originated in the early October 1961 events (4370N and 4372N). As was found with debris from the 1957 and 1958 events (Chapter 6), the age indicated by comparison with Dolan's beta decay curve may be too young by about ten days for some events. Thus the shot date for samples 4306N and 4312H was probably 10, 12 or 14 September, not 20 September, and the shot date for 4370N and 4372N was probably 4 or 6 October, not 13 or 15 October. On the other hand, the fresh debris in samples 4405N and 4429N probably originated in the 20 October, or perhaps the 23 October event, in reasonable agreement with the shot dates indicated by the rates of beta decay.

The more precise dating of these samples was accomplished by analyzing them for short-lived fission products such as 67 hour molybdenum-99, 12.8 day barium-140, etc., and calculating the age of the debris from the ratios of fission products it exhibited. Table 35 lists apparent shot dates for a number of samples based on two fission product ratios: Mo^{99}/Zr^{95} and Ba^{140}/Sr^{89}. The initial ratios and half-lives used to calculate these ages

TABLE 34. Some Samples Containing Radioactivity from Late 1961 USSR Tests

Sample Number	Collection Date	Latitude	Altitude (km)	pCi β SCM	pCi Sr^{90} SCM	Indicated Shot Date
4299H	30 Sep 1961	54° - 50°N	20.1	12,400	2.6	21 Sep 1961
4306N	4 Oct 1961	33° - 28°N	18.6	30,500	7.1	20 Sep 1961
4312H	4 Oct 1961	48° - 43°N	20.0	260,000	35	20 Sep 1961
4321H	5 Oct 1961	30°N	18.3	17,400	4.0	21 Sep 1961
4372N	25 Oct 1961	43° - 38°N	18.3	72,900	12	13 Oct 1961
4371N	25 Oct 1961	38° - 33°N	18.3	103,000	13	15 Oct 1961
4370N	25 Oct 1961	33° - 28°N	18.3	87,500	12	15 Oct 1961
4367H	26 Oct 1961	30°N	18.2	118,000	17	14 Oct 1961
4382N	31 Oct 1961	43° - 38°N	18.4	49,900	12	11 Oct 1961
4405N	7 Nov 1961	30°N	18.3	37,000	8.7	21 Oct 1961
4429N	15 Nov 1961	30°N	18.3	34,600	11	23 Oct 1961
4460N	22 Nov 1961	30°N	20.1	68,700	35	13 Oct 1961
4461N	22 Nov 1961	30°N	20.1	50,100	25	15 Oct 1961

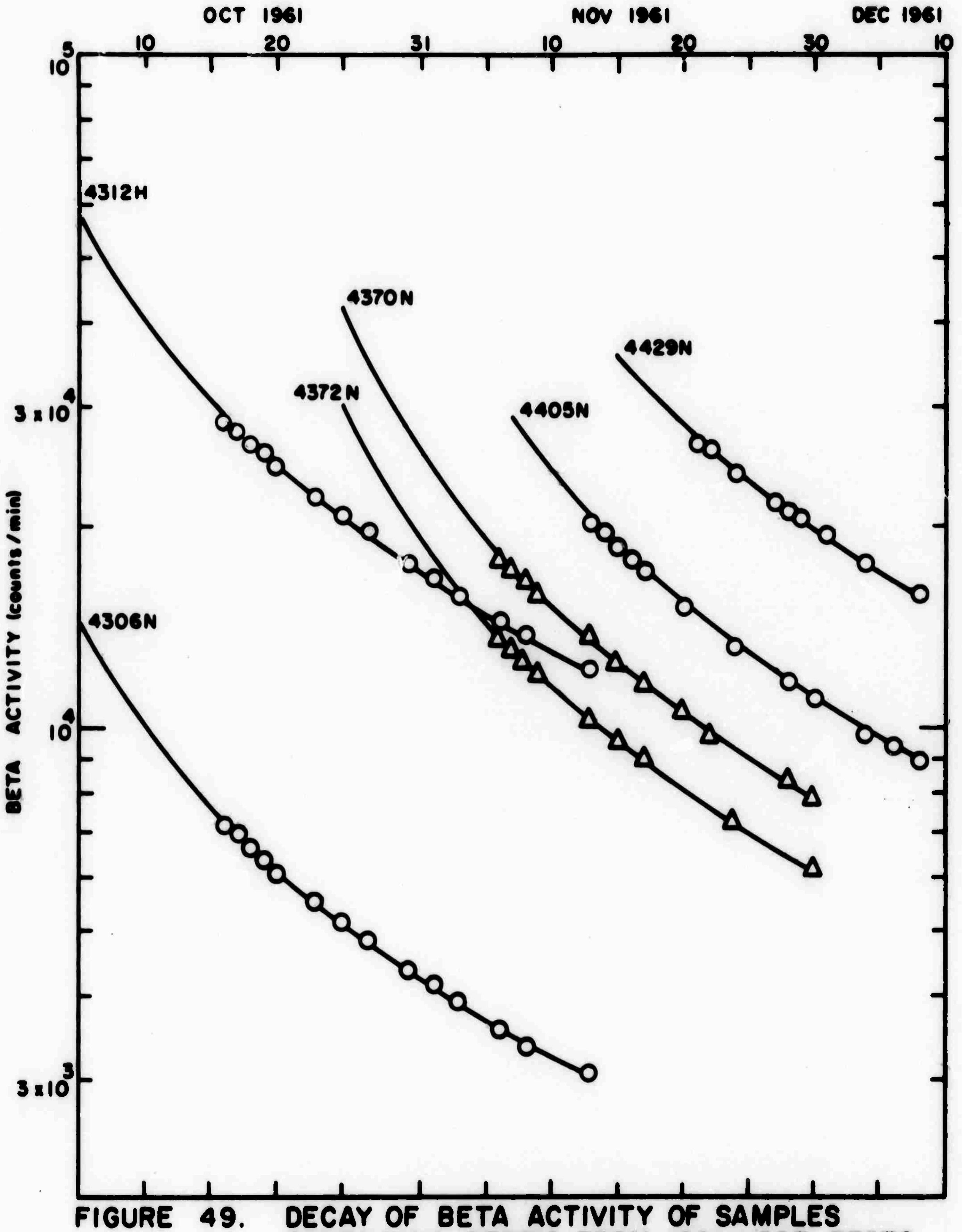

FIGURE 49. DECAY OF BETA ACTIVITY OF SAMPLES CONTAINING DEBRIS FROM 1961 USSR TESTS

TABLE 35. Apparent Shot Dates of Samples with High Total Beta Activities (>10,000 pCi β/SCM) Collected During Late 1961

Collection Date	Latitude Range	Altitude (km)	pCi β / SCM	pCi Sr^{89} / 10^2 SCM	Mo^{99}/Zr^{95} Ratio	Mo^{99}/Zr^{95} Shot Date	Ba^{140}/Sr^{89} Ratio	Ba^{140}/Sr^{89} Shot Date
30 Sep 61	54° - 50°N	20	12,420	6,190	0.36	12 Sep 61	4.4	15 Sep 61
4 Oct 61	33° - 28°N	18	30,500	50,500	0.11	11 Sep 61	2.3	3 Sep 61
4 Oct 61	48° - 43°N	20	260,800	367,000	0.07	10 Sep 61	2.4	4 Sep 61
4 Oct 61	38° - 33°N	20	11,000	15,900	0.10	11 Sep 61	2.4	4 Sep 61
5 Oct 61	30°N	18	18,300	33,100	0.12	13 Sep 61	2.1	2 Sep 61
5 Oct 61	30°N	18	17,300	25,900	0.09	11 Sep 61	2.4	5 Sep 61
25 Oct 61	48° - 43°N	18	12,160	15,810	0.55	9 Oct 61	2.6	27 Sep 61
25 Oct 61	43° - 38°N	18	72,800	117,200	0.24	6 Oct 61	2.3	24 Sep 61
25 Oct 61	43° - 38°N	18	77,270	135,100	0.23	5 Oct 61	2.3	24 Sep 61
25 Oct 61	38° - 33°N	18	101,600	141,200	0.37	7 Oct 61	2.8	29 Sep 61
25 Oct 61	33° - 28°N	18	87,450	114,700	0.31	7 Oct 61	2.7	28 Sep 61
26 Oct 61	30°N	18	117,700	-	0.19	6 Oct 61	-	-
26 Oct 61	30°N	19	25,280	98,400	-	-	1.0	4 Sep 61
31 Oct 61	48° - 43°N	18	18,760	48,400	0.06	6 Oct 61	1.6	22 Sep 61
31 Oct 61	48° - 43°N	18	18,760	51,900	0.05	5 Oct 61	1.3	15 Sep 61
31 Oct 61	43° - 38°N	18	49,930	125,000	0.0[illegible]	3 Oct 61	1.8	24 Sep 61
31 Oct 61	43° - 38°N	18	51,680	144,000	0.05	5 Oct 61	1.5	21 Sep 61
1 Nov 61	48° - 43°N	17	24,490	73,600	0.08	8 Oct 61	1.2	16 Sep 61
1 Nov 61	48° - 43°N	15	19,080	46,550	0.34	14 Oct 61	1.5	22 Sep 61
1 Nov 61	43° - 38°N	15	21,000	35,000	0.64	17 Oct 61	1.9	27 Sep 61
1 Nov 61	43° - 38°N	15	33,400	44,300	0.47	15 Oct 61	2.2	30 Sep 61
7 Nov 61	30°N	18	37,050	90,800	0.24	19 Oct 61	1.6	28 Sep 61
7 Nov 61	30°N	18	37,520	70,000	0.15	17 Oct 61	1.8	2 Oct 61
15 Nov 61	48° - 43°N	20	11,540	42,000	-	-	0.9	22 Sep 61
15 Nov 61	30°N	18	34,700	106,400	-	-	1.4	4 Oct 61
15 Nov 61	30°N	18	30,700	85,900	0.06	21 Oct 61	1.0	26 Sep 61
15 Nov 61	30°N	20	13,390	52,800	0.02	15 Oct 61	0.9	21 Sep 61
16 Nov 61	48° - 38°N	20	11,730	41,900	-	-	0.9	23 Sep 61
16 Nov 61	38° - 28°N	20	11,650	41,100	-	-	0.9	22 Sep 61
16 Nov 61	38° - 33°N	18	20,200	68,300	0.05	21 Oct 61	-	-
16 Nov 61	33° - 28°N	18	21,000	61,400	0.03	19 Oct 61	-	-

TABLE 35. (continued)

Collection Date	Latitude Range	Altitude (km)	pCi β SCM	pCi Sr^{89} 10^2 SCM	Mo^{99}/Zr^{95} Ratio	Mo^{99}/Zr^{95} Shot Date	Ba^{140}/Sr^{89} Ratio	Ba^{140}/Sr^{89} Shot Date
22 Nov 61	30°N	18	12,510	52,800	0.03	25 Oct 61	0.8	26 Sep 61
22 Nov 61	30°N	18	13,040	63,100	-	-	0.6	19 Sep 61
22 Nov 61	30°N	20	68,700	309,000	-	-	0.8	28 Sep 61
22 Nov 61	30°N	20	66,500	272,000	-	-	1.0	2 Oct 61
22 Nov 61	30°N	20	50,100	220,000	-	-	0.9	30 Sep 61
22 Nov 61	30°N	20	55,200	198,500	-	-	1.1	4 Oct 61
29 Nov 61	18° - 15°N	20	12,780	12,800	-	-	0.4	14 Sep 61

were 26.4 and 2.88 days for Mo^{99}/Zr^{95}, and 6.73 and 17.1 days for Ba^{140}/Sr^{89}. Since molybdenum-99 and zirconium-95 are both "refractories", and barium-140 and strontium-89 both have "volatile precursors", these ratios should not be adversely affected by fractionation of the debris. The short half-life of molybdenum-99 permits precise dating, although the gradual accumulation of a "background" of zirconium-95 would introduce uncertainties into dates for later samples. The relatively long half-lives of barium-140 and strontium-89 prevent the Ba^{140}/Sr^{89} ratio from yielding better than an approximate date.

It is noteworthy that very little debris from any of the late October - early November events was intercepted. Since some of these events had yields of several megatons, comparable to the yields of the mid-September and early October events, the failure of the STARDUST missions to collect debris from them is most likely related to a change in the circulation of the stratosphere between mid-September and mid-October, with a decrease in the rate of transport of debris in the meridional direction. It is possible that the debris from the 23 October and 30 October very high yield events was mainly deposited initially at altitudes above 20 km, so that STARDUST aircraft did not intercept it. This hypothesis is not necessary to explain the lack of interceptions, and does not explain the failure of STARDUST flights to intercept debris from the events with yields of only "several megatons". It is hypothesized, therefore, that debris from the late 1961 USSR tests was held almost entirely at high latitudes within the winter night polar vortex circulation into which it was injected until the breakdown of this circulation occurred in the early spring of 1962. Telegadas[36] discussed such an effect following the late 1962 USSR test series.

The pattern of the initial interception of the USSR radioactive debris by the STARDUST aircraft was interesting. This initial interception occurred on 30 September 1961, twenty days following the first megaton yield event in the USSR series. Flight data and total beta data are given in Table 36 for the samples collected on this date, and also for samples collected on 6 September 1961, on an earlier sampling of the polar stratosphere for Project STARDUST. The activities intercepted by aircraft 715 were entirely comparable to those intercepted on 6 September 1961. Aircraft 714, which was following 15 to 20 minutes behind aircraft 715, but along the same flight track, intercepted fresh debris in notable quantities at three or more different locations between 60°N and 37°N. Probably the aircraft were flying at slightly different altitudes, and only aircraft 714 passed through a contaminated layer. It would be fortuitous indeed if the radioactive debris actually reached the flight track at three different places during the 15 to 20 minutes which elapsed between the passage of aircraft 715 and the arrival of aircraft 714. Several sets of vertical soundings of concentrations of debris which were made during Project STARDUST confirmed the common occurrence of pronounced layering of the stratospheric radioactivity. Table 37 contains two examples. Both profiles include samples collected a few hours apart by different aircraft, indicating that the concentrations were not changing rapidly with time during the course of the sampling mission. The rapid decrease of activity with height above 19.8 km in each profile must thus represent a change with location and not with time of sampling. Both profiles indicate more than a factor of three change in concentration over a difference in height of less than 2 km.

TABLE 36. Total Beta Activities of Some Samples Collected Between 64°N and 30°N in September 1961

6 Sep 1961, A/C 714			30 Sep 1961, A/C 715			30 Sep 1961, A/C 714		
Latitude	Altitude (km)	pCi β SCM	Latitude	Altitude (km)	pCi β SCM	Latitude	Altitude (km)	pCi β SCM
64° - 57°N	19	38	60° - 57°N	19	53	60° - 57°N	19	3,340
57° - 51°N	19	40	57° - 55°N	20	47	57° - 54°N	20	63
			55° - 51°N	20	52	54° - 50°N	20	12,400
51° - 45°N	20	47	51° - 47°N	20	50	50° - 47°N	20	71
			47° - 43°N	20	54	47° - 43°N	21	54
45° - 36°N	19	29	43° - 40°N	20	51	43° - 40°N	21	96
						40° - 37°N	21	4,750
			36° - 33°N	21	44	37° - 33°N	21	49
			33° - 30°N	21	37	33° - 30°N	21	50

TABLE 37. Variations in Concentrations of Total Beta Activity Between Samples Collected in Certain Vertical Soundings

Latitude Interval	Longitude	Altitude (km)	Time Interval (Z)	Beta Activity (pCi/SCM)	Aircraft Number
Collection Date: 1 March 1962					
70° - 65°N	147°W	20.7	22:42 - 23:24	119	717
70° - 65°N	147°W	20.1 - 20.7	21:42 - 22:38	132	717
70° - 65°N	147°W	19.8	23:40 - 00:20	418	705
70° - 65°N	147°W	19.5 - 19.8	20:57 - 21:37	470	717
70° - 65°N	147°W	18.6 - 18.3	22:39 - 23:32	976	705
70° - 65°N	147°W	18.3	19:58 - 20:48	853	717
Collection Date: 14 June 1962					
70° - 65°N	147°W	20.1 - 20.4	22:46 - 23:30	1,810	716
70° - 65°N	147°W	19.8 - 20.1	21:53 - 22:38	4,030	716
70° - 65°N	147°W	19.8	23:30 - 00:13	6,370	715
70° - 65°N	147°W	19.5 - 19.8	20:57 - 21:46	7,320	716
70° - 65°N	147°W	18.3 - 18.6	19:57 - 20:43	1,200	716
70° - 65°N	147°W	18.3	22:23 - 23:17	1,250	715

All of the early interceptions of the USSR radioactive debris seemed to suggest that it occurred mainly in layers or clouds of limited vertical and horizontal extent. The distribution of concentrations of total beta activity in the STARDUST sampling corridor at four times during October 1961 to January 1962 are indicated in Table 38. The data suggest that the radioactive debris was initially distributed rather unevenly within the stratosphere as numerous small fragments of clouds, and that this condition persisted at least into January 1962. Nevertheless, the distribution during 17 to 30 January 1962 exhibited certain characteristics which were observed repeatedly during subsequent months: The highest concentrations of radioactive debris were found between 14 and 18 km in the polar stratosphere, and a layer of gradually decreasing concentrations extended toward the equator, rising in height and thinning as it was followed to lower latitudes.

There was ample evidence that some of the USSR radioactive debris penetrated into the tropical stratosphere during late 1961, but there was little evidence that any measurable amount reached or crossed the equator. Table 39 contains data for STARDUST samples collected in the equatorial stratosphere during October 1961 to April 1962, and Table 40 contains data for samples collected in the stratosphere of the southern hemisphere during the same period. By 23 October 1961 some fresh debris had penetrated south of 18°N, but there was no indication in samples collected on 8 December 1961 that any fresh debris had penetrated south of 9°N by then. The sample collected between 2°N and 16°S on 16 April 1962 did have a significantly higher beta activity than any sample previously collected in that region, however, so it seems likely that by mid-April 1962 some fresh debris had at least reached the

TABLE 38. Total Beta Activities (pCi β/SCM) of Some Samples Collected During Late 1961 and Early 1962

4 and 5 Oct 1961

Alt (km)	45°N	40°N	35°N	30°N
21	-	-	-	121
20	260,000	780	11,000	114
18	43	135	-	24,200
17	-	-	-	573

12, 13, 20 and 24 Oct 1961

Alt (km)	45°N	40°N	35°N	30°N	25°N	20°N	15°N
21	-	-	57	41	38	33	33
20	570	226	902	2,290	5,360	38	-
18	-	-	-	1,590	-	-	-
17	4,250	6,530	878	461	-	-	-
15	859	480	178	123	-	-	-

6, 7, 12 and 13 Dec 1961

Alt (km)	45°N	40°N	35°N	30°N	25°N
21	-	-	1,240	900	1,350
20	1,060	1,425	2,580	2,430	-
18	2,000	1,610	1,130	5,400	-
17	8,910	10,600	3,080	1,685	-
15	9,750	5,230	2,940	1,620	-

TABLE 38. (continued)

17, 18, 19, 23, 25 and 30 Jan 1962

Alt (km)	70°N	65°N	60°N	55°N	50°N	45°N	40°N	35°N	30°N	25°N	20°N	15°N
21	2,110	1,200	-	-	-	-	124	86	353	800	195	1,030
20	1,240	955	172	206	291	440	581	780	1,210	2,190	1,020	1,860
18	13,500	7,490	1,540	1,690	1,920	1,840	1,920	2,500	1,010	714	1,040	1,170
17	21,300	12,100	5,200	5,310	38	-	-	-	693	127	25	27
16	-	-	-	-	-	2,430	2,820	985	256	-	-	-
15	17,000	10,550	2,140	1,960	2,320	-	-	-	-	-	-	-
14	10,600	7,450	7,030	6,970	5,800	3,420	3,910	127	60	-	-	-
13	-	-	-	-	-	38	238	-	-	-	-	-
12	4,860	3,240	3,660	2,070	70	-	-	-	2	-	-	-

TABLE 39. Total Beta Activities of Samples Collected in the Equatorial Stratosphere During Late 1961 and Early 1962

23 Oct 1961, A/C 714

Latitude Band	Altitude (km)	pCi β SCM
18°N - 1°S	20	37
1° - 17°S	21	35

23 Oct 1961, A/C 716

Latitude Band	Altitude (km)	pCi β SCM
18°N - 1°S	19	300
1° - 16°S	20	30

8 Dec 1961, A/C 716

Latitude Band	Altitude (km)	pCi β SCM
20° - 10°N	20	1,310
9° - 1°N	20	8
1°N - 7°S	20	8
8° - 16°S	20	7

9 Mar 1962, A/C 718

Latitude Band	Altitude (km)	pCi β SCM
18° - 0°N	20	690
0° - 18°S	20	60

16 Apr 1962, A/C 718

Latitude Band	Altitude (km)	pCi β SCM
2°N - 16°S	20	119

TABLE 40. Total Beta Activities of Some Samples Collected in the Stratosphere of the Southern Hemisphere During Late 1961 and Early 1962

25 Oct 1961, 30 Oct 1961			26 Nov 1961			5 Dec 1961		
Latitude Band	Altitude (km)	pCi β SCM	Latitude Band	Altitude (km)	pCi β SCM	Latitude Band	Altitude (km)	pCi β SCM
19° - 25°S	20	44	38°S	17	24	18° - 21°S	20	22
25° - 35°S	20	44	38°S	18	29	21° - 25°S	20	30
			38°S	20	42	25° - 27°S	20	35
40° - 50°S	20	44	40° - 50°S	20	37	27° - 35°S	20	35
50° - 60°S	20	42	50° - 60°S	20	39			

11 Mar 1962, 20 Mar 1962			9 Apr 1962, 14 Apr 1962		
Latitude Band	Altitude (km)	pCi β SCM	Latitude Band	Altitude (km)	pCi β SCM
20° - 26°S	20	25	19° - 25°S	20	32
26° - 38°S	20	29	25° - 35°S	20	25
40° - 50°S	20	30	40° - 50°S	20	26
50° - 61°S	20	31	50° - 60°S	20	25

equator. By the end of April 1962, the 1962 U. S. weapon test series had begun, and some of the events in this series injected radioactivity into the equatorial stratosphere, making it impossible to trace further the slow southward movement of debris from the USSR tests. We may conclude, however, from the data in Tables 39 and 40, that no significant amount of radioactivity from the 1961 USSR test series reached the southern hemisphere during the first six months following the end of that series.

While we may safely conclude that during the first six months following its injection, the radioactive debris from the USSR test series was almost entirely confined to the stratosphere of the northern hemisphere, and was largely confined to the region covered by the polar vortex circulation, we may not reach, with equal safety, any conclusions regarding its distribution in the vertical direction. This does not mean that we are without evidence, but rather that the evidence is only suggestive rather than conclusive. The main limitation on the available evidence results from the fact that STARDUST sampling during the winter of 1961 - 1962 was performed almost entirely outside the region of the polar vortex, while the radioactive debris was contained almost entirely within that region. The polar vortex was fairly symmetrically arranged around the North Pole during late 1961, but by the time routine sampling of the polar stratosphere for Project STARDUST was begun in January 1962, it had begun to lose this symmetrical arrangement. During January the vortex became elongated along an axis joining central North America and the Caspian Sea. As a result, the STARDUST sampling corridor, which was located along the western coast of North America, intercepted only the outer edge of the vortex at the 20 km level at least. Thus the vertical profiles measured by STARDUST during January 1962 are not necessarily representative of the vertical distribution of the bulk of the USSR debris. During February 1962 the center of the polar vortex migrated toward Eurasia. Apparently the USSR debris migrated with it, for as the Aleutian anticyclone moved into the STARDUST sampling corridor, it brought with it air which was relatively uncontaminated by fresh radioactivity. During March and April the polar vortex weakened, and USSR debris reappeared in the STARDUST sampling corridor in high concentrations. By May the summer circulation had developed within the polar stratosphere, and STARDUST measurements henceforth were probably representative of the distribution of USSR debris within the entire polar region.

The circulation of the northern polar stratosphere during early 1962 is illustrated by the contour maps of the 30 mb and 100 mb surfaces in Figures 50 to 53 (which are based on maps published by The Free University of Berlin[37, 38]), and the changes in the stratospheric radioactivity which accompanied changes in the circulation are illustrated by Figures 54 and 55, and by Table 41. Figure 50 shows the distortion of the polar vortex into an ellipse at the 30 mb level during January 1962. Figure 51 shows its displacement toward the Eurasian continent at the 30 mb level in mid-February 1962, and Figure 52 shows the more complex pattern of the circulation at the 100 mb level at this same time. Figure 53 shows the circulation on 6 March 1962. By this date the polar vortex had again migrated over Western North America, and high concentrations of debris from the very high yield USSR weapon tests of late October 1961 were intercepted between 49° and 40°N. The distribution of total beta activity in the STARDUST sampling corridor on 6 March 1962 is shown in Figure 54, together with the distributions during the second half of January and mid-February 1962.

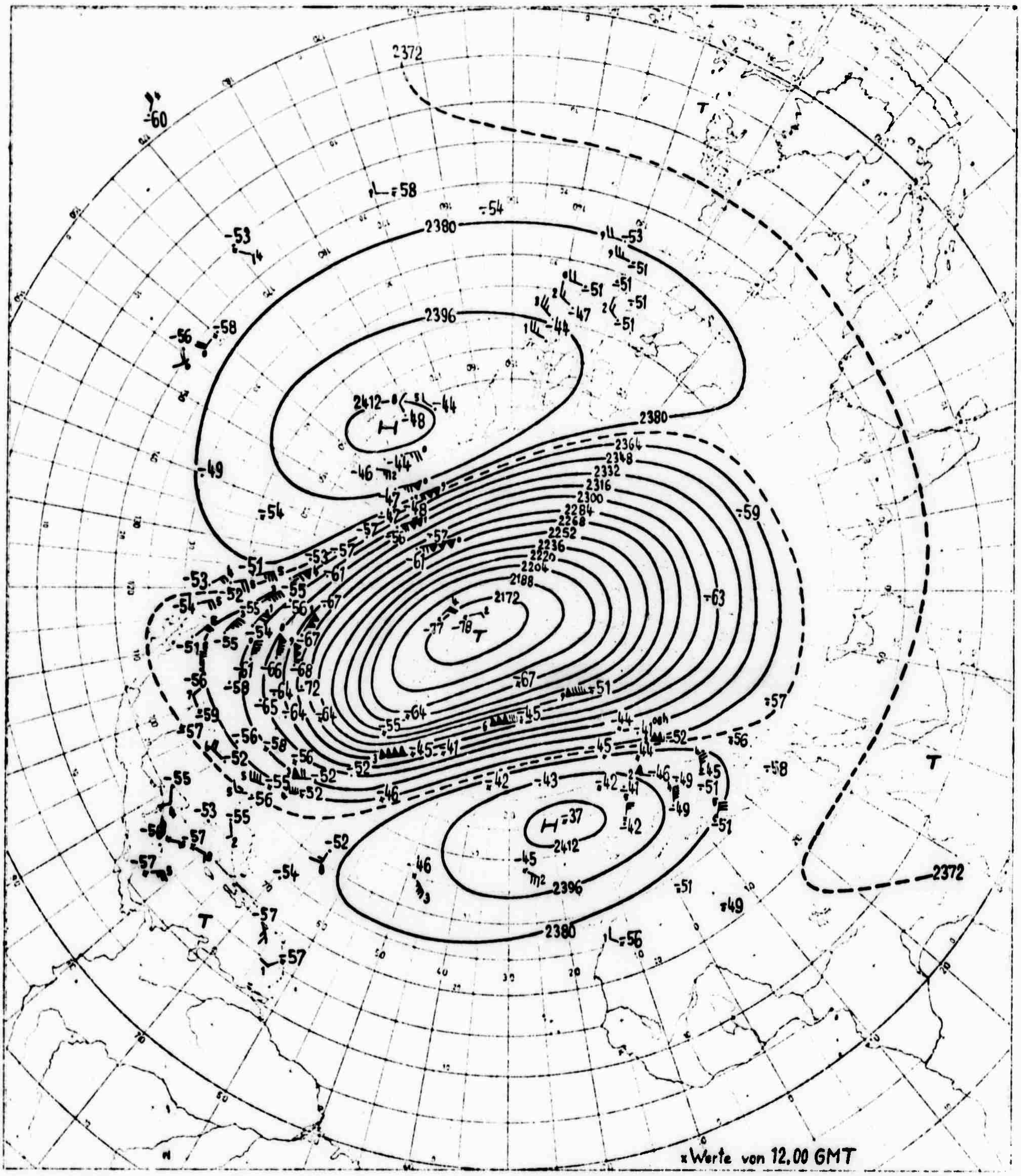

FIGURE 50. HEIGHT (decameters) OF THE 30 MB SURFACE AT 00:00 GMT ON JANUARY 23, 1962

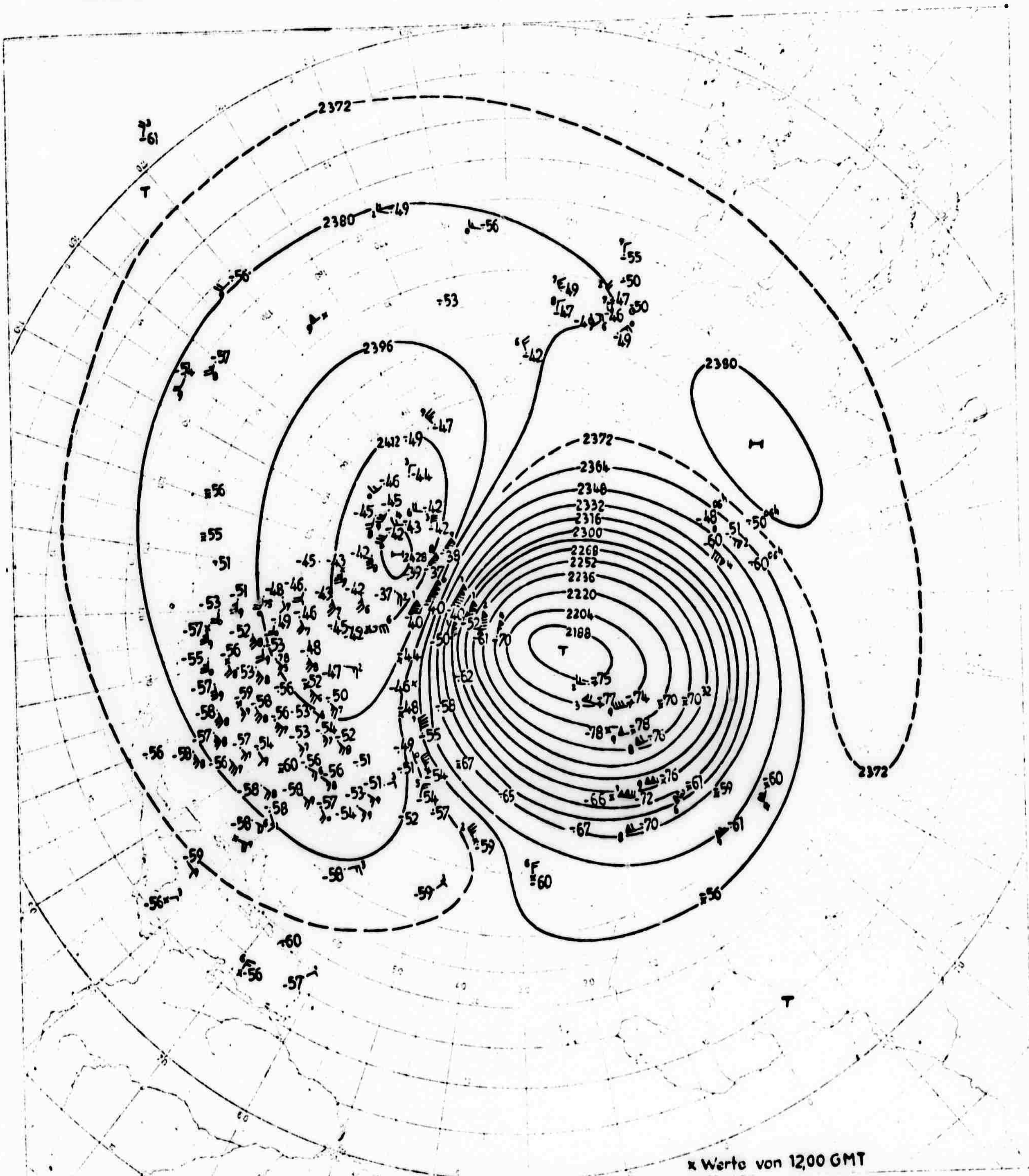

FIGURE 51. HEIGHT (decameters) OF THE 30 MB SURFACE AT 00:00 GMT ON FEBRUARY 14, 1962

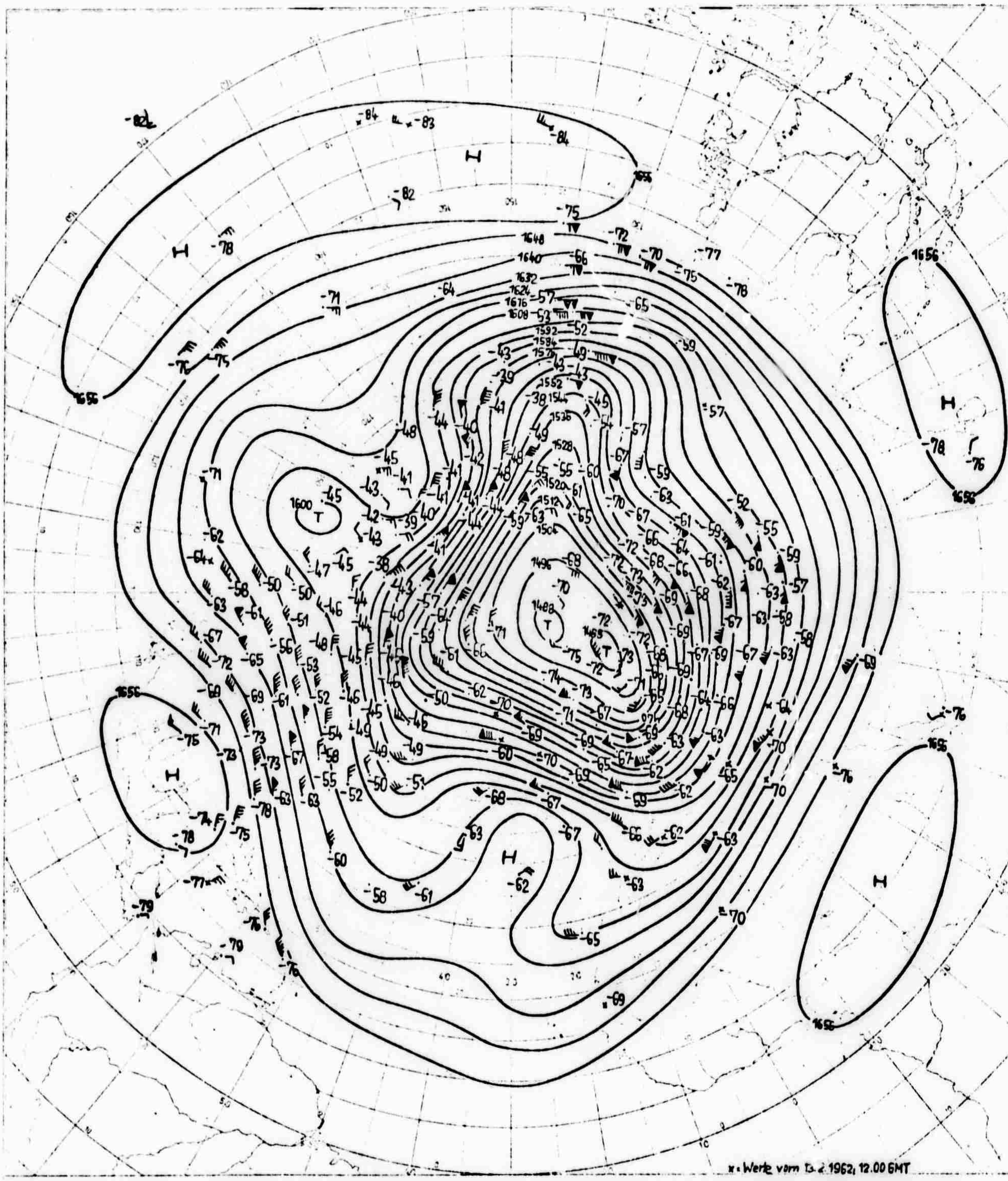

FIGURE 52. HEIGHT (decameters) OF THE 100 MB SURFACE AT 00:00 GMT ON FEBRUARY 14, 1962

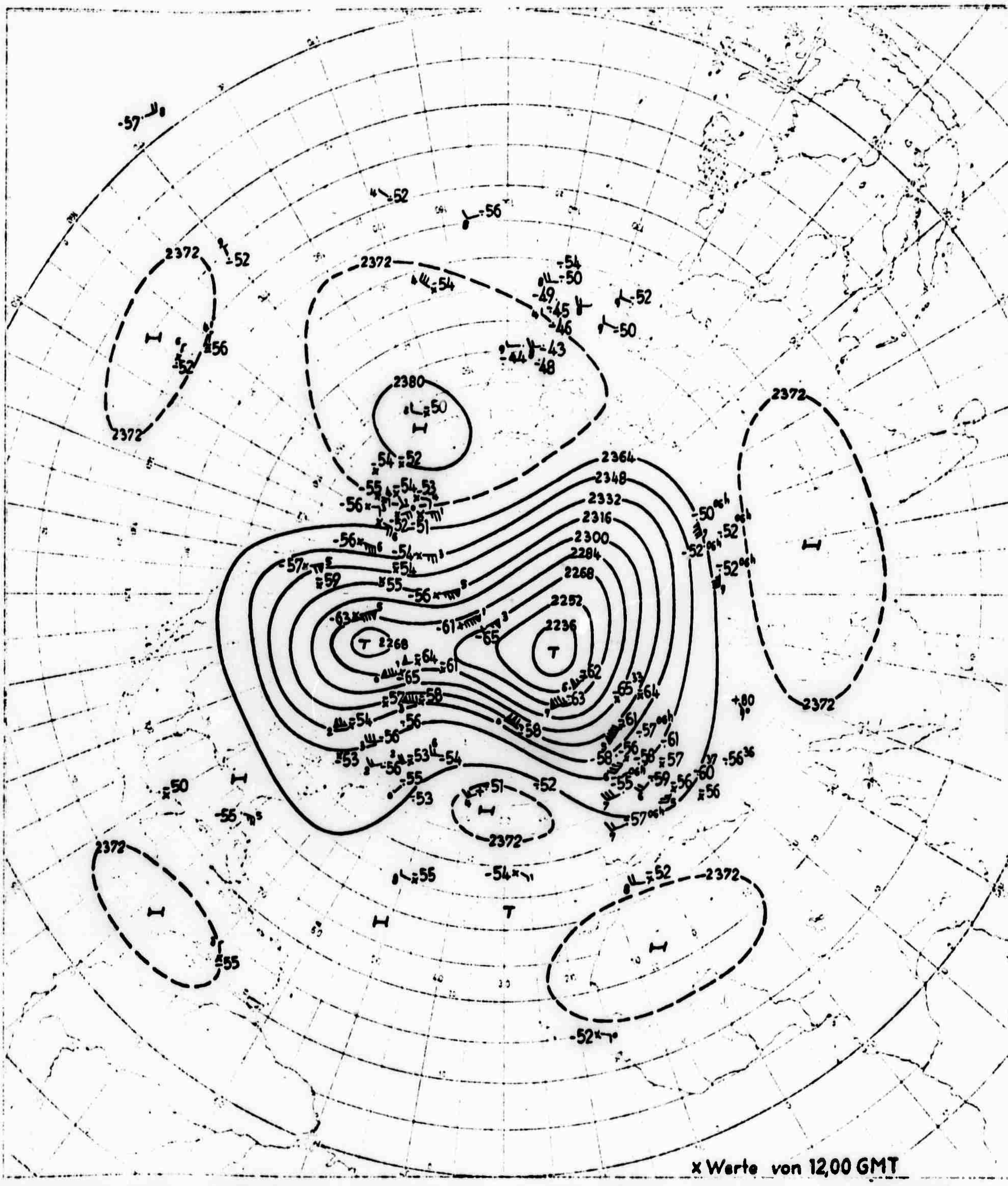

FIGURE 53. HEIGHT (decameters) OF THE 30 MB SURFACE AT 00:00 GMT ON MARCH 6, 1962

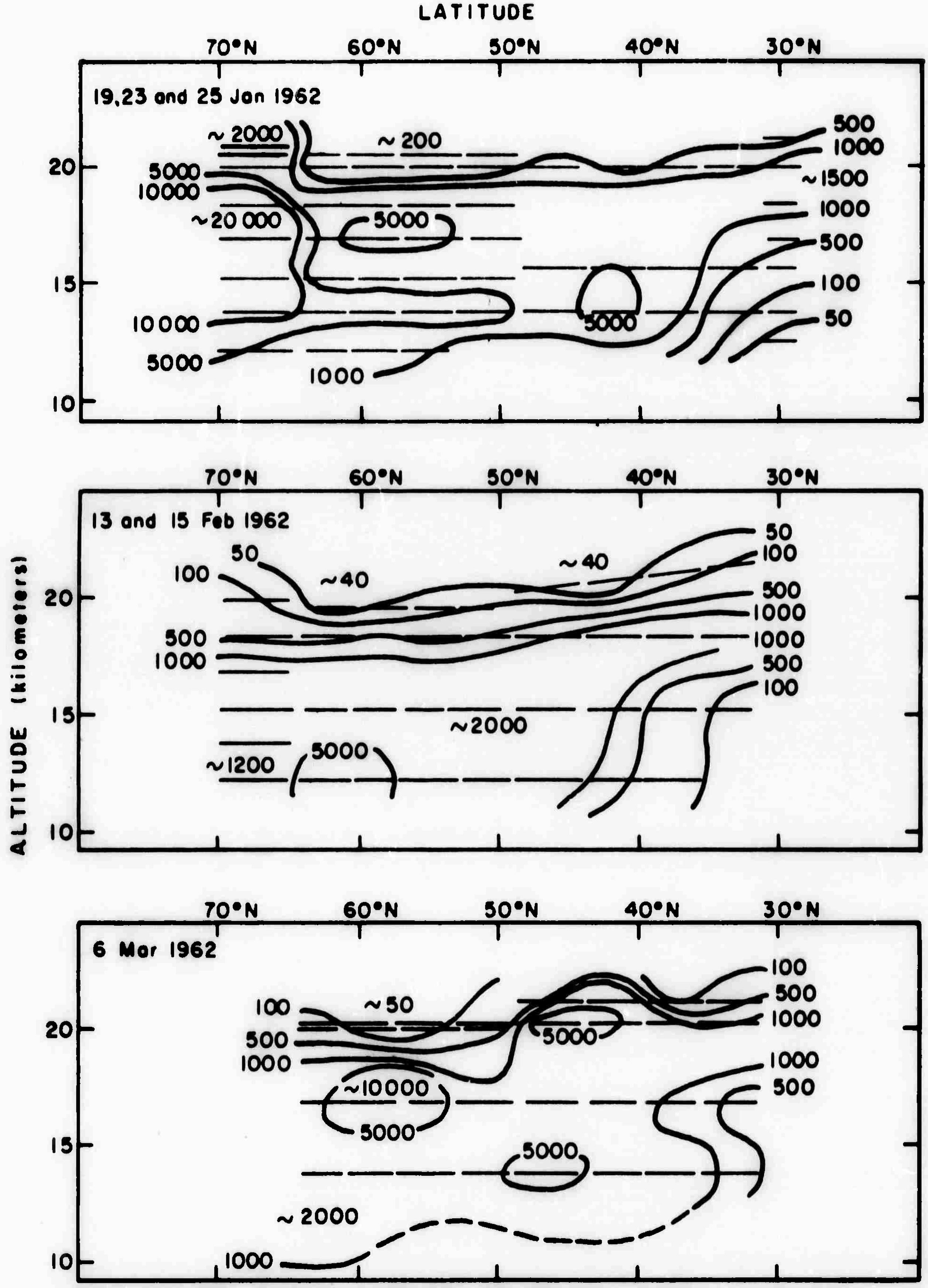

FIGURE 54. DISTRIBUTION OF TOTAL BETA ACTIVITY (pCi/SCM) AT THREE TIMES DURING EARLY 1962

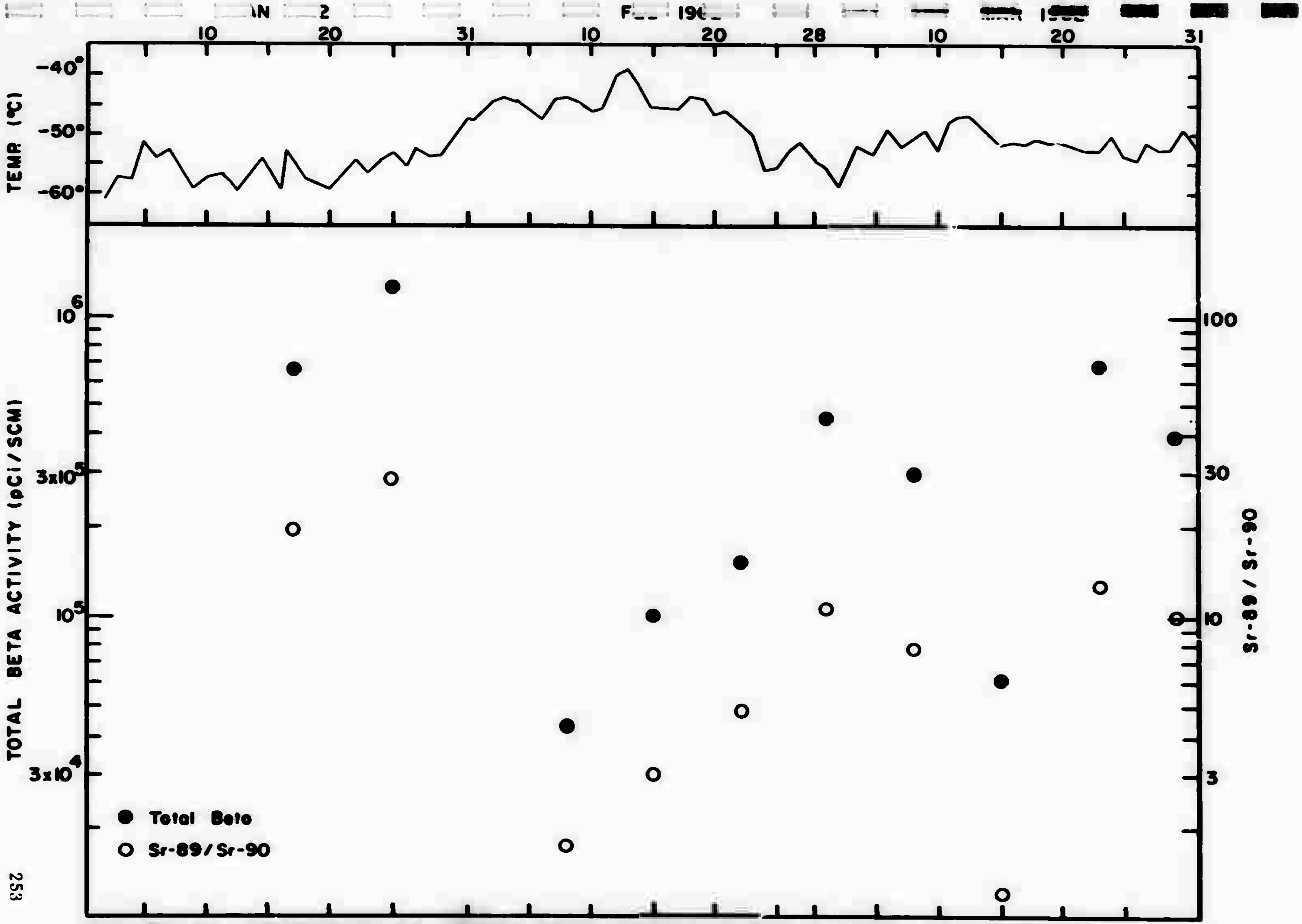

FIGURE 55. TEMPERATURE, TOTAL BETA ACTIVITY AND Sr-89/Sr-90 AT 20 KM AT 65°N, JANUARY–MARCH 1962

TABLE 41. Total Beta Activities in pCi/SCM of Some Samples Collected at Altitudes of 17 km and Higher at 65°N During the First Two Thirds of 1962

Date	Altitude (km)				
	17	18	19	20	21
17 Jan 62	2,890	1,495	-	670	296
25 Jan 62	21,430	13,500	-	1,720	2,040
8 Feb 62	1,510	368	49	38	-
15 Feb 62	1,240	264	110	-	-
22 Feb 62	8,130	543	-	153	-
1 Mar 62	1,320	915	-	460	127
8 Mar 62	1,005	439	-	299	296
15 Mar 62	760	729	-	60	-
23 Mar 62	2,130	2,580	-	1,100	-
29 Mar 62	3,160	2,450	-	388	-
2 Apr 62	-	-	-	286	-
19 Apr 62	-	-	-	281	-
3 May 62	1,910	3,770	-	565	-
4 May 62	1,340	2,670	-	484	-
10 May 62	1,480	780	-	645	-
17 May 62	3,750	990	-	275	-
24 May 62	2,430	2,160	-	428	-
31 May 62	4,700	2,420	-	4,340	-
7 Jun 62	1,540	4,250	-	542	-
14 Jun 62	2,420	1,200	-	5,540	-
21 Jun 62	2,160	1,550	-	930	-
28 Jun 62	1,730	1,845	-	1,780	-
6 Jul 62	-	1,005	-	-	785
10 Jul 62	1,720	870	-	526	-
13 Jul 62	1,340	-	-	458	-
20 Jul 62	-	1,450	-	-	343
24 Jul 62	1,520	1,030	-	730	-
26 Jul 62	1,920	-	-	803	-
3 Aug 62	-	1,040	-	-	796
26 Aug 62	-	2,400	-	1,350	-
27 Aug 62	-	2,160	-	1,750	-
31 Aug 62	-	1,860	-	-	-

In Figure 55 are plotted the temperatures recorded at the 50 mb level (about 20.6 km) over Fairbanks (65°N) and the total beta activities and Sr^{89}/Sr^{90} ratios of debris intercepted at about 20 km near this location during January to March 1962. The migration of the Aleutian anticyclone across Western North America in early February 1962 was marked by a rise in temperatures and a decline in concentrations of fresh radioactive debris above Fairbanks. The migration of the polar vortex circulation back over the area in late February 1962 was marked by decreasing temperatures and rising levels of fresh radioactivity. Table 41 lists the concentrations of total beta activity encountered at heights of 17 to 21 km at 65°N during January to August 1962. The relatively low activities encountered at all sampled altitudes on 8 and 15 February 1962 reflect the effects of the maximum penetration of the Aleutian anticyclone over North America. If, then, the data in Table 41 are to be used to deduce the vertical distribution of the radioactive debris from the 1961 USSR tests, the data for March 1962 and later months should be given the most weight. Nevertheless, the data for 17 and 25 January 1962 do represent air from the outer fringe of the polar vortex, and both profiles show concentrations decreasing rapidly with height above the 17 km level. Most profiles for collection dates in March 1962 and later show the same situation, but a few show a maximum at 18 km, and two (31 May and 14 June 1962) show a maximum at 20 km.

On the basis of Table 41, it may be concluded that generally the highest concentraticns (and always the largest total amounts) of radioactive debris from the 1961 USSR weapons tests were found at or below the 18 km level by sampling missions flown during 1962. The fact that this distribution was found on 17 and 25 January 1962 suggests that most debris from the USSR test series was present below the 18 km layer by that time. This does not disprove the hypothesis that most of this debris was initially injected at higher levels, and that particle settling or subsidence during the early winter of 1961 - 1962 brought about the distribution which was found in late January 1962 and in subsequent months. There is, however, no real support for such a hypothesis in the STARDUST data. Indeed, it seems more appropriate to conclude that most of the radioactive debris from this test series was initially injected into the lower polar stratosphere between the tropopause and the 18 km level.

One could attribute the occasional appearance of high concentrations of radioactive debris at the 20 km level at 65°N during the first half of 1962 (as shown in Table 41 for 25 January, 23 March, 31 May, 14 June and 28 June 1962) to the influx of debris injected initially mainly at altitudes above 20 km, and presumably produced by the 55 to 60 megaton event of 30 October 1961. Further information on this point is supplied by results of measurements of products of neutron activation, such as manganese-54 and antimony-124, in the samples. These nuclides appeared in unprecedented quantities in some samples of radioactive debris from the 1961 USSR tests, and presumably this reflects the production of an unusually high neutron flux during one or more event in the series. None of the samples collected for STARDUST during late 1961 contained especially large amounts of manganese-54 or detectable amounts of antimony-124. These samples did contain debris from the September USSR events, the early October events, and one or more late October event. It does appear, therefore, that these products of neutron activation were not characteristic of the test series as a whole, but probably mainly of the very high yield event of 30 October 1961. It is noteworthy that this event was described as having a small fission yield (Table 32). As a result, the Mn^{54}/Sr^{90} ratio should be much higher than in the other events in the series, including the 25 megaton event of 23 October 1961, which presumably had relatively high ratios of fission yield to total yield. Most likely, the ratios of fission yield to total yield and of neutron flux to total yield varied in about the same manner from one event to another in the series, with the exception of the 55 to 60 megaton event. If this is true, all radioactive debris from events in the test series other than the 55 to 60 megaton event should have displayed a fairly uniform ratio of manganese-54 to strontium-90. The presence of large amounts of antimony-124 in the debris is also quite unusual, and is probably best attributed to the most unusual event in the series: the 55 to 60 megaton event.

Table 42 lists the results of measurements of total beta activity, strontium-90 and manganese-54 in samples collected at 19 to 21 km altitude at 65°N during January to September 1962. Large concentrations of manganese-54 and high Mn^{54}/Sr^{90} ratios were encountered on 25 January, 23 March, 3 May and 10 May 1962, but the highest concentrations and highest ratios found at this site were not encountered until 31 May and 14 June 1962. This suggests that the air which contained the highest concentrations of debris from the 55 to 60 megaton event was probably prevented from reaching the STARDUST sampling corridor during approximately the first five months of 1962. Perhaps it was trapped within the polar vortex over Eurasia and Eastern North America, and so did not reach the STARDUST sampling corridor in representative quantities

TABLE 42. Trends in the Concentrations of Total Beta Activity, Strontium-90 and Manganese-54 at 19 to 21 km at 65°N During January to September 1962 (The manganese-54 data are corrected for radioactive decay to 15 October 1961)

Date	Altitude (km)	Total Beta (pCi/SCM)	Sr^{90} (pCi/100 SCM)	Mn^{54} (pCi/100 SCM)	$\frac{Mn^{54}}{Sr^{90}}$
17 Jan 1962	19.8	670	208	-	-
17 Jan 1962	21.0	290	175	-	-
25 Jan 1962	19.8	1,720	257	-	-
25 Jan 1962	20.4	2,040	310	20,600	64
8 Feb 1962	19.5	49	129	-	-
8 Feb 1962	19.8	38	140	-	-
15 Feb 1962	19.8	110	171	189	1
22 Feb 1962	19.8	178	142	745	5
22 Feb 1962	20.4	132	141	-	-
1 Mar 1962	19.8	460	210	-	-
1 Mar 1962	20.7	127	188	-	-
8 Mar 1962	19.8	299	184	2,360	13
8 Mar 1962	20.4	296	188	-	-
15 Mar 1962	19.8	60	64	-	-
23 Mar 1962	19.8	685	223	-	-
23 Mar 1962	20.5	1,520	321	27,500	86
29 Mar 1962	19.8	388	204	-	-
2 Apr 1962	19.8	286	154	-	-
19 Apr 1962	19.8	281	157	-	-
3 May 1962	19.8	808	384	22,900	60
3 May 1962	20.1	279	195	6,580	34
4 May 1962	19.5	645	-	-	-
4 May 1962	20.4	328	208	-	-
10 May 1962	20.1	645	304	14,000	46
17 May 1962	19.8	275	-	-	-
24 May 1962	19.8	329	251	-	-
24 May 1962	20.4	526	386	-	-
31 May 1962	20.1	4,200	1,440	156,000	108
7 Jun 1962	19.8	605	315	-	-
7 Jun 1962	20.4	474	255	-	-
14 Jun 1962	19.8	7,300	2,250	258,000	115
14 Jun 1962	19.8	4,020	1,390	118,000	85
14 Jun 1962	20.1	1,810	596	66,800	112
21 Jun 1962	19.8	1,230	501	-	-
21 Jun 1962	20.4	678	338	-	-
28 Jun 1962	19.8	1,780	857	70,100	82
10 Jul 1962	19.8	526	292	-	-
24 Jul 1962	19.8	549	374	-	-
24 Jul 1962	20.1	830	523	36,600	70

TABLE 42. (continued)

Date	Altitude (km)	Total Beta (pCi/SCM)	Sr^{90} (pCi/100 SCM)	Mn^{54} (pCi/100 SCM)	$\frac{Mn^{54}}{Sr^{90}}$
26 Aug 1962	19.8	1,530	539	-	-
27 Aug 1962	20.4	1,780	534	42,500	80
31 Aug 1962	19.8	1,680	495	-	-
5 Sep 1962	20.1	5,850	925	-	-
7 Sep 1962	19.2	1,860	605	-	-
9 Sep 1962	18.9	1,620	550	-	-
10 Sep 1962	19.8	1,270	514	-	-
19 Sep 1962	20.4	1,760	500	-	-
23 Sep 1962	19.5	2,050	538	-	-
25 Sep 1962	20.4	1,970	545	28,700	53

until after the polar vortex circulation broke down in the spring of 1962. Alternatively, it may have been held largely at altitudes above those sampled by STARDUST during most of early 1962, and brought down by subsidence or particle settling to the 20 km level during the late spring. The vertical profiles of fission products and neutron activation products given in Tables 43 and 44 are of significance to this question.

The concentration profiles of radioactive debris at certain locations on specific dates are indicated in Table 43. The total beta and strontium-90 activities are measures of total amount of debris present, and the value of the Sr^{89}/Sr^{90} ratio is a measure of its age. Both the total beta activities and the Sr^{89}/Sr^{90} ratios decreased steadily as a result of radioactive decay following the end of the 1961 test series. The data for these activities in Table 43 indicate that 1961 USSR debris was dominant in all samples listed. The antimony-124 activities may be taken as a measure of the amount of debris present which was derived from the 55 to 60 megaton event. The relative constancy of the Sb^{124}/Mn^{54} ratio indicates a common origin for antimony-124 and manganese-54. Evidently then, the manganese-54 data are also a measure of the amount of debris present from the 55 to 60 megaton event. The rapid decrease with altitude above 16.8 km of the concentrations of total beta and strontium-90 activity on 25 January 1962 suggest, as was mentioned above, that most debris from the events which had high fission yields stabilized at or below 18 km. On the other hand, the high concentrations of manganese-54 and antimony-124 found at about 20 km on this and subsequent dates indicate that much of the debris from the 55 to 60 megaton event stabilized at or above 20 km. High concentrations of these neutron activation products were found at the lower

TABLE 43. The Vertical Distribution of Total Beta Activity, Strontium-90, Manganese-54 and Antimony-124 on Various Dates During January to July 1962 (The manganese-54 and antimony-124 data are corrected for radioactive decay to 15 October 1961)

Altitude (km)	Total Beta (pCi/SCM)	Sr^{90} (pCi/100 SCM)	$\frac{Sr^{89}}{Sr^{90}}$	Mn^{54} (pCi/100 SCM)	$\frac{Mn^{54}}{Sr^{90}}$	Sb^{124} (pCi/100 SCM)	$\frac{Sb^{124}}{Mn^{54}}$
25 Jan 1962, 70° - 65°N							
20.4	2,040	310	37	20,600	64	61,700	3.0
19.8	1,720	257	28	-	-	29,900	-
18.3	13,900	1,780	44	23,000	11	N. D.	-
16.8	23,100	3,420	39	-	-	45,200	-
15.2	18,500	2,510	45	5,750	2.1	19,000	3.3
13.7	10,400	1,800	38	-	-	N. D.	-
12.2	4,880	730	38	910	1.3	N. D.	-
6 Mar 1962, 49° - 40°N							
20.7	1,230	267	14	16,700	62	64,900	3.9
20.1	6,550	929	29	79,600	86	262,000	3.3
16.8	2,150	361	20	2,050	5.5	7,950	3.9
13.7	4,750	-	-	1,047	-	N. D.	-
23 Mar 1962, 65°N							
20.5	1,520	321	17	27,500	86	101,000	3.7
19.8	685	223	13	-	-	38,700	-
18.3	2,640	615	19	36,600	59	137,000	3.7
16.8	2,190	600	16	-	-	29,100	-
15.2	7,950	1,880	21	20,300	11	74,400	3.7
13.4	4,450	1,100	22	-	-	17,000	-
12.2	2,830	711	20	1,075	1.5	N. D.	-
31 May 1962, 70° - 65°N							
20.1	4,200	1,440	6	156,000	108	615,000	3.9
18.3	2,340	1,080	-	50,000	46	170,000	3.4
16.8	4,700	2,190	7	59,000	27	203,000	3.4
15.2	1,190	775	-	5,800	7	25,600	4.4
13.7	1,290	737	8	-	-	-	-
12.2	945	483	-	1,280	3	N. D.	-

TABLE 43. (continued)

Altitude (km)	Total Beta (pCi/SCM)	Sr^{90} (pCi/100 SCM)	$\frac{Sr^{89}}{Sr^{90}}$	Mn^{54} (pCi/100 SCM)	$\frac{Mn^{54}}{Sr^{90}}$	Sb^{124} (pCi/100 SCM)	$\frac{Sb^{124}}{Mn^{54}}$
24 Jul 1962, 70° - 65°N							
20.1	829	507	-	36,600	72	123,000	3.5
19.8	549	374	-	-	-	-	-
18.3	1,050	670	4	32,100	48	117,000	3.7
16.8	1,510	885	-	22,300	25	67,800	3.0
15.2	3,240	1,160	15	11,400	10	42,600	3.7
13.7	1,730	548	14	-	-	-	-
12.2	638	268	7	1,310	5	$\leq$ 3,000	$\leq$ 2.3

levels also, indicating that much, and perhaps most, of the debris from this event either stabilized at levels below 20 km or was carried down below that level during November 1961 to January 1962. The presence of large amounts of neutron activation products at levels down to 15.2 km on 25 January 1962 cannot reasonably be attributed to gravitational settling from above 20 km, and it seems unlikely that subsidence of air during the winter could have been adequate to have achieved such a transfer. It seems most likely, rather, that the vertical distribution of products of neutron activation found on 25 January 1962, which was quite similar to that found in subsequent months, was primarily produced by the initial injection of the bomb debris, and not by its subsequent transport.

STARDUST sampling was limited to altitudes below 21 km, so the distribution above 21 km of the debris from the 55 to 60 megaton event cannot be determined from the STARDUST data. It seems likely, however, that data from the U. S. Atomic Energy Commission balloon program[39] should provide this information. Table 44 contains the vertical profiles of the Sr^{89}/Sr^{90} ratio and of the concentrations of strontium-90, manganese-54 and antimony-124 at San Angelo (31°N) during March, May, July and September 1962. Relatively little radioactive debris from the 1961 USSR tests was intercepted at this location in March 1962, probably because this debris was still mainly retained within the circumpolar vortex at higher latitudes at this time. During May and later months, high concentrations of this debris were found at and below the 22 km level. This debris included significant amounts of manganese-54 and antimony-124, presumably derived from the 55 to 60 megaton event. This situation was similar to that noted in the STARDUST results. Only the sample

TABLE 44. Radioactivity in Some Balloon Samples Collected at 31°N During 1962 (The manganese-54 and antimony-124 data are corrected for radioactive decay to 15 October 1961)

Altitude (km)	$\frac{\text{pCi } Sr^{90}}{100 \text{ SCM}}$	$\frac{Sr^{89}}{Sr^{90}}$	$\frac{\text{pCi } Mn^{54}}{100 \text{ SCM}}$	$\frac{\text{pCi } Sb^{124}}{100 \text{ SCM}}$
March 1962				
31.1	56	-	≤ 570	-
26.8	81	-	332	2,470
24.4	79	≤ 1	≤ 185	-
21.0	173	≤ 2	≤ 83	-
18.6	258	15	-	-
May 1962				
31.4	78	-	≤ 280	≤ 2,500
26.8	83	2	1,160	6,880
23.8	105	6	3,400	11,500
21.4	154	4	4,500	18,000
18.3	593	6	12,700	42,700
July 1962				
31.4	52	≤ 4	560	≤ 6,300
26.2	78	3	2,480	25,500
24.1	87	4	2,520	-
21.7	989	8	91,600	338,000
18.6	668	20	7,030	36,900
September 1962				
34.2	41	1.1	≤ 500	-
31.1	49	≤ 0.3	392	-
26.5	120	≤ 0.7	1,930	-
24.4	168	≤ 0.5	2,070	-
20.1	890	≤ 1	17,700	-

collected at 21.7 km in July really contained large quantities of debris from that very high yield event, as indicated by the Mn^{54}/Sr^{90} ratio as well as by the absolute concentrations. Thus, even if the reported concentrations for the higher levels are too low because of calibration errors in the balloon sampler, as some have suggested, the Mn^{54}/Sr^{90} ratios, which range between about 10 and 30, indicate that the debris from the 55 to 60 megaton event was not dominant at altitudes above 22 km. Presumably at the higher levels relatively low concentrations of debris from the very high yield event were mixed with older "background" debris from earlier test series. Data from San Angelo may not give a representative picture of the vertical distribution above the 20 km level in the polar stratosphere, but some data are better than no data. In the absence of data to the contrary, therefore, it seems safest to conclude that the bulk of the debris from the 55 to 60 megaton event was injected into the lower polar stratosphere between 15 and 22 km (or at least was transported into the 15 to 22 km layer by May 1962), and that relatively little debris from that event penetrated to higher levels.

7.2 Interceptions of Fresh Debris from the 1962 U. S. Weapon Tests

The first event in the 1962 U. S. series of nuclear weapon tests, OPERATION DOMINIC, occurred on 25 April 1962. Table 45 contains a list of some reported events in that series[13], including all of those reported to have had yields in the megaton range. The first interception of radioactive debris from this test series by aircraft sampling for Project STARDUST occurred on 8 May and 10 May 1962 between 30°N and 43°N at 15 to 18 km. Table 46 lists the concentrations of total beta activity encountered at 15, 17 and 18 km at 30°N during the first half of 1962. Clearly, the beta activities sampled at

TABLE 45. Some Events in OPERATION DOMINIC, the 1962 U. S. Series of Nuclear Weapon Tests in the Equatorial Pacific[13]

Date	Name	Yield	Remarks
2 May 1962	Arkansas	Low megaton	Air burst
4 May 1962	Questa	Intermediate	Air burst
10 Jun 1962	Yeso	Low megaton	Air burst
27 Jun 1962	Bighorn	Megaton	Air burst
30 Jun 1962	Bluestone	Low megaton	Air burst
9 Jul 1962	Starfish Prime	1.4 megatons	Detonated at altitude of 400 km.
11 Jul 1962	Pamlico	Low megaton	Air burst
18 Oct 1962	Chama	Low megaton	Air burst
30 Oct 1962	Housatonic	Megaton	Air burst

TABLE 46. Total Beta Activities of Some Samples Collected at 30°N During the First Half of 1962 (pCi/SCM)

Collection Date	Altitude (km)		
	15	17	18
4 Jan 1962	650	-	-
11 Jan 1962	-	900	3,720
18 Jan 1962	-	620	450
25 Jan 1962	256	716	1,570
1 Feb 1962	-	1,550	2,740
8 Feb 1962	-	185	1,510
9 Feb 1962	71	366	-
15 Feb 1962	-	248	1,150
21 Feb 1962	650	650	1,490
1 Mar 1962	-	105	500
8 Mar 1962	60	645	2,740
15 Mar 1962	-	618	1,120
22 Mar 1962	226	219	663
29 Mar 1962	825	3,480	760
3 Apr 1962	1,040	-	485
27 Apr 1962	460	485	1,880
3 May 1962	-	1,960	1,750
10 May 1962	528,000	135,000	109,000
17 May 1962	-	72,100	24,000
22 May 1962	1,350	-	-
24 May 1962	14,000	28,800	5,250
31 May 1962	-	2,320	32,400
7 Jun 1962	702	1,860	16,100
14 Jun 1962	-	1,310	5,310
21 Jun 1962	-	2,350	4,040
22 Jun 1962	12,000	2,530	-
28 Jun 1962	-	4,420	3,100

these locations on 10 May 1962 were far in excess of the activities present there during early 1962 as a result of the late 1961 USSR tests. Some subsequent interceptions of fresh debris from OPERATION DOMINIC occurred at this location, as Table 46 indicates, but most such interceptions occurred farther south, near the latitudes of injection.

Both the rate of decay of the total beta activity and the ratios of fission products in the debris were used in an attempt to identify the specific events which had produced the various clouds of radioactivity which were intercepted in the STARDUST sampling corridor. Table 47 lists flight and analytical data for several samples which contained high concentrations of radioactive debris from the U. S. tests. The decay curves of the beta activities of some of these are shown in Figures 56 and 57. These data indicate that debris was intercepted from one or more events in May, one or more events in June and from one or more events in July 1962, but they do not permit identification of the specific events that produced the debris. There was no interception of debris which was clearly attributable to the October 1962 events, both because STARDUST sampling was curtailed during late 1962, and because large amounts of radioactive debris with similar dates of origin were injected into the stratosphere by the late 1962 USSR weapon test series.

Apparent shot dates derived from measurements of fission product ratios in STARDUST samples are given in Tables 48 and 49. Table 48 contains data for three samples collected during early May 1962. The radioactive debris in these samples is attributed to the 4 May 1962 Questa event, both on the basis of these measurements and on the basis of trajectories for the radioactive cloud from Questa as calculated by the U. S. Weather Bureau[40]. Table 49

TABLE 47. Some Samples Containing Radioactivity from 1962 U. S. Tests

Sample Number	Collection Date	Latitude	Altitude (km)	pCi β SCM	pCi Sr^{90} SCM	Indicated Shot Date
5845H	8 May 1962	43° - 38°N	15.2	893,000	18	29 Apr 1962
5844H	8 May 1962	37° - 31°N	15.6	428,000	39	1 May 1962
5838H	8 May 1962	37° - 31°N	18.3	79,000	12	28 Apr 1962
5868H	10 May 1962	30°N	15.2	528,000	62	30 Apr 1962
5961N	18 May 1962	35° - 31°N	16.8	171,000	39	14 May 1962
6505H	23 Jun 1962	2°N - 2°S	18.3	369,000	52	10 Jun 1962
6522H	29 Jun 1962	9° - 3°N	21.0	392,000	113	7 Jun 1962
6532H	3 Jul 1962	9°N - 4°S	20.9	136,000	32	15 Jun 1962
6883H	7 Aug 1962	22° - 19°N	18.3	36,600	26	4 Jul 1962

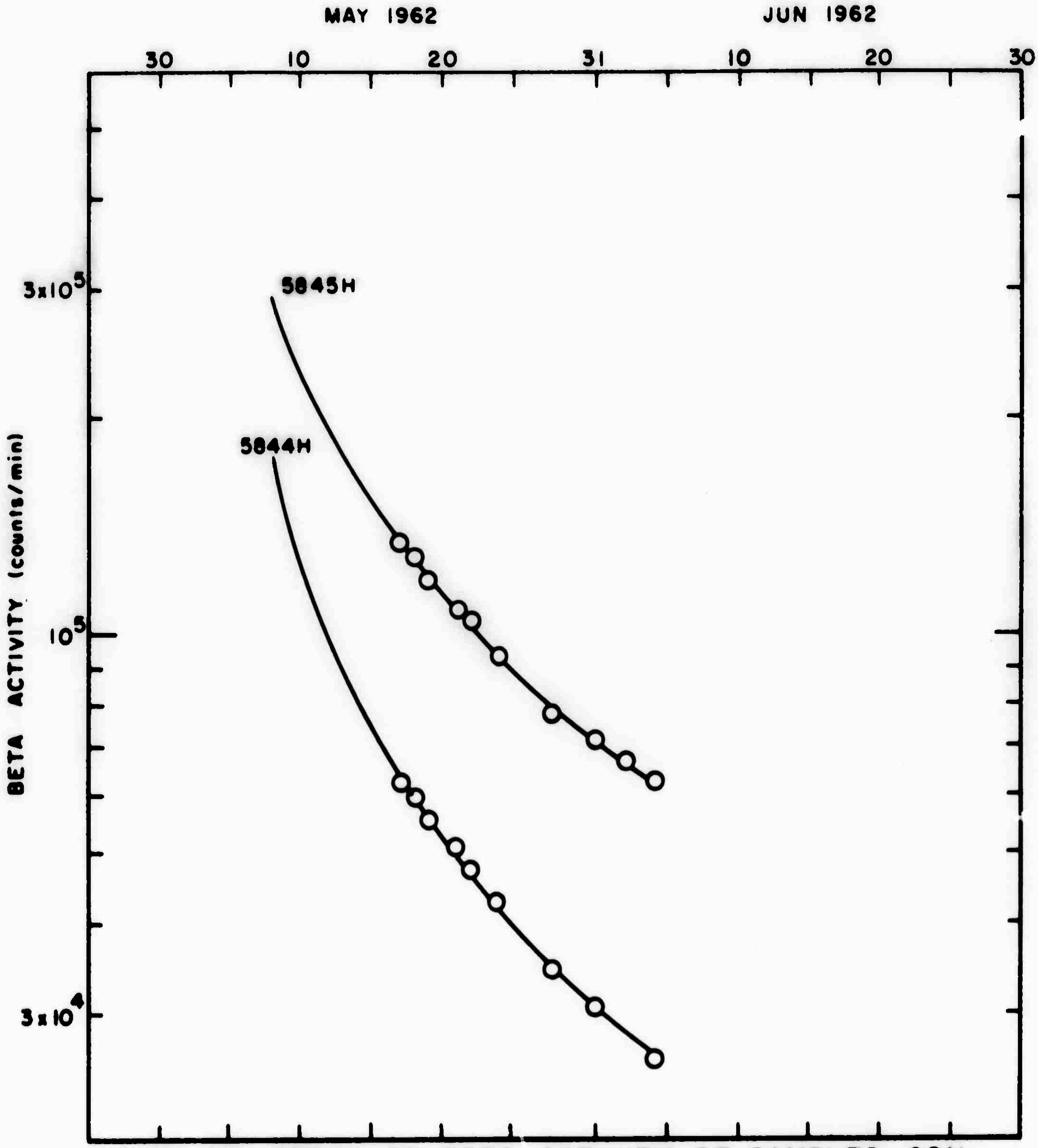

FIGURE 56. DECAY OF BETA ACTIVITY OF SAMPLES CONTAINING DEBRIS FROM 1962 U.S. TESTS

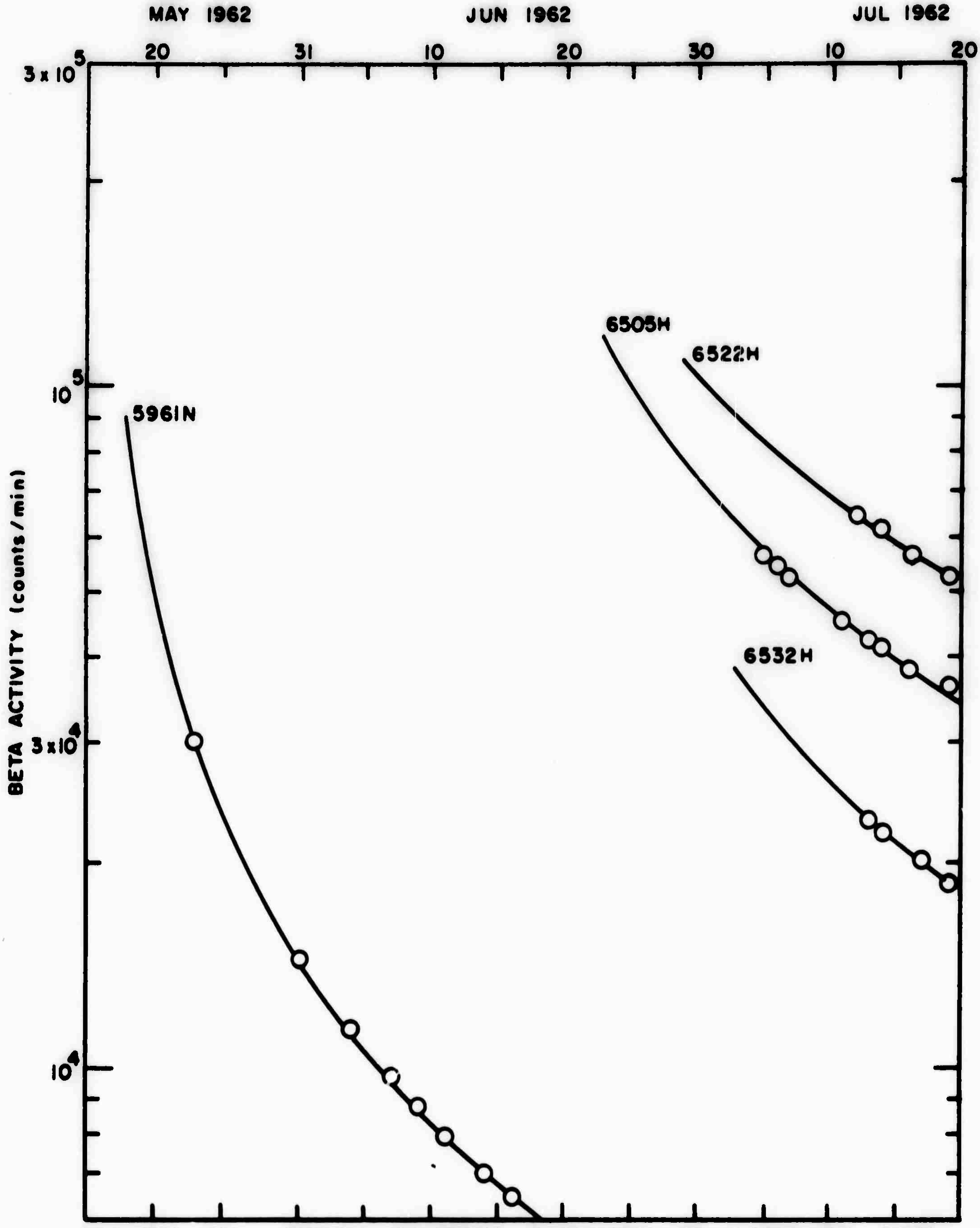

FIGURE 57. DECAY OF BETA ACTIVITY OF SAMPLES CONTAINING DEBRIS FROM 1962 U.S. TESTS

TABLE 48. Apparent Age of Fresh Debris Intercepted During Early May 1962

Collection Date	Latitude	Longitude	Altitude (km)	Activity (pCi/SCM) Total Beta	Ba^{140}	Nuclide Ratios	Apparent Age (days)	Apparent Shot Date
8 May 1962	37° - 31°N	104° - 101°W	15.6	428,000	21,000	$Mo^{99}/Ce^{144} = 51.9$	3	5 May 1962
						$Mo^{99}/Zr^{95} = 10.8$	4	4 May 1962
						$Mo^{99}/Ce^{141} = 6.22$	4	4 May 1962
						$Mo^{99}/Ba^{140} = 3.22$	2	6 May 1962
8 May 1962	43° - 38°N	108° - 104°W	15.2	893,000	49,300	$Mo^{99}/Ce^{144} = 39.1$	5	3 May 1962
						$Mo^{99}/Zr^{95} = 8.43$	5	3 May 1962
						$Mo^{99}/Ce^{141} = 5.54$	4	4 May 1962
						$Mo^{99}/Ba^{140} = 2.66$	3	5 May 1962
						$I^{131}/Sr^{89} = 5.93$	2	6 May 1962
						$I^{131}/Ba^{140} = 1.71$	-	-
10 May 1962	30°N	100°W	15.2	528,000	110,000	$Mo^{99}/Ce^{144} = 22.8$	7	3 May 1962
						$Mo^{99}/Zr^{95} = 3.77$	8	2 May 1962
						$Mo^{99}/Ce^{141} = 2.40$	8	2 May 1962
						$Mo^{99}/Ba^{140} = 0.39$	13	27 Apr 1962

TABLE 49. Apparent Ages of Fresh Debris Intercepted During Late June and Early July 1962

Collection Date	Latitude	Longitude	Altitude (km)	Activity (pCi/SCM) Total Beta	Ba^{140}	Nuclide Ratios	Apparent Age (days)	Apparent Shot Date
19 Jun 1962	44° - 36°N	109° - 103°W	15.2	23,500	4,660	$Mo^{99}/Ce^{144} = 11.4$	9	10 Jun 1962
						$Mo^{99}/Zr^{95} = 1.82$	11	8 Jun 1962
						$Mo^{99}/Ce^{141} = 1.29$	11	8 Jun 1962
						$Mo^{99}/Ba^{140} = 0.19$	16	3 Jun 1962
						$Mo^{99}/I^{131} = 1.40$	9	10 Jun 1962
						$I^{131}/Sr^{89} = 1.48$	21	29 May 1962
22 Jun 1962	30°N	100°W	15.6	12,000	2,320	$Mo^{99}/Ce^{144} = 4.38$	13	9 Jun 1962
						$Mo^{99}/Zr^{95} = 1.52$	12	10 Jun 1962
						$Mo^{99}/Ce^{141} = 0.78$	13	9 Jun 1962
						$Mo^{99}/Ba^{140} = 0.12$	19	3 Jun 1962
						$Mo^{99}/I^{131} = 0.75$	12	10 Jun 1962
						$I^{131}/Sr^{89} = 1.63$	20	2 Jun 1962
23 Jun 1962	2°N - 2°S	79° - 81°W	18.3	369,000	25,100	$Mo^{99}/Ce^{144} = 16.0$	8	15 Jun 1962
						$Mo^{99}/Zr^{95} = 3.07$	9	14 Jun 1962
						$Mo^{99}/Ce^{141} = 2.24$	8	15 Jun 1962
						$Mo^{99}/Ba^{140} = 0.77$	10	13 Jun 1962
						$Mo^{99}/I^{131} = 1.49$	8	15 Jun 1962
						$I^{131}/Sr^{89} = 1.93$	18	5 Jun 1962

TABLE 49. (continued)

Collection Date	Latitude	Longitude	Altitude (km)	Activity (pCi/SCM) Total Beta	Ba^{140}	Nuclide Ratios	Apparent Age (days)	Apparent Shot Date
29 Jun 1962	2°N - 4°S	79° - 82°W	20.7	89,400	5,370	$Mo^{99}/Ce^{144} = 2.63$	15	14 Jun 1962
						$Mo^{99}/Zr^{95} = 0.64$	15	14 Jun 1962
						$Mo^{99}/Ce^{141} = 0.54$	14	15 Jun 1962
						$Mo^{99}/Ba^{140} = 0.32$	14	15 Jun 1962
						$Mo^{99}/I^{131} = 0.74$	12	17 Jun 1962
						$I^{131}/Sr^{89} = 1.12$	25	4 Jun 1962
3 Jul 1962	15°N - 9°N	83° - 80°W	18.3	87,000	5,470	$Mo^{99}/Ce^{144} = 0.83$	20	13 Jun 1962
						$Mo^{99}/Zr^{95} = 0.23$	19	14 Jun 1962
						$Mo^{99}/Ce^{141} = 0.18$	19	14 Jun 1962
						$Mo^{99}/Ba^{140} = 0.13$	18	15 Jun 1962
						$Mo^{99}/I^{131} = 0.53$	14	19 Jun 1962
						$I^{131}/Sr^{89} = 0.47$	37	27 May 1962
3 Jul 1962	4° - 10°S	82° - 79°W	17.1	20,500	1,590	$Mo^{99}/Ce^{144} = 2.74$	15	18 Jun 1962
						$Mo^{99}/Zr^{95} = 0.91$	14	19 Jun 1962
						$Mo^{99}/Ce^{141} = 0.47$	15	18 Jun 1962
						$Mo^{99}/Ba^{140} = 0.31$	14	19 Jun 1962

contains data for four samples collected during the second half of June 1962 and two samples collected on 3 July 1962. The fresh debris in the samples collected on 19 and 22 June 1962 can be assigned to the Yeso event of 10 June 1962, which had a yield in the low megaton yield range. The fresh debris in the samples collected on 23 June, 29 June and 3 July 1962 must be assigned to this event also or to one of the events of "intermediate yield" which took place on 12, 15 and 17 June 1962. Presumably these "intermediate yield" events should not have injected radioactivity into the stratosphere, so (correctly or incorrectly) this debris is also assigned to the 10 June 1962 event.

The upper and middle thirds of Figure 58 portray the distribution of beta activity in the STARDUST sampling corridor on 8 and 10 May and on 15 to 18 May 1962. The radioactivity attributed to the 4 May 1962 event was intercepted between 20° and 45°N. Apparently the radioactive cloud from this event was carried northward rapidly from the site of its injection, was then picked up by the jet stream, and was carried eastward at a very rapid rate. As a result it was intercepted over New Mexico and western Texas (40°N, 105°W) only four days after it was injected at Christmas Island (2°N, 157°W). The lower third of Figure 58 portrays the distribution of beta activity on 29 June and 3, 5, 6 and 10 July 1962. An area of high concentrations, attributed to the 10 June 1962 event, was found between 15°N and 10°S, near the latitude of injection. Probably this debris was transported almost directly westward by the easterlies common in the equatorial stratosphere, and did not reach the STARDUST sampling corridor until almost three weeks following its injection.

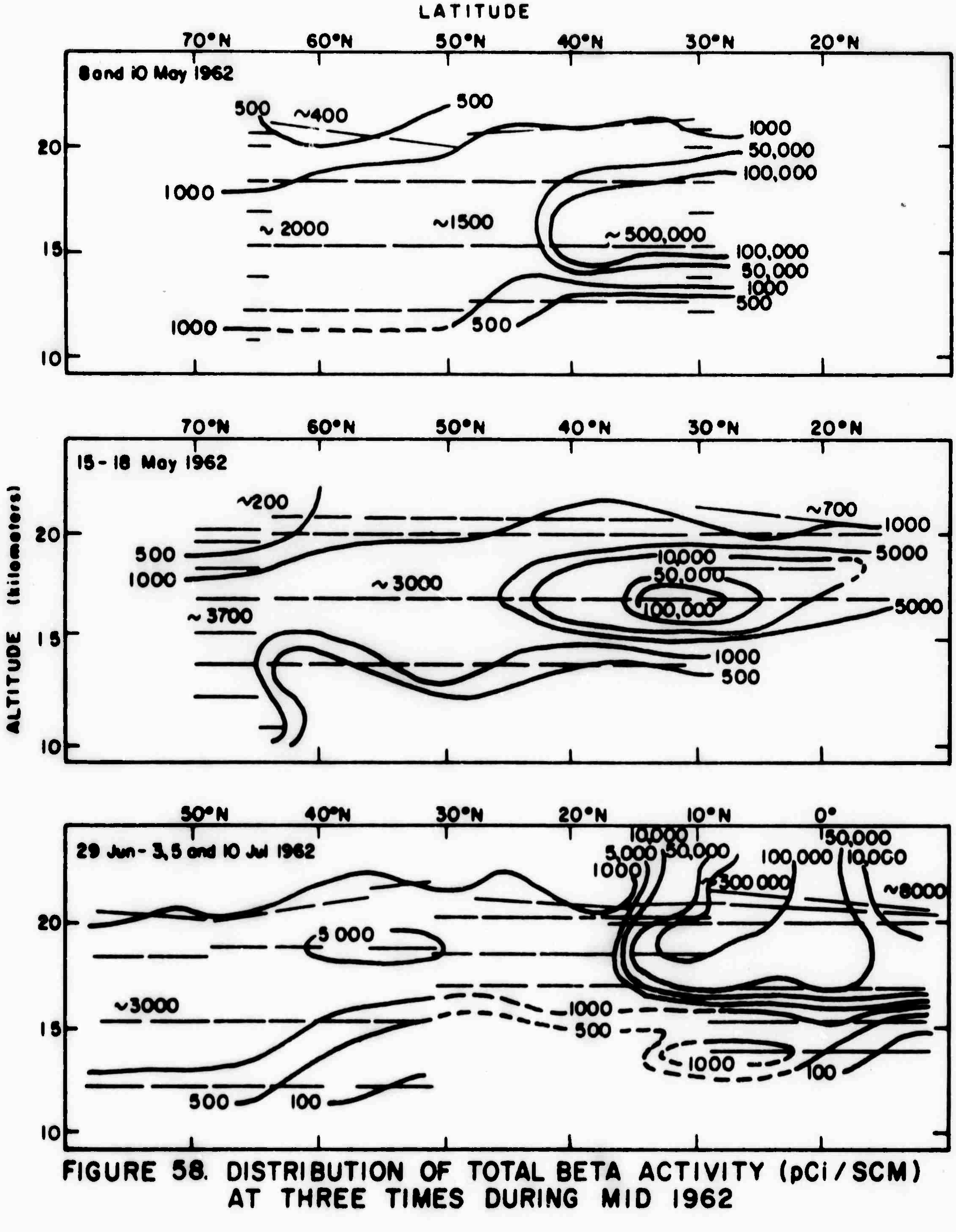

FIGURE 58. DISTRIBUTION OF TOTAL BETA ACTIVITY (pCi/SCM) AT THREE TIMES DURING MID 1962

Interceptions were made of radioactive debris from other events also, but generally the sampling frequency was inadequate to delineate the distribution of the debris with latitude and height. Tables 50 to 53 summarize measurements of concentrations of total beta activity made on samples collected during May to August 1962. During August regular STARDUST sampling patterns were replaced temporarily by a series of daily flights by a single aircraft between about 30°N and 65°N. No further information was obtained on the distribution of radioactive debris specifically from the U. S. tests after this replacement was made. In Table 50 are listed the concentrations of total beta activity intercepted at each altitude at 10°S, 0°N, 15°N, 30°N and 45°N. It is noteworthy that at 10°S to 15°N the high concentrations were intercepted at 20 and 21 km as well as at the lower levels, but at 30°N high concentrations of U. S. debris were not intercepted at altitudes above 18 or 19 km. Evidently transport of this debris in the meridional direction during May to August 1962 was rather slow at these levels in the tropical stratosphere.

In Tables 51, 52 and 53 the concentrations of total beta activity encountered during May to August 1962 in the tropical stratosphere at 19 to 21 km, at 18 km and at 17 km are presented to indicate the extent of spreading of the various clouds of debris in the meridional direction. The data for 19 to 21 km (Table 51) suggest that detectable amounts of radioactive debris from the U. S. tests spread as far north as 17°N on 14 June and 11 July 1962, but there are no indications of high concentrations, such as were found at 12°N on 3 July and 19 July 1962, reaching 17°N at this level. The data for 18 km (Table 52) show a wider distribution of high concentrations attributable to

TABLE 50. Trends in the Concentrations of Total Beta Activity (pCi/SCM) at 10°S, 0°N, 15°N, 30°N and 45°N During May to August 1962

Date	Altitude (km) 12	14	15	17	18	19	20	21
Latitude 10°S								
23 Jun 1962	37	-	-	-	3,420	-	-	-
29 Jun 1962	-	62	310	-	-	-	8,360	-
3 Jul 1962	-	-	-	20,500	-	-	18,300	-
Latitude 0°N								
23 Jun 1962	141	-	-	-	369,000	-	-	-
29 Jun 1962	-	475	1,210	-	-	-	63,800	89,500
3 Jul 1962	-	-	-	51,500	-	-	-	136,000
Latitude 15°N								
3 May 1962	-	-	-	362	483	-	1,380	-
17 May 1962	-	-	-	7,250	-	-	1,010	-
31 May 1962	-	-	-	4,770	-	39,300	1,020	-
14 Jun 1962	-	-	-	1,520	-	7,770	1,800	-
15 Jun 1962	22	24	176	3,280	8,590	-	7,050	-
27 Jun 1962	-	-	-	-	12,600	-	-	-
28 Jun 1962	-	-	-	2,640	6,310	-	2,600	-
3 Jul 1962	-	-	-	-	-	-	62,500	-
10 Jul 1962	-	-	-	2,300	-	-	1,700	640
11 Jul 1962	-	-	-	-	-	5,200	-	-
13 Jul 1962	-	-	-	-	-	-	5,850	10,150
16 Jul 1962	-	-	-	-	-	-	3,340	-
19 Jul 1962	-	-	-	-	-	-	113,000	-
24 Jul 1962	-	-	-	730	3,150	-	3,750	-
7 Aug 1962	-	-	-	-	26,500	-	2,380	-
21 Aug 1962	-	-	-	520	4,230	-	2,780	-

TABLE 50. (continued)

Date	Altitude (km) 12	14	15	17	18	19	20	21
Latitude 30°N								
1 May 1962	-	920	-	2,050	-	-	356	-
3 May 1962	-	-	-	1,960	1,750	-	1,340	542
8 May 1962	346	-	427,000	-	79,000	-	-	1,000
10 May 1962	369	1,440	528,000	135,000	109,000	-	1,430	482
15 May 1962	-	321	-	-	-	-	1,240	-
17 May 1962	-	-	-	72,100	-	-	990	-
18 May 1962	-	-	-	171,000	-	-	-	-
22 May 1962	216	-	1,350	-	15,600	-	-	245
24 May 1962	67	435	13,900	28,800	-	5,250	1,230	366
29 May 1962	-	950	-	-	-	-	1,110	-
31 May 1962	-	-	-	2,320	32,400	-	1,100	-
5 Jun 1962	186	-	1,860	-	3,040	-	-	463
7 Jun 1962	107	148	702	1,870	16,100	-	1,090	451
12 Jun 1962	-	400	-	1,810	-	-	1,230	696
14 Jun 1962	-	-	-	1,310	5,310	-	980	744
19 Jun 1962	159	-	23,500	-	3,740	-	-	740
21 Jun 1962	-	-	-	2,350	4,040	-	970	877
22 Jun 1962	680	2,000	12,000	2,530	-	-	-	-
26 Jun 1962	-	411	-	12,250	-	-	1,440	1,200
28 Jun 1962	-	-	-	4,420	3,100	-	2,012	2,540
6 Jul 1962	116	-	853	-	6,600	-	-	1,130
10 Jul 1962	-	-	-	1,830	2,600	-	1,570	-
13 Jul 1962	-	153	-	2,520	-	-	1,530	-
20 Jul 1962	13	-	780	-	2,590	-	-	890
24 Jul 1962	-	-	-	-	2,370	-	-	929
27 Jul 1962	-	330	-	21,800	-	-	773	1,460
3 Aug 1962	40	-	795	-	2,080	-	-	-
7 Aug 1962	-	-	-	2,800	2,070	-	1,440	-
17 Aug 1962	-	1,460	-	-	3,180	-	-	-
21 Aug 1962	-	-	-	1,400	1,830	-	1,830	-
23 Aug 1962	-	-	-	-	836	-	-	-
24 Aug 1962	-	-	-	-	1,830	-	-	-
26 Aug 1962	-	-	-	-	-	1,290	-	-
27 Aug 1962	-	-	376	-	-	-	-	-
28 Aug 1962	-	-	-	-	-	1,280	-	-
30 Aug 1962	-	-	-	-	1,460	-	-	-

TABLE 50. (continued)

Date	Altitude (km) 12	14	15	17	18	19	20	21
Latitude 45°N								
1 May 1962	-	1,650	-	1,860	-	-	382	-
8 May 1962	835	-	1,035	-	1,800	-	-	1,150
15 May 1962	-	895	-	-	-	-	1,220	-
16 May 1962	-	-	-	-	-	-	803	-
18 May 1962	-	-	-	3,280	-	-	-	-
22 May 1962	925	-	2,300	-	1,750	-	-	414
28 May 1962	-	-	-	-	-	-	475	-
29 May 1962	-	1,270	-	-	-	-	770	-
30 May 1962	-	-	-	2,540	-	-	-	-
5 Jun 1962	1,020	-	3,012	-	2,580	-	698	-
12 Jun 1962	-	1,220	-	2,380	-	-	2,700	-
19 Jun 1962	552	-	1,640	-	-	4,560	-	1,230
26 Jun 1962	-	650	-	4,230	-	-	1,230	-
6 Jul 1962	817	-	1,750	-	1,720	-	925	-
13 Jul 1962	-	1,620	-	3,780	-	-	925	-
20 Jul 1962	540	-	2,290	-	-	1,570	1,650	-
27 Jul 1962	-	5,500	-	7,360	-	-	1,630	-
3 Aug 1962	605	-	1,670	-	1,460	-	-	710
17 Aug 1962	-	-	853	-	1,910	-	-	-
24 Aug 1962	-	-	-	1,390	-	-	-	-
25 Aug 1962	-	-	-	2,100	-	-	-	-
27 Aug 1962	-	-	2,780	-	-	-	-	-
28 Aug 1962	-	-	-	1,550	-	-	-	-
29 Aug 1962	-	-	-	1,730	-	-	-	-
30 Aug 1962	-	-	-	1,290	-	-	-	-
31 Aug 1962	-	-	-	368	-	-	-	-

TABLE 51. Trends in the Concentrations of Total Beta Activity (pCi/SCM) at 19 to 21 km at Low Latitudes During May to August 1962

Date	Latitude 27°N	22°N	17°N	12°N	5°N	0°N	6°S
3 May 1962	940	911	1,040	-	-	-	-
17 May 1962	905	1,130	1,010	-	-	-	-
31 May 1962	1,110	760	1,020	-	-	-	-
14 Jun 1962	896	1,450	4,610	-	-	-	-
15 Jun 1962	-	-	-	7,050	-	-	-
18 Jun 1962	-	-	-	4,330	-	-	-
22 Jun 1962	1,640	-	-	-	-	-	-
24 Jun 1962	-	1,280	-	-	-	-	-
27 Jun 1962	-	-	1,240	-	-	-	-
28 Jun 1962	2,320	2,350	2,580	-	-	-	-
29 Jun 1962	-	-	-	-	246,000	76,600	8,360
3 Jul 1962	-	-	-	46,100	(136,000)	(136,000)	18,300
10 Jul 1962	2,400	2,510	1,140	-	-	-	-
11 Jul 1962	2,860	3,420	5,000	-	-	-	-
13 Jul 1962	1,570	3,080	3,550	10,200	-	-	-
16 Jul 1962	1,780	1,870	2,570	3,340	-	-	-
19 Jul 1962	-	2,450	2,380	113,000	-	-	-
24 Jul 1962	1,720	1,990	2,110	5,660	-	-	-
7 Aug 1962	1,430	1,560	2,380	-	-	-	-
21 Aug 1962	1,830	2,540	2,780	-	-	-	-

TABLE 52. Trends in the Concentration of Total Beta Activity (pCi/SCM) at 18 km at Low Latitudes During May to August 1962

Date	Latitude						
	27°N	22°N	17°N	12°N	5°N	0°N	6°S
3 May 1962	1,750	1,090	483	-	-	-	-
17 May 1962	24,000	19,600	-	-	-	-	-
31 May 1962	32,400	37,200	39,200	-	-	-	-
14 Jun 1962	5,300	13,100	19,700	-	-	-	-
15 Jun 1962	-	-	-	8,600	-	-	-
18 Jun 1962	-	-	-	12,000	-	-	-
23 Jun 1962	-	-	-	-	-	368,000	3,420
24 Jun 1962	11,800	11,700	-	-	-	-	-
27 Jun 1962	-	-	11,500	-	-	-	-
28 Jun 1962	3,100	3,500	6,300	-	-	-	-
3 Jul 1962	-	-	-	87,000	-	-	-
10 Jul 1962	1,700	750	603	-	-	-	-
24 Jul 1962	1,720	2,270	3,150	-	-	-	-
7 Aug 1962	4,260	23,100	26,600	-	-	-	-
21 Aug 1962	1,830	2,500	4,230	-	-	-	-

TABLE 53. Trends in the Concentration of Total Beta Activity (pCi/SCM) at 17 km at Low Latitudes During May to August 1962

Date	Latitude						
	27°N	22°N	17°N	12°N	5°N	0°N	6°S
3 May 1962	1,960	1,620	862	--	--	--	--
17 May 1962	72,200	9,650	7,260	--	--	--	--
31 May 1962	2,320	3,080	4,770	--	--	--	--
14 Jun 1962	1,310	1,110	1,510	--	--	--	--
15 Jun 1962	--	--	--	3,280	--	--	--
18 Jun 1962	--	--	--	--	2,830	--	--
28 Jun 1962	4,420	7,270	2,060	--	--	--	--
3 Jul 1962	--	--	--	--	50,000	51,500	20,500
10 Jul 1962	1,640	2,540	2,300	--	--	--	--
24 Jul 1962	--	619	784	619	--	--	--
7 Aug 1962	2,800	1,120	--	--	--	--	--
21 Aug 1962	1,400	1,290	520	--	--	--	--

the U. S. test series. In May and June fairly high concentrations were commonly found as far north as 27°N. On 7 August 1962 detectable amounts of debris from the U. S. tests were again found as far north as 27°N, and high concentrations were found as far north as 22°N. The data for 17 km (Table 53) reveal only two dates, 17 May and 3 July 1962, on which high concentrations of fresh debris were found. On 17 May 1962 debris attributed to the 4 May 1962 event was intercepted northward from 17°N. On 3 July 1962 debris attributed to the 10 June 1962 event was intercepted in the equatorial region. Detectable amounts of fresh debris were also found at 27°N and 22°N on 28 June 1962 and at 27°N on 7 August 1962. Apparently debris from the U. S. test series spread more rapidly in the meridional direction at 17 and 18 km than at 19 to 21 km in the tropical stratosphere. This may indicate that the diffusion constant for horizontal eddy diffusion is greater just above the tropopause than at higher levels in the tropical stratosphere. This conclusion would be consistent with the distributions of tungsten-185 from the 1958 U. S. tests reported in Chapter 6 (Figures 40 and 41). An alternative explanation of these data would be that an organized circulation exists in the lower levels of the stratosphere, and that it involves the poleward advection of air which ascends into the stratosphere at low latitudes. Other data, especially those indicating the equatorward spread of debris from the 1966 Chinese nuclear weapon test (Chapter 8), are not easily reconciled with the existence of such an organized circulation. The best conclusion thus appears to be that horizontal eddy diffusion in the tropical stratosphere is most effective immediately above the tropopause.

7.3 Interceptions of Fresh Debris from the 1962 U.S.S.R. Weapon Tests

The 1962 U.S.S.R. series of nuclear weapon tests began during the first week of August 1962. Table 54 lists the events in that series which were described as having yields in the megaton range. It is evident from the number of events of quite high yield that a large amount of radioactive debris was injected into the stratosphere by this test series.

In the preceding section it was mentioned that during August 1962 the regular STARDUST sampling patterns were replaced temporarily by a series of daily flights by a single aircraft between about 30°N and 65°N. These flights were continued from August until December 1962. Apparently these flights intercepted debris from several events in the 1962 U.S.S.R. test series, though the data obtained are inadequate to permit identification of the specific events represented. Many of these flights collected samples at the 16.8 km level in the polar stratosphere. Table 55 summarizes results for samples collected at that level between mid-July 1962 and mid-June 1963.

The results in Table 55 suggest that some debris from the 1962 U.S.S.R. tests was collected as early as 1 September 1962 at about 52°N at the 16.8 km level. Another interception took place at 62°N and 57°N on 12 September 1962. A number of interceptions took place during the last 10 days of September, and during October such interceptions became the norm. High concentrations of fallout beta activity prevailed in the lower stratosphere during November 1962, but thereafter began to decrease perceptibly as a result of radioactive decay and fallout to the troposphere.

The failure of the sampling missions flown during August and early September 1962 to intercept more radioactivity than they did might be used as indirect evidence that the initial injection of the debris from the August events

TABLE 54. High Yield Events in the 1962 U.S.S.R. Series of Nuclear Weapon Tests at Novaya Zemlya[13]

Date	Yield	Remarks
5 Aug 1962	30 megatons	
20 Aug 1962	several megatons	
22 Aug 1962	low megaton	
25 Aug 1962	several megatons	
27 Aug 1962	several megatons	
8 Sep 1962	megaton range	
15 Sep 1962	several megatons	
16 Sep 1962	several megatons	
18 Sep 1962	few megatons	
19 Sep 1962	multi-megaton	
21 Sep 1962	few megatons	
25 Sep 1962	multi-megaton	"Second largest test in the current series". Slightly higher in yield than the test of 19 September 1962.
27 Sep 1962	less than 30 megatons	
22 Oct 1962	several megatons	
24 Dec 1962	about 20 megatons	
23-25 Dec 1962		"The Soviet Union conducted a number of atmospheric nuclear tests in the vicinity of Novaya Zemlya during the period December 23 through 25".

TABLE 55. Concentrations of Total Beta Activity at the 16.8 km Level in the Northern Polar Stratosphere during the Second Half of 1962 and First Half of 1963. (Concentrations are in pCi/100 SCM corrected for decay to collection date.)

Date	62°N	57°N	52°N	47°N	42°N	37°N
13 Jul 1962	14	16	17	38	27	24
27 Jul 1962	27	33	34	17	12	8
24 Aug 1962	17	14	15	14	5	-
25 Aug 1962	16	19	19	21	28	-
28 Aug 1962	9	9	17	16	-	-
29 Aug 1962	17	14	15	17	17	-
30 Aug 1962	19	19	15	13	15	-
31 Aug 1962	18	-	-	-	-	-
1 Sep 1962	21	21	102	13	18	-
3 Sep 1962	-	-	-	-	55	-
5 Sep 1962	16	16	17	19	-	-
7 Sep 1962	23	27	30	48	21	-
8 Sep 1962	19	27	21	-	-	-
9 Sep 1962	13	14	29	18	35	-
11 Sep 1962	53	18	17	24	22	-
12 Sep 1962	107	378	34	22	32	-
13 Sep 1962	36	15	14	15	18	-
15 Sep 1962	-	12	12	10	15	7
18 Sep 1962	16	18	15	11	11	-
20 Sep 1962	18	18	21	20	24	-
21 Sep 1962	55	431	54	15	16	-
22 Sep 1962	53	352	377	57	19	-
23 Sep 1962	46	25	114	223	16	-
24 Sep 1962	28	50	308	24	15	3
25 Sep 1962	160	36	22	21	15	-
26 Sep 1962	639	526	42	66	40	-
27 Sep 1962	99	502	2,420	502	99	-

TABLE 55. (continued)

Date	62°N	57°N	52°N	47°N	42°N	37°N
28 Sep 1962	114	32	67	796	399	-
29 Sep 1962	-	439	217	112	31	28
30 Sep 1962	555	428	69	158	20	-
1 Oct 1962	7	17	703	472	1,000	-
2 Oct 1962	226	1,310	1,430	298	161	53
3 Oct 1962	-	121	3,440	660	170	-
4 Oct 1962	102	172	28	118	266	-
5 Oct 1962	54	28	234	54	66	-
6 Oct 1962	42	23	33	29	25	-
7 Oct 1962	56	38	407	302	1,080	-
8 Oct 1962	-	-	-	16	16	34
9 Oct 1962	141	162	362	362	29	-
11 Oct 1962	539	154	1,180	599	55	-
12 Oct 1962	85	112	154	191	65	11
13 Oct 1962	5,720	114	56	136	111	-
1 Nov 1962	762	334	45	56	56	-
2 Nov 1962	86	765	2,160	32	-	-
3 Nov 1962	147	1,070	98	47	-	-
5 Nov 1962	266	266	204	157	-	-
7 Nov 1962	157	253	273	-	-	-
9 Nov 1962	250	431	119	-	-	-
11 Nov 1962	292	533	449	-	-	423
12 Nov 1962	604	226	186	145	-	-
13 Nov 1962	385	641	372	-	-	-
14 Nov 1962	390	649	442	-	-	-
15 Nov 1962	528	420	404	-	-	-
16 Nov 1962	-	415	415	-	-	-
17 Nov 1962	343	226	243	-	-	-
19 Nov 1962	964	997	315	-	-	-

TABLE 55. (continued)

Date	62°N	57°N	52°N	47°N	42°N	37°N
20 Nov 1962	1,590	887	223	-	-	-
21 Nov 1962	1,390	782	386	-	-	396
22 Nov 1962	781	638	-	-	-	-
23 Nov 1962	1,410	475	639	299	-	-
24 Nov 1962	568	768	531	-	-	-
25 Nov 1962	628	887	650	-	-	-
26 Nov 1962	453	556	582	-	-	-
27 Nov 1962	658	599	547	-	-	-
28 Nov 1962	480	576	453	-	-	-
29 Nov 1962	787	436	315	245	-	-
30 Nov 1962	638	398	305	-	-	-
1 Dec 1962	340	219	242	82	82	-
11 Dec 1962	40	129	146	149	136	126
21 Dec 1962	-	-	-	202	68	49
27 Dec 1962	-	-	-	186	112	98
11 Jan 1963	-	-	-	125	118	109
24 Jan 1963	323	289	377	485	128	83
8 Feb 1963	143	134	126	221	102	24
21 Feb 1963	120	120	111	88	94	50
7 Mar 1963	177	147	130	188	184	119
14 Mar 1963	122	165	157	-	-	-
28 Mar 1963	-	-	-	120	85	44
29 Mar 1963	115	146	136	-	-	-
11 Apr 1963	87	144	99	84	86	16
25 Apr 1963	151	138	106	26	62	63
9 May 1963	86	129	98	36	24	12
23 May 1963	-	-	-	34	28	24
24 May 1963	64	34	38	-	-	-
6 Jun 1963	60	53	51	25	17	11
20 Jun 1963	67	66	62	32	26	30

was almost entirely at levels higher than 17 km in the polar stratosphere. On the other hand, it is possible that the radioactive debris from these events was still restricted to small clouds of high activity during August and early September, and that any samples collected in such clouds were not made available to the STARDUST program.

Samples collected during the August to December 1962 Flights were usually not delivered to the laboratory for analysis until several weeks had elapsed following their collection. As a result, the short-lived fission products which could have been used to identify the specific sources of the debris were no longer present in measurable amounts when these samples were received, and no specific events could be recognized as the sources of the debris sampled. In January 1963, however, numerous samples were collected which contained radioactive debris from the late December 1962 events, and apparent shot dates for the debris were estimated. Table 56 lists flight and analytical data for several samples which contained high concentrations of radioactive debris from the late 1962 U.S.S.R. Test series. The decay curves of the beta activities of some of these are shown in Figures 59 and 60. Table 57 gives the apparent shot dates calculated from fission product ratios for a few samples collected during January 1963. These results are not precise enough to distinguish between the several events in the December 1962 series.

Significant amounts of both barium-140 and antimony-124 were found in many samples collected in the stratosphere of the northern hemisphere, and especially in the polar stratosphere, during the first few months of 1963. The rate of beta decay of this debris, as well as some of the fission product data shown in Table 57, indicate that much of it was produced by the December 1962 U.S.S.R. events. Some of this debris had reached low latitudes by the second

TABLE 56. Some Samples Containing Radioactivity from Late 1962 Tests

Sample Number	Collection Date	Latitude	Altitude (km)	pCi/β SCM	pCi Sr^{90} SCM	Indicated Shot Date
7359H	22 Sep 1962	59°-54°N	16.8	35,200	15	Early Sep 1962
7755H	27 Sep 1962	55°-50°N	16.8	242,000	33	Mid-Sep 1962
8288H	3 Oct 1962	55°-50°N	16.8	344,000	12	Mid-Sep 1962
8304H	11 Oct 1962	55°-50°N	16.8	118,000	34	Mid-Sep 1962
8318H	13 Oct 1962	64°-59°N	16.8	572,000	238	Sep 1962
8341H	2 Nov 1962	56°-52°N	16.8	216,000	32	Oct 1962
8022H	4 Dec 1962	65°-62°N	20.7	91,200	55	Early Oct 1962
8110H	11 Dec 1962	43°-38°N	20.8	71,800	70	Late Oct 1962
8168H	24 Dec 1962	43°-38°N	18.6	42,500	56	Late Oct 1962
8332N	9 Jan 1963	24°-21°N	19.8	360,000	94	26 Dec 1962
8422H	11 Jan 1963	37°-32°N	19.5	84,700	43	22 Dec 1962
8640N	18 Jan 1963	44°-40°N	20.7	100,000	64	24 Dec 1962
8641N	18 Jan 1963	40°-36°N	20.7	100,000	64	21 Dec 1962
8632N	18 Jan 1963	49°-45°N	18.3	79,400	26	26 Nov 1962
8635N	18 Jan 1963	37°-29°N	18.3	80,500	48	26 Dec 1962
9390H	24 Jan 1963	49°-43°N	20.7	126,000	69	31 Dec 1962
10258H	29 Jan 1963	70°N	20.1	112,500	117	17 Dec 1962

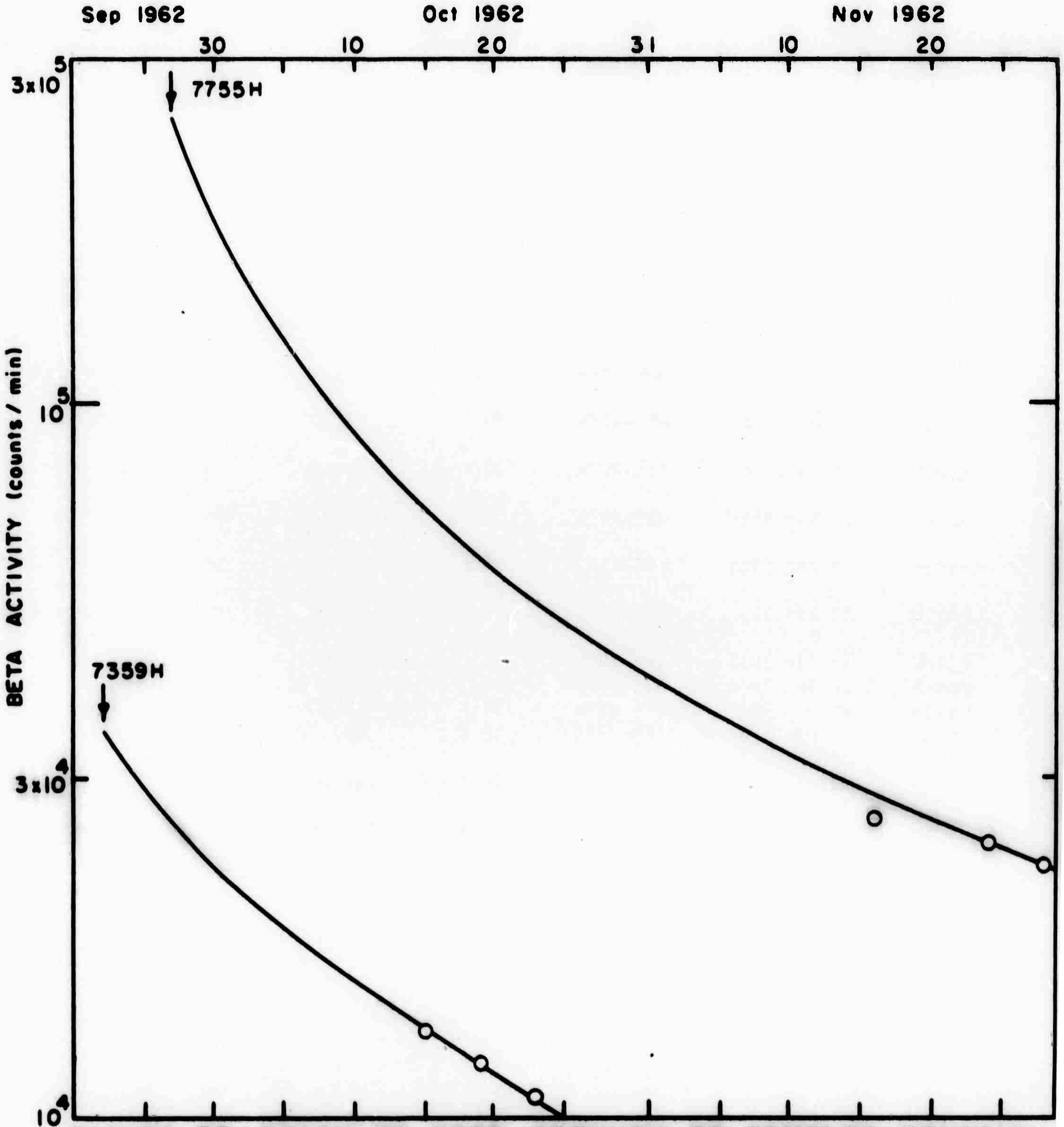

FIGURE 59. DECAY OF BETA ACTIVITY OF SAMPLES CONTAINING DEBRIS FROM LATE 1962 TESTS

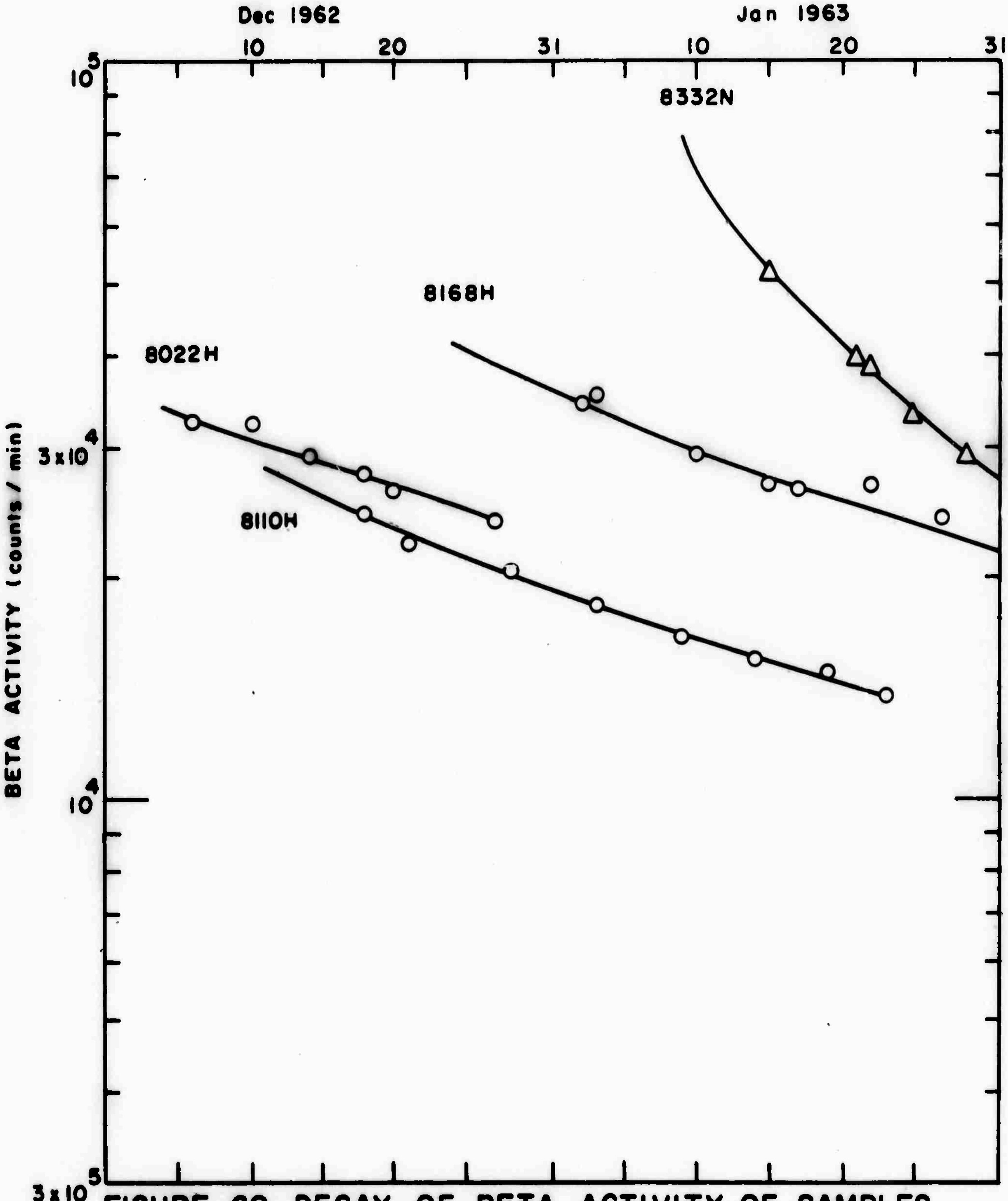

FIGURE 60. DECAY OF BETA ACTIVITY OF SAMPLES CONTAINING DEBRIS FROM LATE 1962 TESTS

TABLE 57. Apparent Age of Fresh Debris Intercepted During January 1963

Collection Date	Latitude	Longitude	Altitude (km)	Activity (pCi/SCM) Total Beta	Ba^{140}	Nuclide Ratios	Apparent Age (days)	Apparent Shot Date
9 Jan 1963	24°/21°N	97°/96°W	19.8	360,000	12,100	Mo^{99}/Ce^{144}=0.843	20	20 Dec 1962
						Mo^{99}/Zr^{95} =0.302	18	22 Dec 1962
						Mo^{99}/Ba^{140}=0.188	17	23 Dec 1962
11 Jan 1963	32°/37°N	100°/103°W	19.5	84,800	2,830	Mo^{99}/Ce^{144}=0.253	25	17 Dec 1962
						Mo^{99}/Zr^{95} =0.054	26	16 Dec 1962
						Mo^{99}/Ba^{140}=0.130	18	24 Dec 1962
11 Jan 1963	37°/31°N	103°/100°W	20.7	41,200	1,940	Mo^{99}/Ce^{144}=0.181	26	16 Dec 1962
						Mo^{99}/Zr^{95} =0.082	24	18 Dec 1962
						Mo^{99}/Ce^{141}=0.181	19	23 Dec 1962
						Mo^{99}/Ba^{140}=0.121	19	23 Dec 1962

week in January 1963, as shown by the data in Table 58. Subsequent interceptions of high concentrations of this debris occurred only at higher latitudes, however. Telegadas[36] has discussed some aspects of the stratospheric circulation which influenced the distribution of this debris during early 1963.

Figure 61 shows the distribution of strontium-90 and Figure 62 shows that of the shorter-lived activities, barium-140 and antimony-124, in the STARDUST sampling corridor on 22 and 24 January 1963. It is evident that the distribution of the short-lived activities was still quite irregular at that time, while the distribution of strontium-90, which was derived mainly from the August-September 1962 events and the 1961 events, was fairly regular. The highest strontium-90 concentrations were found at and above 17 km in the polar stratosphere, and all samples collected in that region contained high strontium-90 concentrations. Some samples collected in the polar stratosphere at and above 17 km contained high barium-140 concentrations, but others contained no more barium-140 than did samples collected in the tropical stratosphere. Two samples collected near 20 km at about 45°N contained high concentrations of antimony-124, as indicated by radiochemical analysis of one, but only semiquantitatively by gamma spectroscopy of the untreated filter for the other. Two samples collected at 17 km contained much barium-140, but little antimony-124. The samples collected at 20 km which contained high concentrations of barium-140 apparently also contained high concentrations of antimony-124. This suggests that debris from at least two of the December 1962 events was sampled at this time. One of these, which may have had a yield in the low megaton range, did not produce antimony-124, and injected much of its debris at about the 17 km level. A second, which may have had a yield in the multi-megaton range, did produce antimony-124 and injected its debris above the 19 km level.

TABLE 58. The Distribution of Strontium-90, Barium-140, Manganese-54 and Antimony-124 at the 20 km Level between 49°N and 10°N in early January 1963. (Concentrations are in pCi/SCM corrected for decay to 31 December 1962.)

Date	Latitude	Altitude (km)	Sr^{90}	Ba^{140}	Mn^{54}	Sb^{124}
11 Jan 1963	49°-37°N	19.8	29.0	280	146	2.8
11 Jan 1963	37°-32°N	19.5	36.8	5,180	183	336
9 Jan 1963	31°-27°N	20.1	30.6	486	173	25
9 Jan 1963	27°-21°N	20.1	53.2	13,200	280	1,020
9 Jan 1963	22°-10°N	20.1	21.2	134	121	2.8

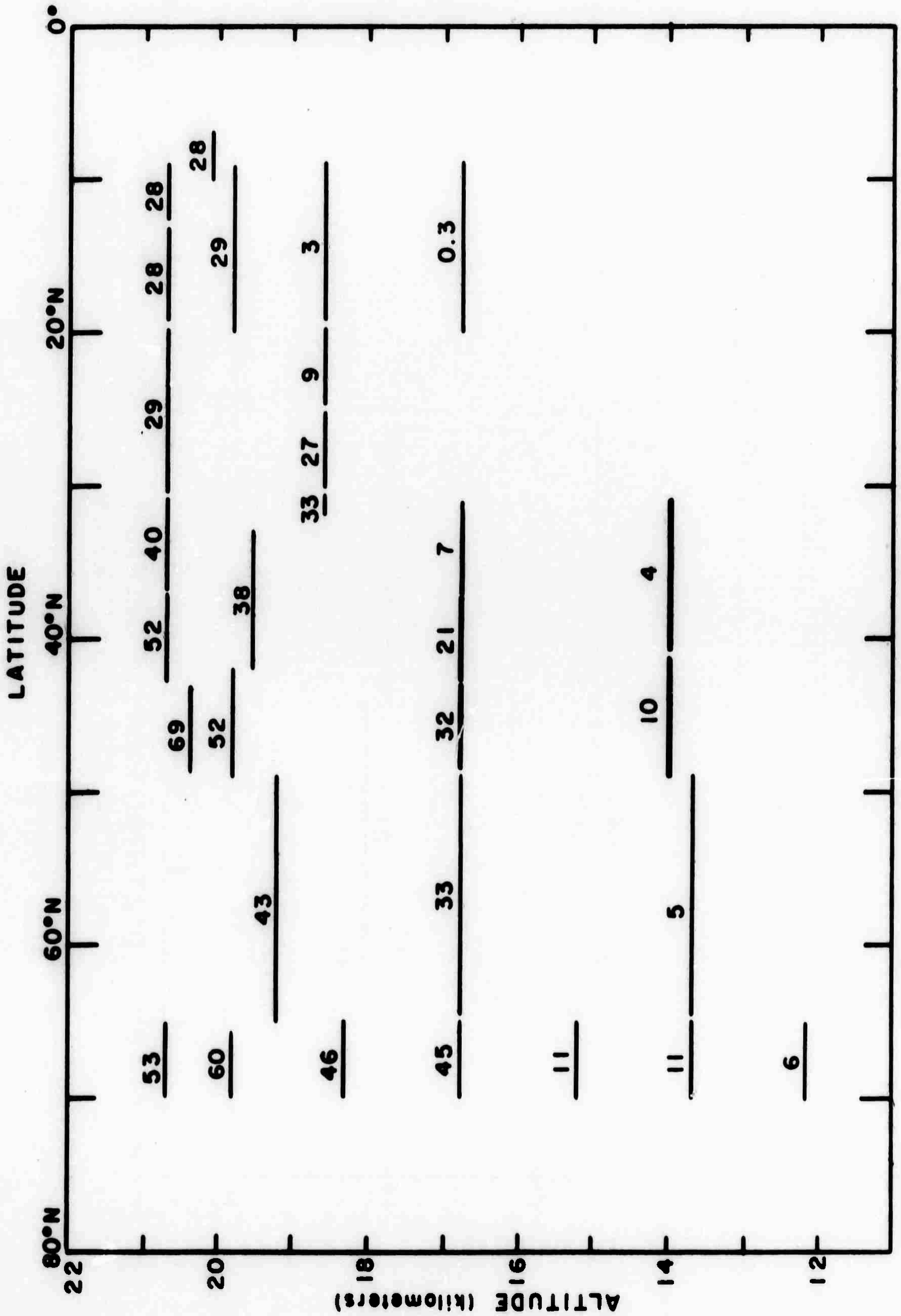

FIGURE 61. DISTRIBUTION OF STRONTIUM-90 (pCi/SCM) ON 22 AND 24 JANUARY 1963

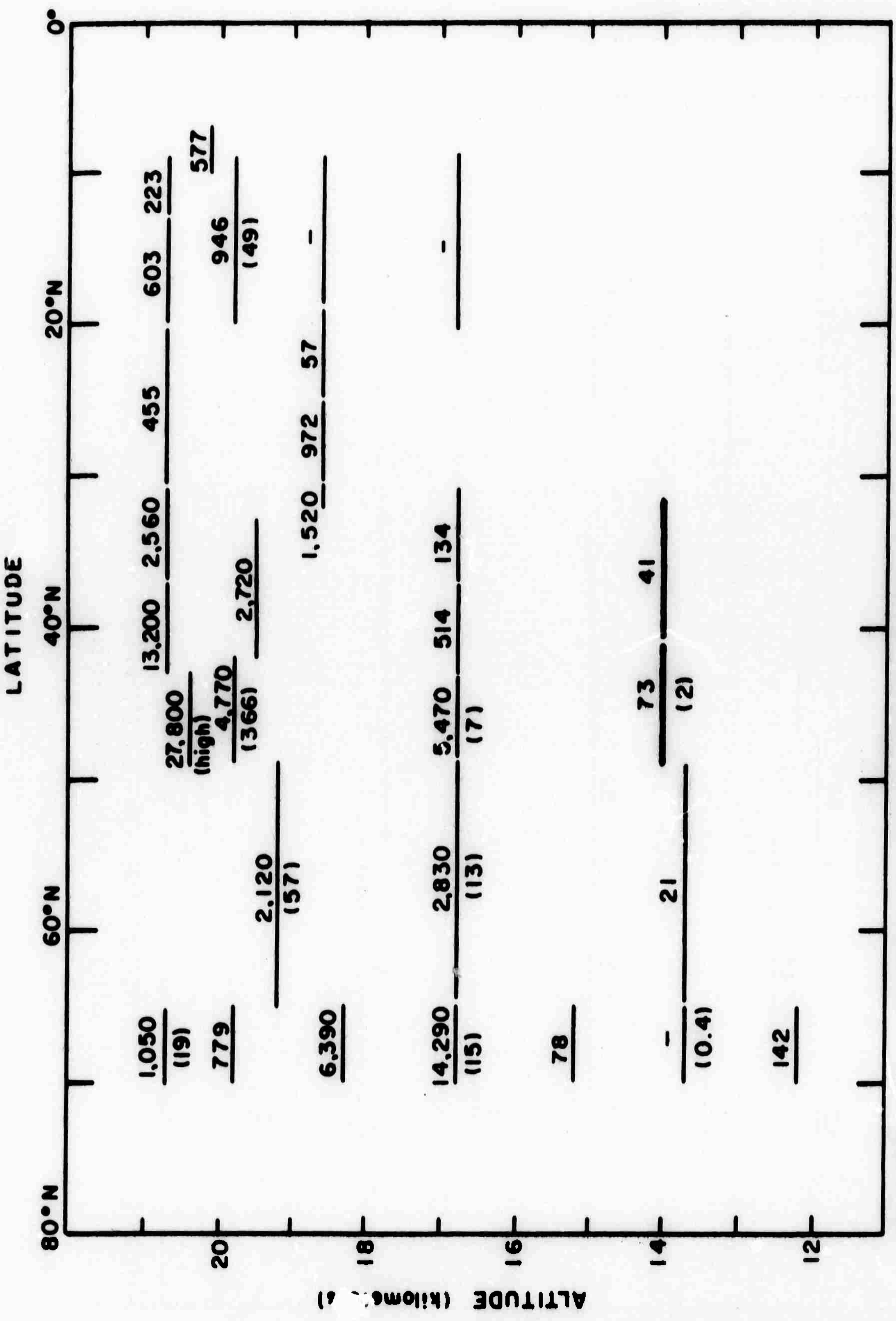

FIGURE 62. DISTRIBUTION OF BARIUM-140 AND, IN PARENTHESES, ANTIMONY-124 (pCi/SCM) ON 22 AND 24 JANUARY 1963

Table 59 contains results of measurements of barium-140, manganese-54 and antimony-124 in samples collected at 67°-70°N during 1962 and the first quarter of 1963. Comparison of the data for 7 December 1962 with those for 24 July 1962 suggests that the August and September 1962 U.S.S.R. events injected little or no manganese-54 and antimony-124 into the stratosphere. The concentrations of these nuclides found at and below the 17 km level in December 1962 were higher than they had been earlier in the year, indicating that additional amounts had been injected or that there had been substantial downward transport of these nuclides into the lower polar stratosphere between July and December. The vertical distribution of barium-140 on 7 December 1962 suggests that the debris from the most recent of the 1962 events, presumably the "several megatons" event of 22 October 1962, was spread mainly between 13.7 and at least 19.5 km, with peak concentrations at about 17 km.

By 22 January 1963, high concentrations of barium-140 were found at most altitudes in this region as debris from the December 1962 events was encountered. Neither the manganese-54 nor the antimony-124 data yield a completely consistent picture, but it appears that the December events did not significantly increase the stratospheric burden of manganese-54, but did increase the burden of antimony-124 at and above the 17 km level. The amount of antimony-124 produced by the 1962 events was small compared to the amount produced by the 1961 events, however.

Some evidence concerning the vertical distribution at levels above 20 km is available for debris from the 1962 U.S.S.R. events in the data obtained by the U.S. A.E.C. high altitude balloon sampling program[39]. Some data for samples collected over San Angelo Texas, at 31°N, are given in Table 60. The February 1962 samples contained only relatively low concentrations of manganese-54

TABLE 59. Vertical Profiles of Barium-140, Manganese-54 and Antimony-124 at 65°-70°N before and after the December 1962 Nuclear Events. (All concentrations are corrected for decay to 31 December 1962.)

Altitude (km)	pCi Ba^{140} / SCM	pCi Mn^{54} / SCM	pCi Sb^{124} / SCM
24 July 1962			
20.1	-	131	7.5
18.3	-	115	7.1
16.8	-	80	4.1
15.2	-	41	2.6
12.2	-	4.7	0.2
7 December 1962			
19.5	88	147	5.0
18.3	79	-	-
16.8	181	131	8.7
15.2	89	-	-
13.7	87	88	7.5
12.2	35	-	-
22 January 1963			
20.7	1,050	-	19
19.8	779	-	-
18.3	6,390	-	-
16.8	14,290	214	15
15.2	78	-	-
13.7	-	39	0.4
12.2	142	-	-

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TABLE 59. (continued)

Altitude (km)	pCi Ba^{140} / SCM	pCi Mn^{54} / SCM	pCi Sb^{124} / SCM
5 February 1963			
19.2	2,770	58	97
18.9	5,090	-	-
18.3	-	93	1,440
16.8	1,910	96	$\leq$ 3
15.2	1,760	316	5.9
13.7	1,220	-	-
12.2	771	85	2.0
19 February 1963			
20.1	2,150	41	86
19.8	4,750	-	-
18.3	9,280	-	-
16.8	2,970	116	68
15.2	3,640	-	-
13.7	1,990	51	4.9
12.2	3,240	-	-
5 March 1963			
20.7	7,870	-	-
20.1	10,000	124	714
18.3	13,500	-	-
16.8	5,880	159	244
15.2	3,240	-	-
13.7	1,720	102	11
12.2	1,350	-	-

TABLE 60. The Vertical Distribution of Radioactive Debris at 31°N as Indicated by Balloon Sampling during 1962 and early 1963. (Data of questionable validity are placed in parentheses. Sr^{90} data and Sr^{89}/Sr^{90} corrected to collection date. Mn^{54} activities corrected to 15 Oct 1961. Sb^{124} activities corrected to 31 Dec 1962.)

Altitude (km)	Sr^{90} (pCi/SCM)	$\frac{Sr^{89}}{Sr^{90}}$	Mn^{54} (pCi/SCM)	Sb^{124} (pCi/SCM)
February 1962				
31.7	(0.6)	-	2	-
26.8	0.6	7	14	0.3
24.1	1.3	1	≤ 0.2	-
20.7	1.2	(3)	≤ 0.2	-
18.3	4.9	15	14	0.2
August 1962				
31.4	0.6	1	(6)	(0.3)
26.6	0.7	(1)	23	(0.6)
23.8	1.7	2	107	2.1
21.7	11.8	(2)	1,050	25.7
18.3	6.5	10	103	(2.7)
November 1962				
32.0	0.6	12	(4)	≤ 1.2
26.5	1.4	-	(25)	≤ 0.5
24.1	3.3	9	8	1.0
20.1	20.5	50	479	9.1
December 1962				
31.4	0.4	11	≤ 5	≤ 1.0
26.2	1.0	4	7	-
24.4	1.8	24	14	(1.0)
19.5	19.9	31	274	(5.2)

TABLE 60. (continued)

Altitude (km)	Sr^{90} (pCi/SCM)	$\frac{Sr^{89}}{Sr^{90}}$	Mn^{54} (pCi/SCM)	Sb^{124} (pCi/SCM)
January 1963				
26.2	1.4	12	7	(0.2)
24.1	4.0	14	32	(0.6)
19.5	32.4	27	336	(5)
February 1963				
26.8	15.4	7	108	-
23.6	10.2	8	103	-
19.5	25.2	14	295	-
March 1963				
31.4	(5.3)	8	(24)	(6)
26.8	12.8	-	66	(3)
24.4	23.2	9	368	(2)
20.1	24.8	20	265	(124)
April 1963				
31.1	2.1	10	$\leq$ 5	4
27.4	11.7	2	57	10
24.4	12.8	3	146	17
19.8	29.3	10	198	121

and antimony-124, indicating that little debris from the very high yield event of 31 October 1961 had yet reached that station. It had arrived by August 1962, and high concentrations of manganese-54 and antimony-124 were found. The concentrations found during the remaining months of 1962 were lower, but high concentrations of manganese-54 were found at sampling levels above 20 km again in February 1963. High concentrations of antimony-124 may have been present in February 1963 also, but no analyses of this nuclide were made. It was probably present in March 1963, but the data are not considered reliable. It was definitely present in April 1963. The vertical profiles for April 1963 indicate that some radioactive debris from at least one of the December 1962 nuclear events had penetrated to heights of at least 27 km in the stratosphere, it appears, however, that the highest concentrations of debris from this event were to be found at levels below 24 km.

The data in Tables 59 and 60 suggest that much of the radioactive debris from the 1962 U.S.S.R. test series was injected at higher levels in the stratosphere than the radioactive debris from the 1961 U.S.S.R. test series; nevertheless, the highest concentrations were still to be found near or below the 20 km level.

7.4 Transport of Carbon-14 from the 1961 and 1962 Weapon Tests

Many of the neutrons emitted by nuclear explosions in the atmosphere react with the nuclei of nitrogen atoms, and produce carbon-14. Large amounts of radiocarbon have been created and injected into the atmosphere in this way. This artificial radiocarbon is of interest both as a potential tracer of atmospheric motions, and as a potential long-range genetic hazard. Accordingly, measurements of carbon-14 in ground-level air were performed during both Project HASP and Project STARDUST, and measurements of carbon-14 in stratospheric air were performed during 1963 to 1967 as part of Project STARDUST.

The measurement of the concentration of carbon-14 in the carbon dioxide of ground level air in the Township of Washington, Bergen County, New Jersey was begun in January 1960, and was continued until 1967. The results of these measurements are listed in Table 61. Carbon-14 data are given as measured $\delta\, C^{14}$ values and calculated $\Delta\, C^{14}$ values, both expressed as per mil differences from the carbon-14 reference standard: 95% of the activity of the NBS oxalic-acid standard. Carbon-13 data are given as measured $\delta\, C^{13}$ values, expressed as per mil differences from the P.D.B. C^{13}/C^{12} standard. The terms $\delta\, C^{14}$, $\delta\, C^{13}$ and $\Delta\, C^{14}$ are defined as follows:

$$\delta\, C^{14} = 1000\,(A-A_s)/A_s, \tag{1}$$

where A = C^{14} activity of the sample, and A_s = 0.950 times the C^{14} activity of the NBS oxalic acid standard;

$$\delta\, C^{13} = 1000\,(R-R_s)/R_s, \tag{2}$$

where R = C^{13}/C^{12} ratio of the sample, and R_s = C^{13}/C^{12} ratio of the P.D.B. standard sample:

$$\Delta\, C^{14} = \delta\, C^{14} - (2\,\delta\, C^{13} + 50)\,(1 + \delta\, C^{14}/1000). \tag{3}$$

Equation 3 is used to convert the measured carbon-14 concentration in the air, $\delta\ C^{14}$, to the equivalent concentration expected, $\Delta\ C^{14}$, if the C^{13}/C^{12} ratio in the air were equal to that in modern wood: $\delta\ C^{13} = -25$. This conversion eliminates any fractionation effects resulting from sample collection or processing which might have increased or decreased the C^{14}/C^{12} ratio. No C^{13}/C^{12} measurements were made on many of the samples listed in Table 61, and for these samples monthly average $\delta\ C^{13}$ values, which are shown in Table 62, were used to calculate the $\Delta\ C^{14}$ values.

The $\Delta\ C^{14}$ values from Table 61, expressed as per mil of activity above the reference standard -- 0.95 times the activity of the NBS standard -- are plotted in Figure 63.

During 1960 and 1961 concentrations of artificial carbon-14 at the Township of Washington ranged between +90 and +232‰, or 9 and 23 percent above the modern standard. In 1962, as carbon-14 produced by the 1961 Soviet weapon test series began to reach the troposphere, carbon-14 concentrations rose, reaching a peak value of +416 ‰, or 42 percent above the modern standard in August 1962. In late 1962 concentrations fell, as they had in late 1960 and late 1961, and as they would again in late 1963, late 1964, late 1965, and late 1966.

By April 1963 large quantities of carbon-14 from the 1961 and 1962 weapon test series had begun to enter the troposphere, and the carbon-14 concentrations rose rapidly, reaching +896 ‰, or 90 percent above the modern standard, in August 1963. Following the usual lowering of carbon-14 concentrations during the autumn and winter seasons, the concentration reached maxima of +911‰ in August 1964, +740‰ in April 1965, and +696‰ in July 1966. The average concentrations during 1963-1967 are shown in Table 63. The decrease from late 1963 to early

TABLE 61. Carbon-14 Concentrations in Ground-level Air at the Township of Washington, Bergen County, New Jersey (40°59'N, 74°04'W). (Carbon-14 concentrations are in per mil above 95% of the activity of the NBS oxalic acid standard. Carbon-13 concentrations are in per mil below the P.D.B. standard sample.)

Sample Number	Collection Interval	δC^{14} (‰)	δC^{13} (‰)	ΔC^{14} (‰)
H-1	19 Jan 60 - 25 Jan 60	208	*	208
H-2	2 Feb 60 - 9 Feb 60	200	*	198
H-3	23 Feb 60 - 1 Mar 60	184	*	182
H-4	1 Mar 60 - 8 Mar 60	224	*	222
H-5	29 Mar 60 - 5 Apr 60	224	*	223
H-6	5 Apr 60 - 12 Apr 60	160	*	159
H-7	26 Apr 60 - 3 May 60	182	*	181
H-8	24 May 60 - 31 May 60	208	*	200
Oak Leaves	28 May 60	178	*	178
H-9	21 Jun 60 - 26 Jun 60	197	*	184
H-10	26 Jul 60 - 2 Aug 60	208	*	196
H-11	23 Aug 60 - 6 Sep 60	181	*	173
H-12	6 Sep 60 - 20 Sep 60	196	*	188
H-13	27 Sep 60 - 4 Oct 60	172	*	164
H-14	4 Oct 60 - 11 Oct 60	172	*	164
SD-15	18 Oct 60 - 1 Nov 60	194	*	186
H-15	1 Nov 60 - 17 Nov 60	141	*	139
SD-18	17 Nov 60 - 1 Dec 60	114	*	112
H-16	1 Dec 60 - 11 Dec 60	120	*	119
SD-5	12 Dec 60 - 31 Dec 60	120	*	119

* Average monthly values of δC^{13}, given in Table 62, were used for all samples in which δC^{13} was not measured.

TABLE 61. (continued)

Sample Number	Collection Interval	δC^{14} (‰)	δC^{13} (‰)	ΔC^{14} (‰)
H-17	31 Dec 60 - 18 Jan 61	90	*	90
H-18	18 Jan 61 - 25 Jan 61	154	*	154
H-19**	18 Jan 61 - 25 Jan 61	144	*	144
SD-16	25 Jan 61 - 1 Feb 61	172	*	172
H-20	1 Feb 61 - 8 Feb 61	191	*	189
SD-19	15 Feb 61 - 1 Mar 61	128	*	126
H-21	16 Mar 61 - 3 Apr 61	204	*	202
H-22	16 Apr 61 - 1 May 61	156	*	155
SD-1	16 May 61 - 1 Jun 61	170	*	163
SD-6	16 Jun 61 - 1 Jul 61	211	*	198
SD-10	1 Jul 61 - 1 Aug 61	229	*	217
SD-2	1 Aug 61 - 4 Sep 61	241	*	232
SD-7	4 Sep 61 - 1 Oct 61	187	*	179
SD-11	15 Oct 61 - 1 Nov 61	178	*	170
SD-3	15 Nov 61 - 1 Dec 61	200	*	198
SD-8	15 Dec 61 - 1 Jan 62	176	*	175

** Collected at Closter, Bergen County, New Jersey (40°58'N, 73°58'W)

TABLE 61. (continued)

Sample Number	Collection Interval	δC^{14} (‰)	δC^{13} (‰)	ΔC^{14} (‰)
SD-20	1 Jan 62 - 17 Jan 62	200	*	200
SD-12A***	17 Jan 62 - 1 Feb 62	250	*	250
SD-12B***	17 Jan 62 - 1 Feb 62	238	*	238
SD-4	15 Feb 62 - 28 Feb 62	235	*	233
SD-9	16 Mar 62 - 31 Mar 62	293	*	291
SD-13	14 Apr 62 - 1 May 62	278	*	277
SD-14	16 May 62 - 1 Jun 62	358	*	349
SD-17	1 Jun 62 - 15 Jun 62	369	*	354
SD-21	15 Jun 62 - 30 Jun 62	361	*	346
SD-22	30 Jun 62 - 16 Jul 62	349	*	336
SD-23	16 Jul 62 - 1 Aug 62	280	*	268
SD-24	1 Aug 62 - 15 Aug 62	247	*	238
SD-25	15 Aug 62 - 1 Sep 62	426	*	416
SD-26	1 Sep 62 - 17 Sep 62	350	*	341
SD-27	17 Sep 62 - 1 Oct 62	415	*	406
SD-28	1 Oct 62 - 16 Oct 62	358	*	349
SD-29	16 Oct 62 - 1 Nov 62	370	*	361
SD-30	1 Nov 62 - 16 Nov 62	280	*	278
SD-31	16 Nov 62 - 30 Nov 62	300	*	298
SD-32	30 Nov 62 - 15 Dec 62	243	*	242
SD-33	15 Dec 62 - 28 Dec 62	249	*	248

*** Analyzed in duplicate

TABLE 61. (continued)

Sample Number	Collection Interval	δ C^{14} (‰)	δ C^{13} (‰)	Δ C^{14} (‰)
SD-34	1 Jan 63 - 16 Jan 63	300	*	300
SD-35	16 Jan 63 - 1 Feb 63	260	*	260
SD-36	1 Feb 63 - 16 Feb 63	350	*	248
SD-37	16 Feb 63 - 1 Mar 63	381	*	379
SD-38	1 Mar 63 - 16 Mar 63	380	*	378
SD-39	16 Mar 63 - 1 Apr 63	345	*	343
SD-40	1 Apr 63 - 17 Apr 63	508	*	507
SD-41	22 Apr 63 - 1 May 63	533	*	532
SD-42	1 May 63 - 14 May 63	640	*	630
SD-43	14 May 63 - 31 May 63	665	*	654
SD-44	31 May 63 - 14 Jun 63	656	*	638
SD-45	14 Jun 63 - 2 Jul 63	802	*	782
SD-46	2 Jul 63 - 15 Jul 63	900	*	882
SD-47	15 Jul 63 - 31 Jul 63	815	*	798
SD-48	31 Jul 63 - 15 Aug 63	910	*	896
SD-49	15 Aug 63 - 31 Aug 63	900	*	886
SD-50	31 Aug 63 - 16 Sep 63	900	*	888
SD-51	16 Sep 63 - 1 Oct 63	851	*	839
SD-52	1 Oct 63 - 15 Oct 63	752	*	740

TABLE 61. (continued)

Sample Number	Collection Interval	δC^{14} (‰)	δC^{13} (‰)	ΔC^{14} (‰)
SD-53	15 Oct 63 - 31 Oct 63	753	*	741
SD-54	31 Oct 63 - 16 Nov 63	789	*	786
SD-55	16 Nov 63 - 1 Dec 63	651	*	648
SD-56	1 Dec 63 - 16 Dec 63	860	*	859
SD-57	16 Dec 63 - 2 Jan 64	778	*	777
SD-58	3 Jan 64 - 20 Jan 64	608	*	608
SD-59	20 Jan 64 - 3 Feb 64	750	*	750
SD-60	3 Feb 64 - 17 Feb 64	756	*	753
SD-61	17 Feb 64 - 2 Mar 64	715	*	712
SD-62	2 Mar 64 - 14 Mar 64	715	*	712
SD-63	14 Mar 64 - 31 Mar 64	788	*	785
SD-64	31 Mar 64 - 16 Apr 64	755	*	754
SD-65	16 Apr 64 - 1 May 64	785	*	784
SD-66	8 May 64 - 15 May 64	863	*	851
SD-67	15 May 64 - 31 May 64	898	*	886
SD-68	31 May 64 - 16 Jun 64	915	*	894
SD-69	16 Jun 64 - 1 Jul 64	786	*	766
SD-70	1 Jul 64 - 15 Jul 64	914	*	896
SD-71	15 Jul 64 - 1 Aug 64	923	*	905
SD-72	1 Aug 64 - 17 Aug 64	925	*	911
SD-73	17 Aug 64 - 1 Sep 64	834	*	821
SD-74	1 Sep 64 - 16 Sep 64	909	*	897
SD-75	16 Sep 64 - 1 Oct 64	887	*	875
SD-76	1 Oct 64 - 17 Oct 64	854	*	842
SD-77	17 Oct 64 - 31 Oct 64	800	*	788

TABLE 61. (continued)

Sample Number	Collection Interval	δC^{14} (‰)	δC^{13} (‰)	ΔC^{14} (‰)
SD-78	31 Oct 64 - 14 Nov 64	737	-23.0	730
SD-79	15 Nov 64 - 1 Dec 64	761	-22.8	753
SD-80	1 Dec 64 - 15 Dec 64	645	-24.3	643
SD-81	15 Dec 64 - 2 Jan 65	642	-22.4	633
SD-82	2 Jan 65 - 19 Jan 65	672	*	672
SD-83	19 Jan 65 - 30 Jan 65	680	*	680
SD-84	30 Jan 65 - 15 Feb 65	699	*	696
SD-85	15 Feb 65 - 28 Feb 65	697	*	694
SD-86	28 Feb 65 - 15 Mar 65	702	*	699
SD-87	15 Mar 65 - 31 Mar 65	721	*	718
SD-88	31 Mar 65 - 15 Apr 65	741	*	740
SD-89	15 Apr 65 - 4 May 65	717	*	716
SD-90	4 May 65 - 21 May 65	725	-19.9	707
SD-91	21 May 65 - 2 Jun 65	721	-18.3	698
SD-92	2 Jun 65 - 1 Jul 65	745	-18.2	721
SD-93	1 Jul 65 - 1 Aug 65	730	-20.7	715
SD-94	1 Aug 65 - 3 Sep 65	727	-20.7	712
SD-95	3 Sep 65 - 1 Oct 65	670	-22.1	660
SD-96	1 Oct 65 - 31 Oct 65	680	-22.1	670
SD-97	31 Oct 65 - 2 Dec 65	710	-26.2	714
SD-98	2 Dec 65 - 1 Jan 66	578	-26.8	584
SD-99	1 Jan 66 - 1 Feb 66	661	-24.3	659
SD-100	1 Feb 66 - 1 Mar 66	587	-23.2	581

TABLE 61. (continued)

Sample Number	Collection Interval	δC^{14} (‰)	δC^{13} (‰)	ΔC^{14} (‰)
SD-101	1 Mar 66 - 2 Apr 66	637	-22.7	630
SD-102	2 Apr 66 - 30 Apr 66	650	-22.0	640
SD-103	30 Apr 66 - 3 Jun 66	654	-21.8	643
SD-104	3 Jun 66 - 1 Jul 66	662	-19.0	642
SD-105	3 Jul 66 - 1 Aug 66	714	-19.7	696
SD-106	1 Aug 66 - 2 Sep 66	696	-22.1	686
SD-107	2 Sep 66 - 8 Oct 66	653	-21.3	641
SD-108	8 Oct 66 - 31 Oct 66	630	-21.3	618
SD-109	31 Oct 66 - 1 Dec 66	582	-23.1	576
SD-110	1 Dec 66 - 3 Jan 67	572	-24.0	569
SD-111	3 Jan 67 - 1 Feb 67	507	-25.9	510
SD-112	1 Feb 67 - 1 Mar 67	584	-25.2	585
SD-113	1 Mar 67 - 1 Apr 67	572	-25.6	574
SD-114	1 Apr 67 - 3 May 67	576	-27.3	583
SD-115	3 May 67 - 3 Jun 67	599	-24.5	597
SD-116	3 Jun 67 - 12 Jul 67	630	-21.2	618

TABLE 62. Monthly Averages of δC^{13} Measured in Ground-level Air Samples

Month	1964	1965	1966	1967	Monthly Average
Jan	-	-	-24.3	-25.9	-25.1
Feb	-	-	-23.2	-25.2	-24.2
Mar	-	-	-22.7	-25.6	-24.2
Apr	-	-	-22.0	-27.3	-24.6
May	-	-19.1	-21.8	-24.5	-21.8
Jun	-	-18.2	-19.0	-21.2	-19.5
Jul	-	-20.7	-19.7	-	-20.2
Aug	-	-20.7	-22.1	-	-21.4
Sep	-	-22.1	-21.3	-	-21.7
Oct	-	-22.1	-21.3	-	-21.7
Nov	-22.9	-26.2	-23.1	-	-24.1
Dec	-23.4	-26.8	-24.0	-	-24.7

Year columns: 1964, 1965, 1966, 1967 grouped under "Year".

TABLE 63. Semiannual and Annual Mean $\Delta\ C^{14}$ Values in Ground-level Air at the Township of Washington, Bergen County, N. J.

	$\Delta\ C^{14}$ (+ ‰)	$\Delta\ C^{14}$ (+ ‰)
Jan - Jun 1963:	479	
Jul - Dec 1963:	812	1963: 646
Jan - Jun 1964:	771	
Jul - Dec 1964:	808	1964: 789
Jan - Jun 1965:	705	
Jul - Dec 1965:	676	1965: 690
Jan - Jun 1966:	632	
Jul - Dec 1966:	631	1966: 632
Jan - Jun 1967:	578	

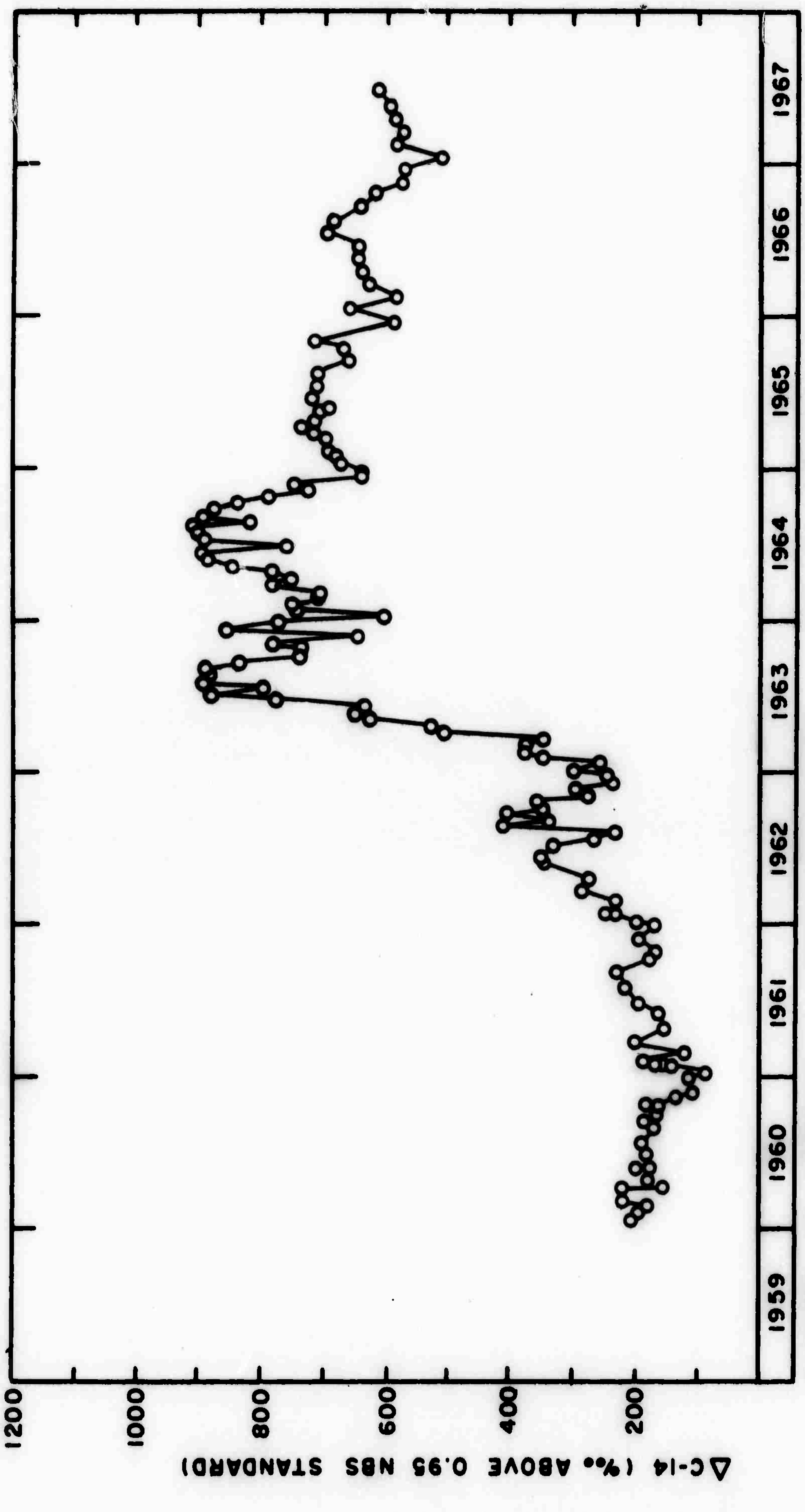

FIGURE 63. CARBON-14 CONCENTRATIONS IN GROUND-LEVEL AIR AT THE TOWNSHIP OF WASHINGTON, BERGEN COUNTY, NEW JERSEY

1967 corresponds to an apparent net residence half time of about 6.8 years at 41°N for bomb-produced carbon-14. It will be of interest during the coming years to monitor the decrease of the carbon-14 concentrations in tropospheric air, and from these data and the data on concentrations in the stratosphere to calculate the residence time of carbon-14 in the atmosphere. This will provide a quantitative measure of the rate of exchange of carbon dioxide between the hemispheres and between the atmosphere and the oceans.

Measurements by the Argonne National Laboratories have monitored the distribution of carbon-14 in the atmosphere since 1953, and the results of these measurements have been reported elsewhere [2]. Each series of thermonuclear weapon tests, which began in 1952, injected significant amounts of carbon-14 into the stratosphere. The last major injections were the result of USSR tests which were concluded in late 1962. Beginning in August, 1963, eight months after the last major stratospheric injections, compressed air samples for carbon-14 analyses were collected on STARDUST missions flown in the regions between approximately 70° or 75°N and 15°N latitudes. During early 1967 a few samples were also collected at more southerly latitudes. The procedures used in the collection and analyses of these samples have been described in Chapters 2 and 4. The resulting data have been used to calculate the distribution of carbon-14 in carbon dioxide in the stratosphere of the Northern Hemisphere for various intervals during 1963 to 1967.

The expected concentration of natural carbon-14, 74.0×10^5 atoms per gram of air, given by Hagemann et al. [2] has been subtracted from each concentration to obtain the concentration of artificial "excess" carbon-14: carbon-14 produced by atmospheric nuclear tests.

That the concentration of carbon-14 in the stratosphere of the Northern Hemisphere decreased from 1963 to 1967 is apparent from the data presented in Table 64. In this table are listed bimonthly mean values of carbon-14 concentrations measured at 14, 17, and 20 km at 55° and 70°N, and at 20 km at 40°, 25°, 10°N, and 42°S. The increases in carbon-14 concentrations which occur at the lower altitudes in the high northern latitudes during the winter months may be attributed to an increase in the rate of downward movement of carbon-14 in the polar stratosphere during the winter season, most likely as a result of increased rates of vertical exchange at that time.

The data in Table 65 provide some evidence that there was a layer of maximum concentration at a height of about 18 to 20 km in the polar stratosphere (possibly reflecting a large injection into the 17 to 20 km layer by the late 1962 test series) during late 1963 which sloped upwards towards the equator, and reached a height of more than 21 km in the tropical latitudes. During subsequent periods, however, the highest concentrations have been found at the highest altitudes at which the aircraft sampled: 20 to 21 km. These data are listed in Tables 66 and 67. The data in Table 67, which were provided by Argonne, are the result of sampling using balloons and indicate that the altitude of maximum concentration may be as high as about 24 km at 30°N. Table 68 lists data provided by Argonne for 42°S, which also show the maximum concentration of carbon-14 at the highest altitude sampled. The main change in the vertical distribution of carbon-14 since the beginning of 1964 has been the gradual decrease of concentrations in the regions above about 12 km in the northern polar stratosphere and above about 14 km in the northern tropical stratosphere. Trends in time of vertical profiles of carbon-14 concentrations at several latitudes are given in Tables 66, 67 and 68. If vertical mixing rate

TABLE 64. Trends with time in the C^{14} concentration (10^5 atoms/gram of air) at various locations in the stratosphere.

A. High Northern Latitudes

Time Interval	70°N 20km	70°N 17km	70°N 14km	55°N 20km	55°N 17km	55°N 14km
Aug 1963	1530(2)	982(4)	-	1390(5)	688(1)	-
Sep-Oct 1963	1410(9)	1098(9)	317(3)	1270(16)	875(4)	226(4)
Nov-Dec 1963	1000(3)	786(7)	232(1)	1048(16)	843(3)	194(4)
Jan-Feb 1964	1000(11)	844(7)	556(2)	1073(15)	825(4)	402(5)
Mar-Apr 1964	922(2)	632(4)	674(1)	635(2)	536(1)	591(2)
May-Jun 1964	683(1)	491(3)	-	734(4)	498(2)	-
Jul-Aug 1964	608(2)	420(4)	-	631(4)	356(2)	-
Sep-Oct 1964	660(2)	412(5)	-	582(4)	333(3)	-
Nov-Dec 1964	524(1)	501(5)	-	516(4)	308(1)	108(1)
Jan-Feb 1965	481(2)	428(2)	219(1)	496(4)	322(4)	219(1)
Mar-Apr 1965	463(3)	316(4)	230(2)	467(3)	351(3)	186(3)
May-Jun 1965	442(1)	345(2)	184(1)	460(3)	265(3)	186(2)
Jul-Aug 1965	-	277(2)	147(1)	367(3)	206(3)	130(2)
Sep-Oct 1965	373(1)	232(2)	100(2)	319(4)	186(2)	91(3)
Nov-Dec 1965	380(1)	-	-	318(2)	148(2)	92(1)
Jan-Feb 1966	364(1)	276(1)	132(1)	318(3)	295(1)	146(2)
Mar-Apr 1966	244(2)	226(2)	136(1)	307(2)	160(1)	120(1)
May-Jun 1966	-	-	-	-	227(2)	-
Jul-Aug 1966	300(4)	210(3)	122(1)	278(3)	-	88(3)
Sep-Oct 1966	-	-	-	-	-	89(1)
Nov-Dec 1966	-	234(1)	86(1)	-	184(2)	79(2)
Jan-Feb 1967	257(1)	-	-	-	-	97(1)
Mar-Apr 1967	-	-	102(1)	-	-	102(1)
May-Jun 1967	-	-	88(1)	197(1)	-	84(4)

B. Mid - to Low Latitudes

Time Interval	40°N 20km	25°N 20km	10°N 20km	42°S, 20km (Argonne Data)
Jan-Feb 1963	-	-	-	122(5)
Mar-Apr 1963	-	-	-	125(3)
May-Jun 1963	-	-	-	119(3)
Jul-Aug 1963	1319(8)	680(4)	909(1)	123(4)
Sep-Oct 1963	1153(15)	850(10)	702(3)	142(3)
Nov-Dec 1963	1057(13)	725(8)	628(3)	138(4)
Jan-Feb 1964	951(14)	591(8)	500(2)	138(4)
Mar-Apr 1964	992(4)	460(6)	456(2)	122(2)
May-Jun 1964	738(3)	479(5)	-	121(2)
Jul-Aug 1964	642(4)	315(4)	266(1)	147(5)
Sep-Oct 1964	588(4)	301(3)	-	164(4)
Nov-Dec 1964	571(1)	310(4)	-	154(4)

TABLE 64. (continued)

Time Interval		40°N 20km	25°N 20km	10°N 20km	42°S, 20km (Argonne Data)
Jan-Feb	1965	500(2)	398(5)	-	172(4)
Mar-Apr	1965	420(3)	322(7)	126(1)	139(4)
May-Jun	1965	479(1)	398(2)	-	153(5)
Jul-Aug	1965	334(2)	271(4)	205(1)	170(4)
Sep-Oct	1965	307(3)	190(2)	1[illegible]0(4)	154(4)
Nov-Dec	1965	330(4)	260(5)	155(2)	155(4)
Jan-Feb	1966	311(2)	224(2)	143(1)	178(2)
Mar-Apr	1966	310(2)	210(2)	143(1)	170(2)
May-Jun	1966	277(2)	197(3)	128(1)	165(2)
Jul-Aug	1966	272(2)	216(2)	-	142(4)
Sep-Oct	1966	-	152(2)	-	-
Nov-Dec	1966	237(1)	202(2)	91(1)	-
Jan-Feb	1967	234(1)	163(2)	95(3)	137(3)
Mar-Apr	1967	182(3)	150(2)	129(3)	-
May-Jun	1967	235(1)	99(1)	-	-

(Number of samples represented by each average given in parenthesis)

TABLE 65. Vertical profiles of C^{14} concentration ($10^5 C^{14}$ atoms/gm air) at various locations in the stratosphere in late 1963

Altitude	15 km	17 km	18 km	20 km	21 km	15 km	17 km	18 km	20 km	21 km
	70° N					65° N				
Aug 1963	*645(3)	1050(2)	1538(2)	1795(2)	-	403(3)	914(2)	1382(4)	1531(2)	-
Sep 1963	*631(3)	1078(2)	1361(1)	1484(5)	-	444(3)	936(2)	1128(4)	1452(4)	-
Oct 1963	-	1158(3)	1252(2)	1322(7)	-	744(5)	1192(2)	1199(5)	1347(6)	-
Nov 1963	*909(3)	937(2)	*1115(1)	1071(3)	947(1)	653(4)	677(2)	980(4)	1069(4)	-
Dec 1963	*790(3)	929(1)	* 981(3)	1024(3)	852(1)	435(4)	671(1)	860(3)	1000(3)	-
	60° N					55° N				
Aug 1963	-	-	-	-	-	503(1)	688(1)	1121(2)	1350(2)	-
Sep 1963	-	-	1444(1)	1326(3)	-	-	929(2)	-	-	-
Oct 1963	-	-	1275(3)	1309(5)	-	352(2)	791(2)	1129(4)	-	-
Nov 1963	-	-	932(2)	1100(4)	-	745(2)	890(2)	1020(2)	-	-
Dec 1963	-	-	943(1)	928(3)	-	500(2)	769(1)	733(2)	1076(1)	-
	50° N					45° N				
Aug 1963	-	-	1124(1)	1323(3)	-	244(2)	482(1)	950(3)	1276(4)	-
Sep 1963	-	-	896(1)	1271(3)	-	195(2)	219(2)	745(4)	1163(3)	-
Oct 1963	-	-	895(2)	1200(5)	-	163(1)	290(1)	816(5)	970(4)	-
Nov 1963	-	-	1037(2)	1160(4)	1080(1)	613(2)	674(3)	898(2)	1042(3)	-
Dec 1963	-	-	914(3)	1000(3)	1008(1)	281(2)	301(1)	942(2)	1054(2)	-
	40° N					35° N				
Aug 1963	113(1)	431(2)	838(3)	1362(4)	-	232(2)	292(1)	821(3)	1268(1)	
Sep 1963	122(1)	249(1)	616(3)	1310(1)	1263(2)	87(1)	249(1)	*888(1)	-	-
Oct 1963	214(2)	334(2)	890(3)	1177(2)	1122(1)	264(1)	334(2)	717(1)	-	-
Nov 1963	294(2)	186(1)	643(3)	1048(4)	1111(1)	*178(2)	186(1)	652(4)	988(1)	-
Dec 1963	281(1)	204(2)	866(4)	929(2)	1132(1)	58(1)	108(1)	833(3)	-	-

* ANL data

TABLE 65 (continued)

Altitude	15 km	17 km	18 km	20 km	21 km	15 km	17 km	18 km	20 km	21 km
		30° N					25° N			
Aug 1963	-	-	-	-	-	-	614(2)	749(2)	502(2)	640(1)
Sep 1963	-	-	-	-	-	-	287(2)	631(2)	806(3)	-
Oct 1963	-	-	-	-	-	-	245(2)	618(3)	852(3)	-
Nov 1963	-	-	-	-	-	-	122(2)	431(2)	484(2)	-
Dec 1963	-	-	-	-	-	-	81(1)	530(2)	938(2)	-
		20° N					15° N			
Aug 1963	-	-	-	690(8)	-	-	206(2)	275(2)	909(1)	-
Sep 1963	-	287(2)	631(2)	740(6)	-	-	155(2)	314(2)	647(1)	-
Oct 1963	-	-	-	822(10)	-	-	161(3)	248(3)	662(3)	-
Nov 1963	-	74(1)	319(1)	595(5)	-	-	82(2)	328(2)	605(1)	-
Dec 1963	-	-	190(1)	750(7)	-	-	73(2)	165(2)	663(3)	-
		10° N					42° S			
Aug 1963	*85(2)	-	*264(2)	-	*459(1)	* 72(1)	-	*101(1)	-	*135(1)
Sep 1963	*67(2)	-	*340(2)	-	*458(2)	* 73(2)	-	*116(2)	-	*144(1)
Oct 1963	*65(2)	-	*160(2)	-	*522(2)	* 54(2)	-	*103(1)	-	*141(2)
Nov 1963	*84(2)	-	*118(2)	-	*451(2)	* 85(2)	-	*128(2)	-	*141(1)
Dec 1963	*51(2)	-	*150(3)	-	*350(3)	*128(2)	-	*120(3)	-	*121(2)

* ANL data

Numbers in parentheses indicate number of samples averaged.

TABLE 66. Trends with time in C^{14} vertical concentration profile (10^5 atoms/gm air) at 55°N

Time Interval		15km	17km	18km	20km
May-Aug	1963	503(1)	688(1)	1120(2)	1350(2)
Sep-Dec	1963	532(6)	861(7)	1053(9)	1216(2)
Jan-Apr	1964	430(5)	767(5)	870(4)	1075(1)
May-Aug	1964	294(4)	437(3)	-	-
Sep-Dec	1964	157(3)	333(3)	506(2)	564(4)
Jan-Apr	1965	231(1)	310(3)	435(3)	487(1)
May-Aug	1965	110(1)	202(3)	305(4)	399(2)
Sep-Dec	1965	-	158(2)	229(3)	337(3)
Jan-Apr	1966	-		302(3)	307(2)
May-Aug	1966	148(3)	-	247(2)	-
Sep-Dec	1966	117(2)	202(1)	-	-
Jan-Apr	1967	142(3)	-	197(5)	-
May-Aug	1967	130(1)	-	164(1)	197(1)

Numbers in parentheses indicate number of samples averaged

TABLE 67. Trends with time in vertical C^{14} concentration (10^6 atoms/gm air) profile at 30° N

Time Interval		15km	17km	18km	20km	24km	27km
Jan-Apr	1965	-	104(2)	238(2)	442(4)	-	*342(1)
May-Aug	1965	-	-	199(3)	345(3)	*462(3)	*310(4)
Sep-Dec	1965	-	94(3)	-	341(2)	*303(3)	*317(3)
Jan-Apr	1966	93(1)	85(1)	-	-	*267(5)	*(313)(1)
May-Aug	1966	80(2)	113(3)	129(2)	264(2)	*295(1)	-
Sep-Dec	1966	65(1)	-	-	219(1)	*293(2)	-

Numbers in parentheses indicate number of samples averaged

* ANL data

TABLE 68. Trends with time in vertical C^{14} concentration (10^5 atoms/gm air) profile at 42°S (data from Argonne National Lab)

	Altitude			
	12km	15 km	18km	20km
Sep-Dec 1958	25 (6)	51 (7)	106 (20)	145 (7)
Jan-Apr 1959	35 (4)	55 (4)	112 (4)	145 (3)
May-Aug 1959	31 (12)	55 (14)	91 (14)	126 (11)
May-Aug 1960	28 (5)	31 (5)	77 (5)	105 (5)
Sep-Dec 1960	27 (5)	43 (5)	93 (5)	118 (5)
May-Aug 1961	23 (5)	34 (5)	96 (5)	125 (5)
Sep-Dec 1961	31 (5)	31 (5)	69 (5)	90 (5)
Jan-Apr 1962	36 (5)	38 (5)	88 (5)	112 (5)
Sep-Dec 1962	54 (4)	85 (7)	120 (7)	137 (8)
Jan-Apr 1963	42 (9)	65 (9)	107 (9)	123 (8)
May-Aug 1963	57 (8)	63 (8)	104 (8)	121 (7)
Sep-Dec 1963	56 (6)	84 (8)	117 (8)	140 (7)
Jan-Apr 1964	57 (5)	70 (6)	104 (6)	132 (6)
May-Aug 1964	63 (9)	78 (8)	118 (9)	135 (9)
Sep-Dec 1964	60 (8)	76 (8)	121 (9)	158 (8)

Numbers in parentheses indicate number of samples averaged.

varied greatly with season, one might expect to find significant changes in the steepness of the profile during different seasons, especially at the 55°N station. This is however, not apparent in these data which average values over several months, but can be observed in some values for a given day. A reasonable explanation for this is the possibility that the increased rate of mixing occurs in some air masses, but not others.

It is noteworthy that at 20 km the carbon-14 concentrations in the tropical stratosphere, at 25°N and 15°N, have never reached values comparable to those in the polar stratosphere, at 60°N and 40°N (Table 69). Strontium-90 concentrations at 20 km have been approximately the same in the tropical and polar stratosphere of the Northern Hemisphere since mid-1963 (see Table 70). It has been hypothesized that the differences in the distributions of excess carbon-14 and of particulate debris, such as strontium-90, in the stratosphere are attributable to the effect of particule settling in the region of the stratosphere above about 20 km[20]. When radioactive debris in the stratosphere moves in the meridional direction it appears to do so within layers which slope upward toward the equator. As a result, debris in the 15 to 20 km layer in the polar stratosphere may be carried into the region above 20 km as it moves equatorward. Within this region the effects of gravitational settling may separate the particulate debris, such as strontium-90, from the gaseous debris, such as carbon-14. As this debris is subsequently carried back toward the pole the carbon-14 will be found within the same layer which originally contained it, but the particulate debris may be found in a lower layer. This process should be most effective immediately following the injection of debris into the stratosphere (for example, during 1963), but should decrease in effectiveness with the passage of time. Similarly it would probably be more effective with

TABLE 69. Horizontal profiles of C^{14} concentration (10^5 atoms/gm air) at 20 km altitude during 1963-1967

Time Interval	70°N	60°N	50°N	40°N	30°N	20°N	10°N	0°	10°S	20°S	30°S	40°S	50°S
May-Aug 1963	1795(1)	1482(2)	1323(3)	1362(4)	-	690(8)	*456(9)	-	-	-	-	-	-
Sep-Dec 1963	1267(9)	1179(15)	1164(15)	1120(10)	*958(1)	716(29)	*434(4)	-	-	-	-	-	-
Jan-Apr 1964	932(8)	1064(8)	972(8)	873(9)	-	542(19)	*290(6)	-	-	-	-	-	-
May-Aug 1964	633(3)	737(2)	664(6)	660(2)	-	391(4)	*321(8)	-	-	-	-	-	-
Sep-Dec 1964	660(2)	402(3)	556(4)	612(2)	-	304(6)	*249(8)	-	-	-	-	-	-
Jan-Apr 1965	479(2)	477(3)	490(3)	442(3)	442(4)	318(4)	126(1)	-	-	-	-	-	-
May-Aug 1965	442(1)	430(2)	412(2)	432(2)	345(3)	189(1)	205(1)	-	-	-	-	-	-
Sep-Dec 1965	-	379(2)	433(1)	337(4)	341(2)	164(2)	144(3)	-	-	-	-	-	-
Jan-Apr 1966	244(2)	333(3)	282(1)	320(3)	-	208(2)	143(2)	-	-	-	-	-	-
May-Aug 1966	301(2)	303(1)	265(2)	286(2)	264(2)	128(1)	*116(6)	-	-	83(1)	-	-	-
Sep-Dec 1966	-	-	-	237(1)	219(1)	152(2)	-	86(1)	88(1)	115(2)	111(1)	-	-
Jan-Apr 1967	257(1)	-	-	196(2)	-	144(2)	147(1)	90(1)	-	92(1)	142(1)	143(4)	130(1
May-Aug 1967	227(1)	197(1)	-	235(1)	-	-	-	-	-	-	-	148(1)	-

* ANL data

Numbers in parentheses indicate number of samples averaged.

TABLE 70. Atmospheric Burden of Excess Carbon-14 (in units of 10^{27} atoms)

Time Interval	Northern Hemisphere			Southern Hemisphere			Total Atmosphere		
	Strato	Tropo	Total	Strato	Tropo	Total	Strato	Tropo	Total
Jan-Apr 1963	31±10	11±4	42±11	5±3	9±3	14±4	36±10	20±5	56±12
May-Aug 1963	25±8	13±4	38±9	5±3	9±3	14±4	30±9	22±5	52±10
Sep-Dec 1963	20±5	14±4	34±6	6±3	10±3	16±4	26±6	24±5	50±8
Jan-Apr 1964	21±5	14±4	35±6	6±3	10±3	16±4	27±6	24±5	51±8
May-Aug 1964	14±5	15±5	29±6	6±3	11±4	17±5	20±6	26±6	46±8
Sep-Dec 1964	12±4	14±4	26±6	6±3	11±4	17±5	18±5	25±6	43±8
Jan-Apr 1965	11±3	14±4	25±5	6±3	11±4	17±5	17±4	25±6	42±7
May-Aug 1965	10±3	14±4	24±5	6±3	13±4	19±5	16±4	27±6	43±7
Sep-Dec 1965	9±3	14±4	23±5	6±3	13±4	19±5	15±4	27±6	42±7
Jan-Apr 1966	9±3	14±4	23±5	6±3	13±4	19±5	15±4	27±6	42±7
May-Aug 1966	8±3	13±4	21±5	6±3	12±4	18±5	14±4	25±6	39±7
Sep-Dec 1966	7±3	13±4	20±5	5±3	13±4	18±5	12±4	26±6	38±7
Jan-Apr 1967	7±3	12±4	19±5	5±3	13±4	18±5	12±4	25±6	37±7
May-Jun 1967	7±3	12±4	19±5	5±3	12±4	17±5	12±4	24±6	36±7

debris from surface burst than with debris from air bursts, and more effective with debris from megaton yield bursts than with debris from multimegaton yield bursts, assuming that the average particle size of the stratospheric debris produced decreases going from surface bursts to air bursts and from lower yield to higher yield events. On the other hand, the higher the altitude of injection of the debris, the more effective will particle settling be in separating particulate debris from gaseous debris.

Using the distributions presented in the aforementioned tables and ANL data to estimate distribution of carbon-14 in the stratosphere above 20 km, and in the Southern Hemisphere, atmospheric burdens of excess carbon-14 have been calculated and are presented in Table 71, and displayed graphically in Figure 64. While the data show a decrease in the total atmospheric burden, the rate of decrease was not constant. In 1963 through 1964 the stratospheric residence half-time was about 15 months, and for the troposphere about 11 months. By 1966 to 1967, however, these values had increased to 57 months for the stratosphere and 45 months for the troposphere. The average rate for the total atmosphere from 1963 through 1967 is about 95 months. The change in rate of decrease probably resulted from depletion of initially high carbon-14 concentrations in the lower stratosphere and/or an increase in the concentration in the troposphere.

TABLE 71. Trends with time in the Sr^{90} concentration (pCi/100SCM) at 70°N-65°N, 25°N, 35°S and 35°S-40°S

Time Interval		65°N 15km	65°N 19-21km	25°N 17km	25°N 19-21km	35°S 17km	35°S 19-21km
Nov-Dec	1957	-	142 (1)	118 (7)	345 (9)	-	-
Jan-Feb	1958	590 (1)	-	60 (7)	235 (4)	-	-
Mar-Apr	1958	-	103 (2)	72 (15)	254 (16)	-	-
May-Jun	1958	-	-	167 (6)	205 (3)	-	-
Jul-Aug	1958	-	-	-	-	-	-
Sep-Oct	1958	-	142 (4)	167 (4)	-	97 (1)	205 (1)
Nov-Dec	1958	415 (1)	73 (2)	114 (3)	601 (2)	124 (5)	118 (2)
Jan-Feb	1959	-	-	29 (3)	369 (9)	36 (6)	87 (6)
Mar-Apr	1959	173 (1)	-	95 (8)	347 (18)	40 (4)	94 (7)
May-Jun	1959	199 (2)	378 (11)	68 (10)	332 (22)	43 (2)	116 (7)
Jul-Aug	1959	205 (2)	302 (3)	-	310 (40)	73 (2)	156 (5)
Sep-Oct	1959	142 (8)	294 (22)	-	264 (18)	-	-
Nov-Dec	1959	213 (7)	292 (17)	75 (2)	242 (13)	-	-
Jan-Feb	1960	184 (6)	374 (8)	68 (1)	253 (10)	-	-
Mar-Apr	1960	199 (4)	310 (10)	-	238 (10)	-	-
May-Jun	1960	146 (11)	329 (11)	44 (1)	245 (1)	-	221 (3)
Jul-Aug	1961	-	-	-	146 (3)	-	-
Sep-Oct	1961	-	-	-	175 (3)	-	221 (1)
Nov-Dec	1961	-	-	-	413 (3)	-	168 (1)
Jan-Feb	1962	870 (5)	189 (5)	78 (3)	374 (3)	-	-
Mar-Apr	1962	1360 (6)	172 (7)	75 (1)	485 (3)	-	172 (2)
May-Jun	1962	990 (8)	641 (9)	728 (5)	607 (6)	-	-
Jul-Aug	1962	1000 (5)	445 (7)	331 (3)	825 (8)	-	-
Sep-Oct	1962	-	561 (7)	-	-	204 (1)	226 (2)
Nov-Dec	1962	2290 (3)	3650 (3)	617 (1)	3570 (1)	127 (2)	264 (2)

(Number of samples represented by each average given in parenthesis)

TABLE 71. (continued)

Time Interval		70°N - 65°n 17km	70°N - 65°n 19-21km	25°N 17km	25°N 19-21km	35°S - 40°S 17km	35°S - 40°S 19-21km
Jan-Feb	1963	2850 (8)	4040 (11)	318 (3)	3900 (3)	64 (4)	176 (9)
Mar-Apr	1963	3070 (13)	2830 (5)	223 (4)	2380 (4)	91 (3)	176 (6)
May-Jun	1963	1700 (12)	2500 (14)	544 (2)	2290 (4)	95 (4)	172 (6)
Jul-Aug	1963	1420 (8)	2450 (10)	785 (3)	2370 (3)	95 (4)	258 (6)
Sep-Oct	1963	1090 (9)	1920 (11)	501 (5)	1940 (5)	180 (7)	572 (7)
Nov-Dec	1963	1110 (7)	1110 (7)	347 (4)	1700 (4)	164 (7)	447 (7)
Jan-Feb	1964	1100 (8)	1010 (7)	450 (3)	1390 (4)	118 (9)	356 (10)
Mar-Apr	1964	992 (10)	757 (10)	331 (5)	1010 (4)	162 (5)	348 (7)
May-Jun	1964	704 (3)	730 (3)	208 (2)	884 (2)	210 (4)	388 (4)
Jul-Aug	1964	566 (4)	649 (4)	240 (1)	731 (2)	168 (3)	292 (4)
Sep-Oct	1964	539 (4)	607 (2)	162 (1)	719 (1)	230 (5)	234 (4)
Nov-Dec	1964	593 (4)	518 (1)	-	-	156 (4)	194 (4)
Jan-Feb	1965	469 (4)	547 (2)	-	509 (2)	140 (4)	188 (5)
Mar-Apr	1965	258 (4)	348 (2)	52 (2)	431 (1)	43 (3)	127 (3)
May-Jun	1965	250 (4)	-	127 (2)	323 (2)	97 (6)	140 (3)
Jul-Aug	1965	273 (3)	343 (2)	67 (2)	407 (2)	92 (3)	162 (4)
Sep-Oct	1965	218 (4)	316 (4)	41 (1)	302 (2)	95 (4)	165 (3)
Nov-Dec	1965	191 (2)	178 (2)	29 (2)	245 (2)	83 (4)	143 (3)
Jan-Feb	1966	161 (1)	193 (4)	46 (1)	170 (2)	-	-
Mar-Apr	1966	162 (3)	149 (2)	10 (1)	160 (2)	68 (3)	100 (1)
May-Jun	1966	-	-	54 (4)	151 (3)	-	-
Jul-Aug	1966	102 (2)	137 (2)	56 (3)	144 (2)	84 (2)	80 (1)
Sep-Oct	1966	-	-	15 ([illegible])	123 (2)	77 (1)	96 (1)
Nov-Dec	1966	106 (2)	80 (2)	15 (2)	115 (2)	44 (2)	58 (2)
Jan-Feb	1967	76 (2)	90 (1)	6.3 (3)	81 (1)	54 (2)	56 (2)
Mar-Apr	1967	58 (3)	34 (3)	8. (2)	66 (3)	32 (3)	59 (3)
May-Jun	1967	35 (1)	49 (1)	18 (1)	41 (1)	38 (1)	33 (1)

(Number of samples represented by each average given in parenthesis)

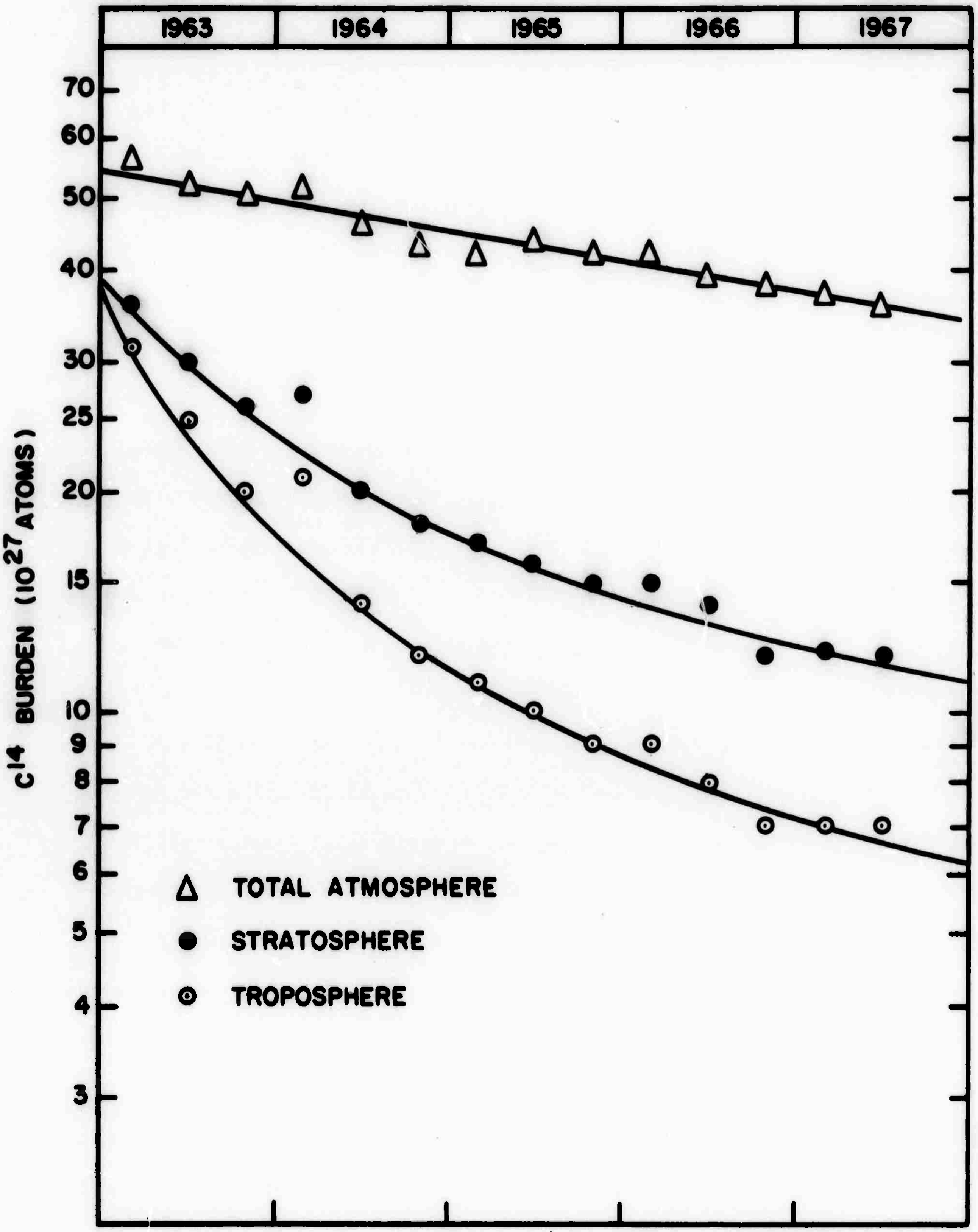

FIG. 64 TRENDS IN THE ATMOSPHERIC BURDEN OF EXCESS CARBON-14.

7.5 The Transport of Particulate Radioactivity from Low Altitude Bursts

Strontium-90 represents a conservative tracer of the movement of particulate radioactivity injected into the stratosphere by nuclear weapons tests: its half-life is long compared to its residence time in the stratosphere. Atmospheric tests of megaton-yield devices have, since 1952, injected large amounts of strontium-90 into the stratosphere. The 1961 - 1962 test series produced especially large injections.

Typically, within about a month following an injection, "clouds" of high concentrations of radioactivity were intercepted by STARDUST flights. Commonly the debris was unevenly distributed with longitude as well as latitude (not well mixed in a zonal direction) for several months immediately following injection. During these periods, the concentrations of radioactive debris found varied greatly from one sampling mission to the next as different air masses with different concentrations were intercepted. Usually by the end of three or four months, however, mixing in the zonal direction had progressed, and concentrations found from one mission to another, at least at altitudes well above the tropopause, tended to agree within 50% of each other. Thereafter, unless new injections occurred, the main trend in concentration was a continuing decrease, partially due to mixing of the debris into other regions of the stratosphere, but mainly due to transfer of debris to the troposphere and its subsequent removal from the atmosphere by fallout.

The trends with time in the concentration of strontium-90 at several locations in the stratosphere are given in Table 71. The data for 1957 - 1960 reflect injections from several sources including U.S.S.R. and U.K. tests in 1957, U.S. tests of mid-1958, and late 1958 U.S.S.R. tests. From 1959 until late 1961 a moratorium on nuclear tests in the atmosphere was observed. In late

1961, however, testing was resumed and included tests by the U.S.S.R. of very high yield devices. In mid-1962, U.S. tests injected debris into the tropical stratosphere, and significant amounts of this debris reached 30°S in late 1963. Penetration of debris from these tests into the Northern Hemisphere was masked by very high concentrations of debris introduced into the stratosphere of the Northern Hemisphere by the series of U.S.S.R. tests which took place in late 1962.

With the exception of the 1966 Chinese test, (see discussion in Chapter 8), there were no significant injections into the stratosphere between 1963 and 1967. The decrease in concentrations which took place during this period gave, then, a good measure of stratospheric residence times of particulate debris injected into the lower stratosphere.

Vertical profiles of strontium-90 concentrations at four latitudes at which balloon sampling was performed by the A.E.C. as well as aircraft sampling for Project STARDUST are shown in Tables 72 to 75. It is apparent from these data that a layer of maximum concentration existed which sloped downwards from the equatorial regions towards the polar latitudes. At 10°N, maximum concentrations were found at 24 km (Table 74). At 30° - 35°N and 65° - 70°N highest activities were found at altitudes of 20 and 18 km respectively (Tables 72, 73). Table 75 shows that at 34° - 40°S the layer of maximum concentration was, again, at about 20 km. Maximum concentrations have generally been found at the upper limits of aircraft sampling at mid-latitudes, and above those altitude limits at 10°N. It has been suggested that problems associated with balloon calibrations cause underestimates of concentrations in the upper stratosphere, and that the maximum concentration is actually at high altitude at all latitudes. The presence of the maximum below 20 km at 65° - 70°N,

TABLE 72. Vertical profiles of Sr^{90} Concentrations (pCi/100 SCM) at 65° - 70°N, 1963 - 1967

	Altitude (km)						
	12	15	17	18	20	24	32
July 63	470(5)	1670(9)	2180(11)	2890(12)	2340(17)	985	795
July 64	250(1)	596(6)	734(4)	923(5)	722(5)	165	80
July 65	-	298(2)	291(2)	322(3)	295	107(4)	29(3)
July 66	-	107(1)	154(1)	168(1)	148(1)	45(3)	8(3)
May 67	-	35(1)	59(1)	-	49(1)	-	-

TABLE 73. Vertical profiles of Sr^{90} Concentrations (pCi/100 SCM) at 30° - 35°N, 1963 - 1967

	Altitude (km)						
	12	15	17	18	20	24	32
July 63	6(3)	64(1)	1220(5)	2300(7)	2480(6)	2070	540
July 64	3(2)	162(2)	324(4)	456(2)	810(6)	795	97
July 65	-	4	54(1)	143	440(1)	177(6)	45(4)
July 66	-	15(4)	68(3)	113(6)	152(1)	132(3)	15(4)
May 67	-	5(4)	18(2)	48(3)	-	-	-

TABLE 74. Vertical profiles of Sr^{90} Concentrations (pCi/100 SCM) at 10°N, 1963 - 1967

	Altitude (km)					
	15	17	18	20	24	32
Oct 63	17(1)	268(5)	572(4)	1650(7)	-	-
Oct 64	-	-	453(1)	588(2)	890	248
Apr 65	-	-	100(1)	186(7)	642(3)	126(3)
Sep 65	-	-	127(1)	248(1)	399(1)	37(1)
Mar 66	3(1)	10(1)	52(1)	128(1)	279(4)	37(4)
Oct 66	1(1)	10(1)	95(1)	104(1)	-	-
Mar 67	0.9(2)	5(1)	49(1)	70(1)	-	-

(Number of samples represented by each average given in parenthesis)

TABLE 75. Vertical profiles of Sr^{90} Concentrations (pCi/100 SCM) at 34° - 40°S, 1963-1967

	Altitude (km)						
	12	15	17	18	20	24	32
July 63	46(4)	98(3)	96(4)	215(5)	269(6)	429	104
July 64	81(2)	-	202(4)	305(3)	320(8)	286	80
July 65	-	-	98(2)	146(3)	182(2)	127(3)	42(2)
July 66	15(1)	60(1)	88(1)	-	-	61(4)	17(1)
Mar 67	-	27(2)	37(2)	51(2)	47(1)	-	-

(Number of samples represented by each average given in parenthesis)

within the altitude limits of aircraft, and its gradual slope upwards towards the equator, indicates that such a suggestion is probably incorrect, and that the profiles in Tables 72 to 75 represent the real distribution.

It seems quite significant that concentrations decreased rapidly with time at high altitude, above the layer of maximum concentration, as they did in the lower stratosphere. Upward mixing cannot explain the decreases at 24 to 32 km, since there is very little air above 32 km to accommodate debris which might leave the 20 to 32 km layer. Neither does it seem that the concentration increased sufficiently in the Southern Hemisphere to hypothesize that the debris had been transported across the equator. The debris that entered the Southern Hemisphere in late 1963, (Table 71), appeared to have come from the 1962 U.S. tests (based on its content of neutron activation products: Mn^{54}, Fe^{55}, etc.), while the debris which was removed from the 20 - 32 km layer at 65° - 70°N and 30° - 35°N was apparently derived mainly from the 1962 U.S.S.R. tests. It appears most likely that concentrations in the regions above the layer of maximum concentration decreased as a result of particle settling. This would permit the debris to move downward against the concentration gradient and into the lower stratosphere without causing the layer of maximum concentration to disappear.

Horizontal profiles of strontium-90 concentrations at an altitude of 20 km for a sequence of intervals during 1961 to 1967 are shown in Tables 76 to 78. In March of 1962, following the 1961 series of U.S.S.R. tests, highest concentrations were found at about 17 km at high latitude, and the layer of maximum concentration sloped upwards above the 20 km level only at mid-latitudes. By August 1962, concentrations at all latitudes had increased due in part (at low latitudes) to 1962 U.S. tests, and in part (at high latitude)

TABLE 76. Horizontal profiles of Sr^{90} Concentrations (pCi/100 SCM) at 20 km 1961 - 1962

	Sep. 1961	Mar. 1962	Aug. 1962	Dec. 1962	Jan. 1963
70°N	-	170(4)	528(5)	1960(2)	9620(3)
60°-65°N	154(2)	198(12)	572(5)	3630(5)	4630(10)
50°-55°N	206(4)	208(13)	537(4)	3360(6)	4940(6)
40°-45°N	193(1)	505(9)	834(1)	3900(18)	4070(9)
30°-35°N	-	403(8)	857(5)	3530(15)	3360(6)
20°-25°N	-	400(2)	860(8)	3080(5)	4990(9)
10°-15°N	-	340(4)	906(1)	2600(3)	2340(5)
0°-5°N	-	229(2)	-	-	1400(5)
0°-5°S	-	137(2)	-	-	690(3)
10°-15°S	-	91(1)	-	280(1)	308(3)
20°-25°S	-	121(1)	-	271(2)	259(5)
30°-35°S	-	184(1)	-	280(2)	259(5)
40°-45°S	-	140(2)	-	-	103(1)
50°-55°S	-	130(4)	-	-	-
60°S	-	121(2)	-	-	-

(Number of samples represented by each average given in parenthesis)

TABLE 77. Horizontal profiles of Sr^{90} Concentrations (pCi/100 SCM) at 20 km 1963 - 1964

	Jan. 1963	Mar. 1963	Sep. 1963	Mar. 1964	Sep. 1964
70°N	9620(3)	3220(5)	2070(4)	810(5)	565(1)
60°-65°N	4630(10)	2670(13)	2180(8)	850(9)	560(3)
50°-55°N	4940(6)	2880(10)	2270(4)	900(4)	635(3)
40°-45°N	4070(9)	2780(2)	2680(2)	1040(4)	790(1)
30°-35°N	3360(6)	2510(5)	2290(6)	1000(9)	747(3)
20°-25°N	4990(9)	2040(8)	2060(14)	1100(13)	702(4)
10°-15°N	2340(5)	1630(14)	2000(6)	1080(4)	682(2)
0°-5°N	1400(5)	830(8)	1170(4)	723(4)	563(1)
0°-5°S	690(3)	426(3)	1170(4)	723(4)	563(1)
10°-15°S	308(3)	293(5)	865(9)	533(10)	403(2)
20°-25°S	259(5)	175(2)	624(12)	323(6)	242(1)
30°-35°S	259(5)	180(5)	611(7)	255(11)	226(2)
40°-45°S	103(1)	199(1)	600(5)	358(7)	229(2)
50°-55°S	-	-	600(4)	-	-
60°S	-	-	522(3)	-	-

(Number of samples represented by each average given in parenthesis)

TABLE 78. Horizontal profiles of Sr^{90} Concentrations (pCi/100 SCM) at 20 km 1964 - 1967

	Sep. 1964	May 1965	Jun. Jul. 1966	Mar. 1967
70°N	565(1)	-	-	18(1)
60°-65°N	560(3)	-	-	32(2)
50°-55°N	635(3)	288(2)	180(1)	68(3)
40°-45°N	790(1)	288(2)	180(1)	77(2)
30°-35°N	747(3)	317(1)	135(3)	-
20°-25°N	702(4)	317(1)	152(2)	-
10°-15°N	682(2)	-	-	70(1)
0°-5°N	563(1)	180(1)	134(1)	-
0°-5°S	563(1)	180(1)	134(1)	6(2)
10°-15°S	403(2)	180(1)	94(1)	42(1)
20°-25°S	242(1)	119(2)	94(1)	42(1)
30°-35°S	226(2)	119(2)	94(1)	45(2)
40°-45°S	229(2)	102(2)	-	47(1)
50°-55°S	-	102(2)	-	47(1)

(Number of samples represented by each average given in parenthesis)

to appearance of debris from a very high yield U.S.S.R. detonation on 23 October 1962 (as indicated by high concentrations of neutron activation products - see discussion to follow). Late 1962 U.S.S.R. test series produced extremely high concentrations in the north polar stratosphere by December of that year, and January of 1963. High strontium-90 concentrations were found as far south as 15°N soon after this series, though as noted above, carbon-14 concentrations at low latitudes never approached those found at high latitudes. This suggests that some mechanism separated particulate debris from gaseous debris as it moved southward. Particle settling appears to be the most likely process that would accomplish this separation: gaseous material would rise above 20 km with air as air moved equatorward, but particles would tend to settle out into lower layers as the air rose.

As late as March, 1963, a steep concentration gradient existed across the tropical stratosphere. Concentrations at 30° - 35°N were 2510 pCi per 100 SCM, while at corresponding latitudes in the Southern Hemisphere they were only 180 pCi per 100 SCM. By September of the same year the concentrations at 30° - 35°N were 2290 pCi per 100 SCM, a reduction of about 11 percent. At 30° - 35°S at this time, however, the concentration had increased by a factor of more than three to a level of 611 pCi per 100 SCM. This increase, and the resulting decrease in the gradient suggest a period of rapid transport across the equator. The new gradient was preserved until at least May, 1965, as fallout proceeded with equal percentage depletion in both hemispheres. Within a year the gradient was much diminished with concentrations at the respective latitudes mentioned of 135 vs. 95 pCi per 100 SCM. This further decrease was, perhaps, the result of another occurence of rapid transport across the equator, though it is not possible to document such an occurrence. A short interval of rapid trans-equatorial transfer had been suggested previously from data from Project HASP (see Chapter 6), which indicated such a process in mid-1959.

The mean distribution of strontium-90 in the stratosphere as a function of latitude and altitude is portrayed in Figures 65 to 71 for various time intervals between 1961 and 1967. In these figures, the meridional plane shown represents the STARDUST sampling corridor. As is evident from the data on distribution of concentrations during June to September 1961, the testing moratorium of 1959 to 1961 had allowed time for most of the debris from the 1952 to 1958 tests to be removed from the stratosphere. That testing had resumed is shown clearly in the distributions of October to December, 1961. Concentrations of strontium-90 were increasing greatly, reflecting measurements of debris from the early October U.S.S.R. tests, rather than residual material from late 1959 events. Comparison of distributions during late 1961 and early 1962 (Figures 65, 66), suggest that patterns of winter circulation of the stratosphere established in the fall of 1961 did not permit southward migration of the debris from the late October tests into regions sampled by STARDUST missions. (A similar observation was made regarding debris from the 1958 U.S.S.R. test during Project HASP, see Chapter 6). The January to April, 1962 distributions displayed in the upper half of Figure 66, show that most debris was below the 20 km level in the polar stratosphere. Since only a few months had elapsed between injection and sampling, it seems likely that this represents initial vertical distribution rather than greatly modified distribution. The U.S. tests in mid-1962 resulted in injections into the tropical stratosphere, and raised concentrations of strontium-90 there, as is shown in the lower half of Figure 66. At an altitude of 18 to 20 km there appears to be little spread poleward during the few months including and following the tests, but at an altitude of 15 to 17 km there was a rapid poleward movement of debris from one or two tests. This rapid movement at these latter heights is evidenced by the interception of

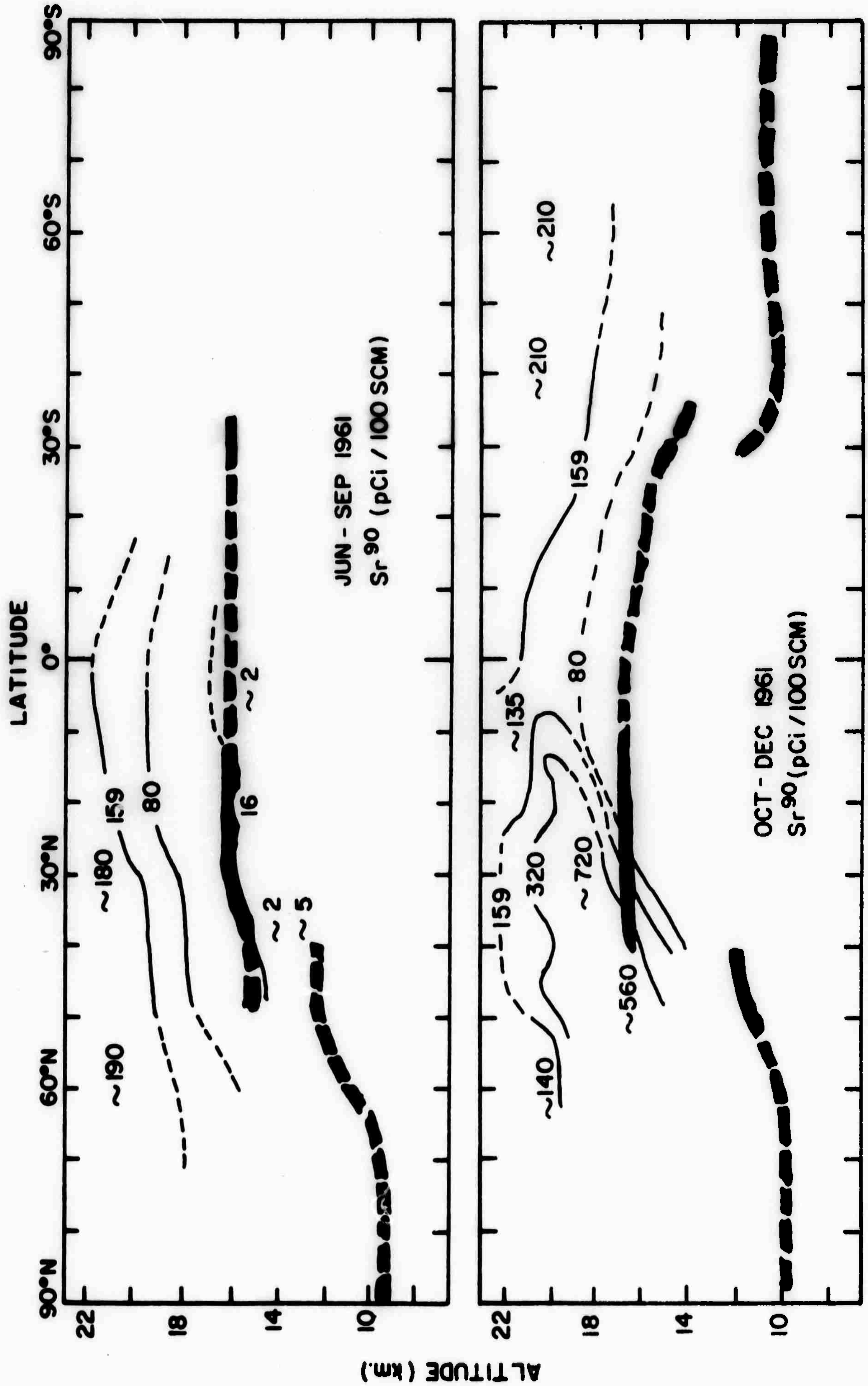

FIGURE 65. DISTRIBUTION OF STRONTIUM-90 IN THE STARDUST SAMPLING CORRIDOR DURING JUNE-SEPTEMBER 1961 AND OCTOBER-DECEMBER 1961.

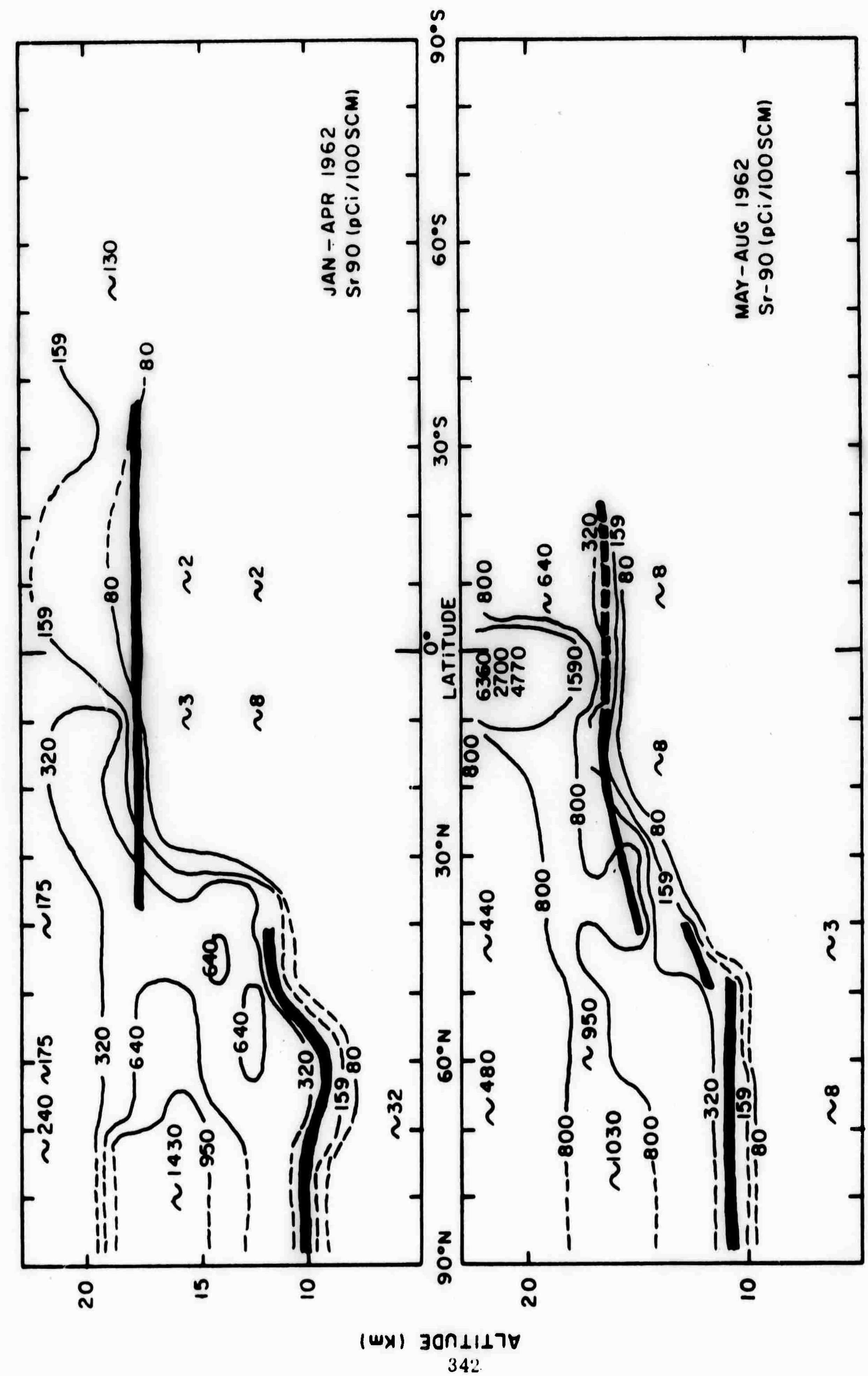

FIGURE 66. DISTRIBUTION OF STRONTIUM-90 IN THE STARDUST SAMPLING CORRIDOR, JANUARY TO APRIL AND MAY TO AUGUST 1962

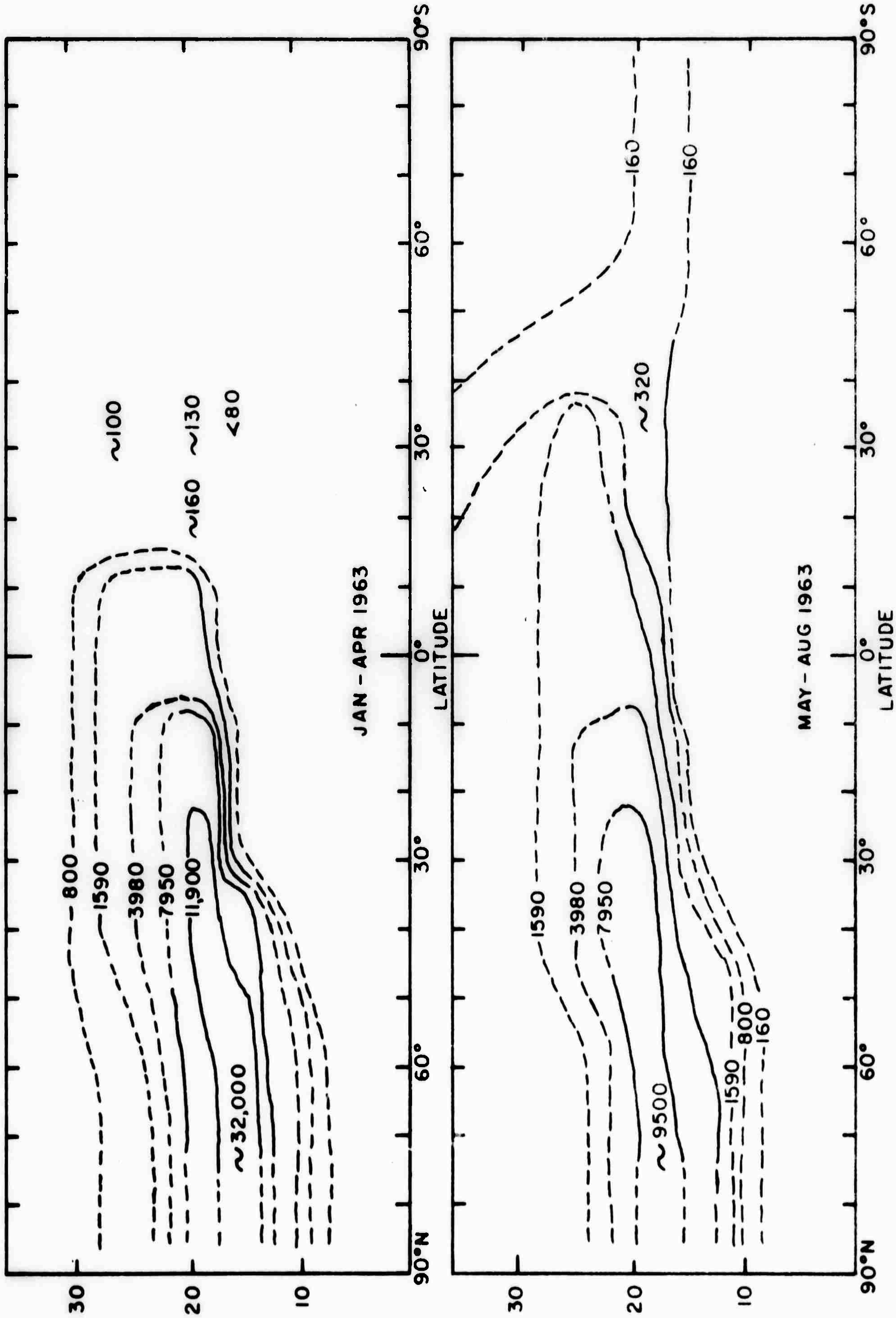

FIGURE 67. THE MEAN DISTRIBUTION OF MANGANESE 54 (pCi/100SCM,corr. for decay to 31 Dec 1962) DURING JAN - APR 1963 AND MAY - AUG 1963

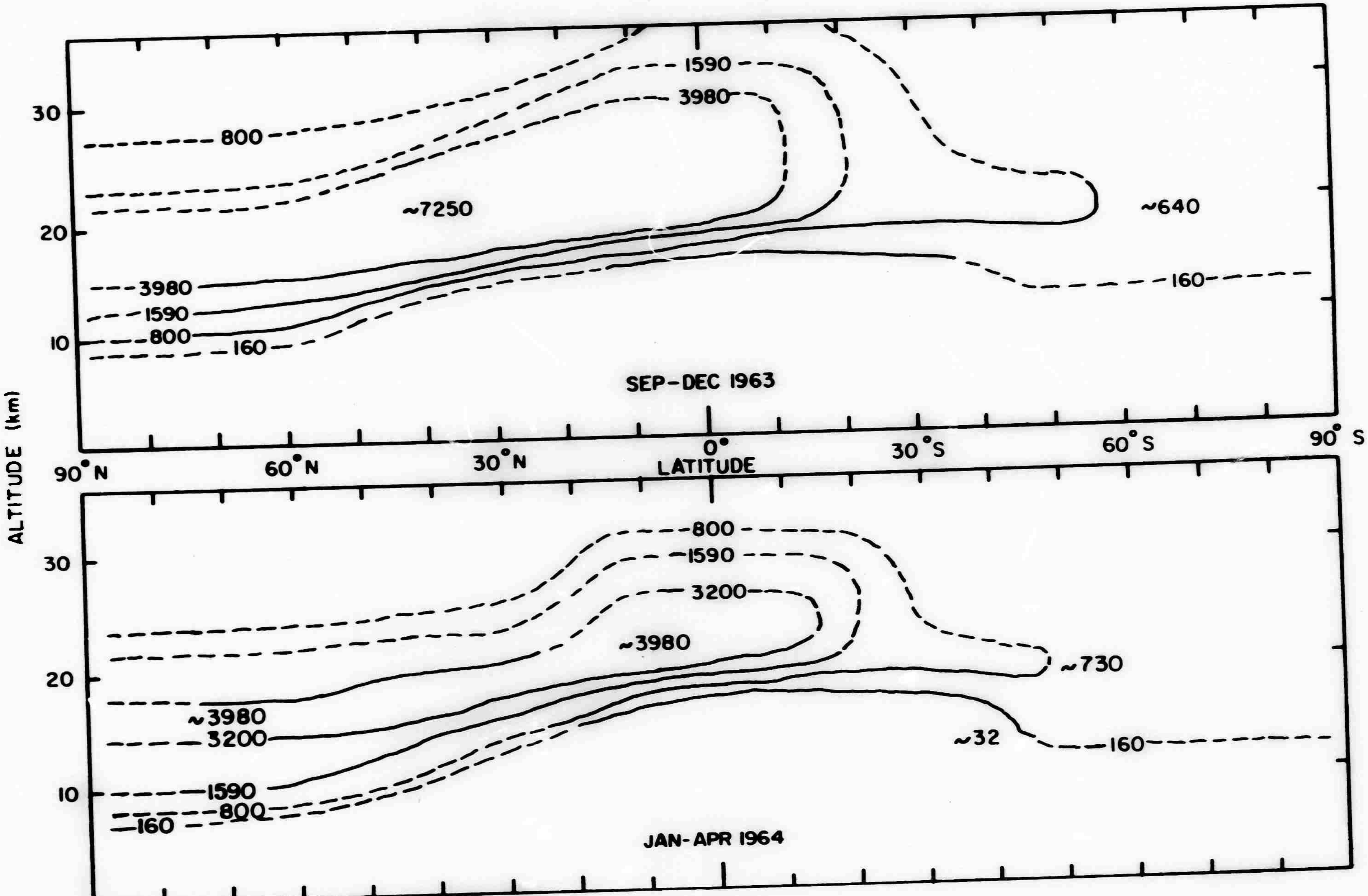

FIGURE 68. THE MEAN DISTRIBUTION OF MANGANESE-54 (pCi/100 SCM corr. for decay to 31 Dec 1962) DURING SEP - DEC 1963 AND JAN - APR 1964.

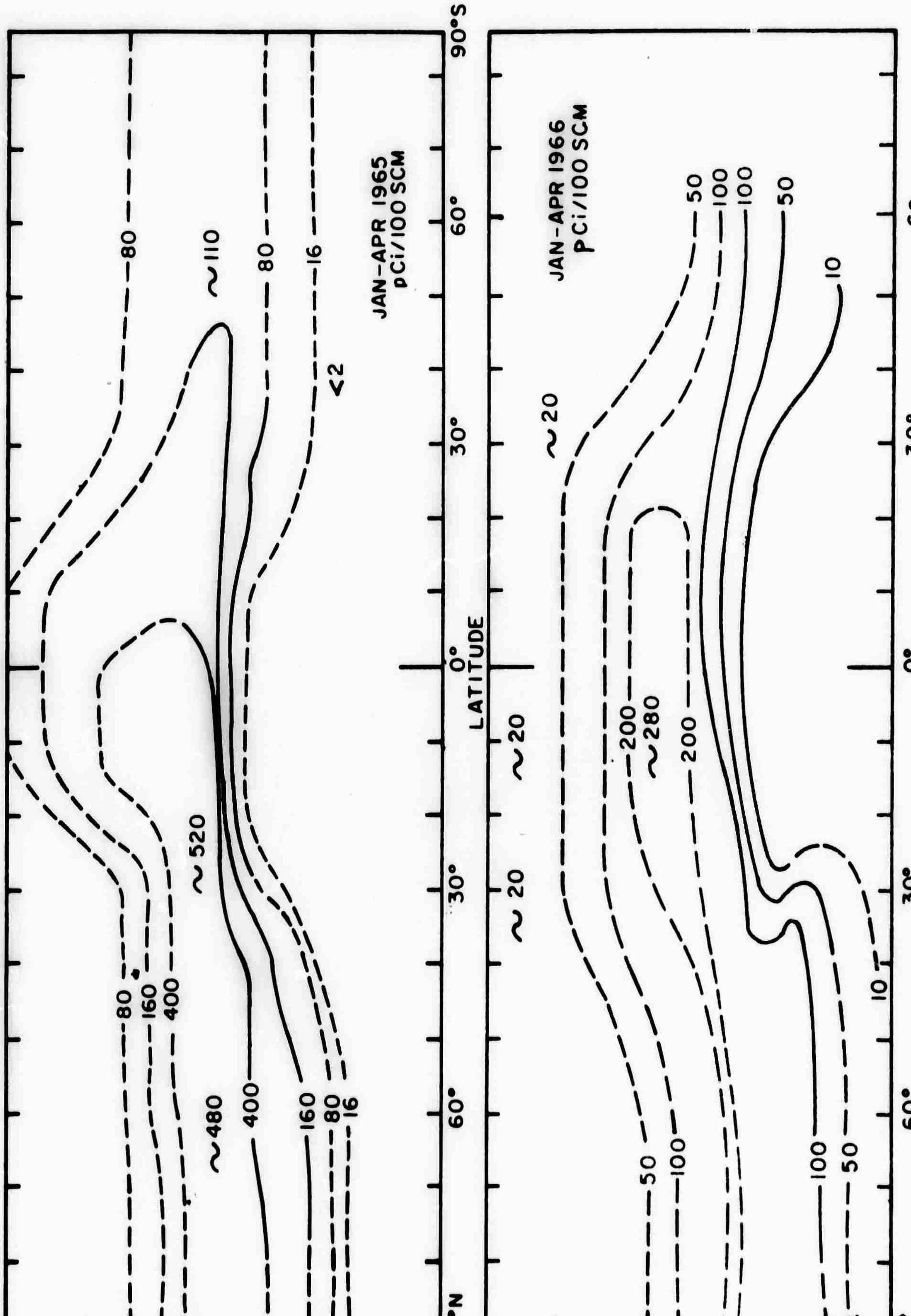

FIGURE 69. THE MEAN DISTRIBUTION OF STRONTIUM-90 DURING JAN-APR 1965 AND JAN-APR 1966

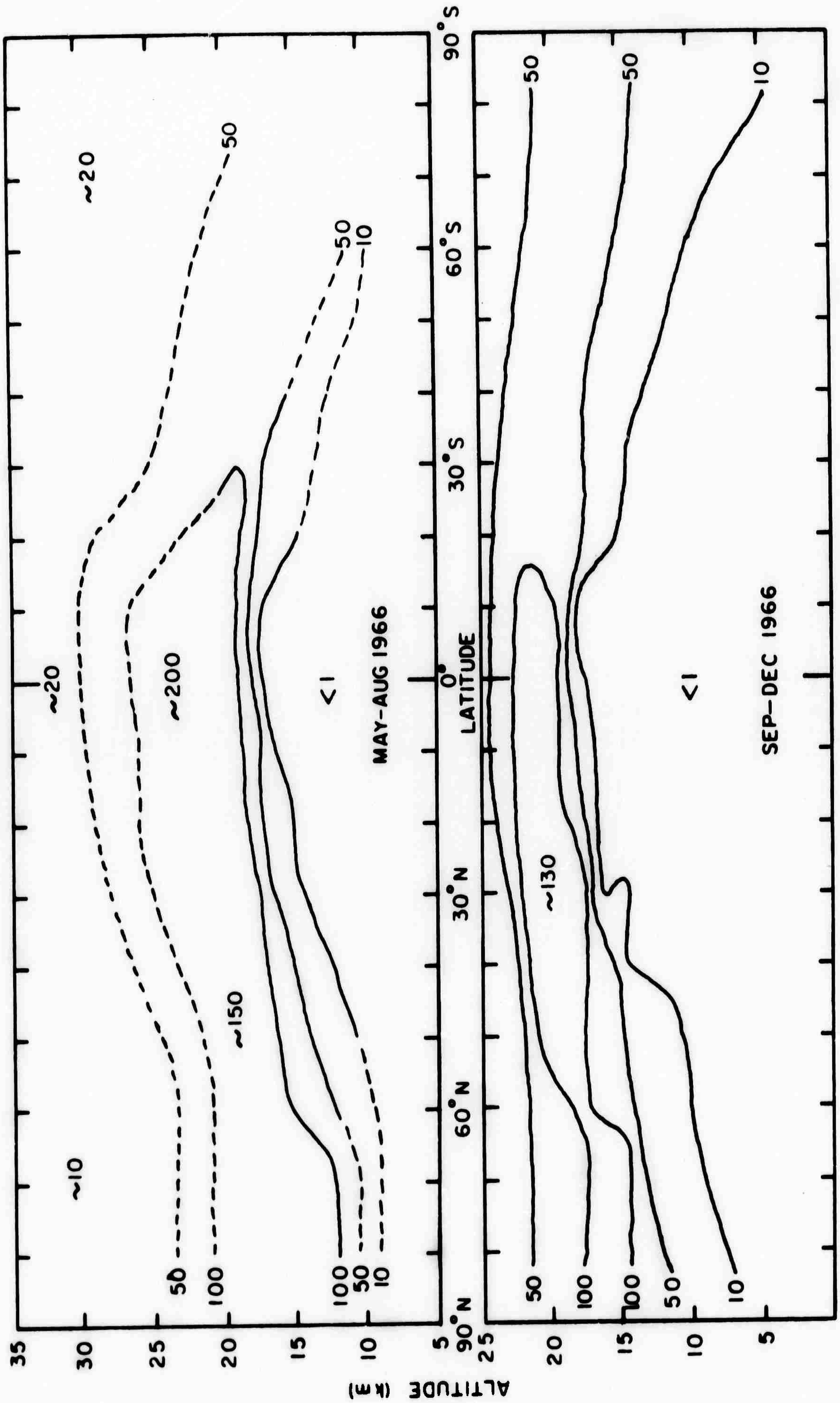

FIGURE 70. DISTRIBUTION OF Sr^{90} IN THE STARDUST SAMPLING CORRIDOR MAY - AUG, SEP - DEC, 1966.

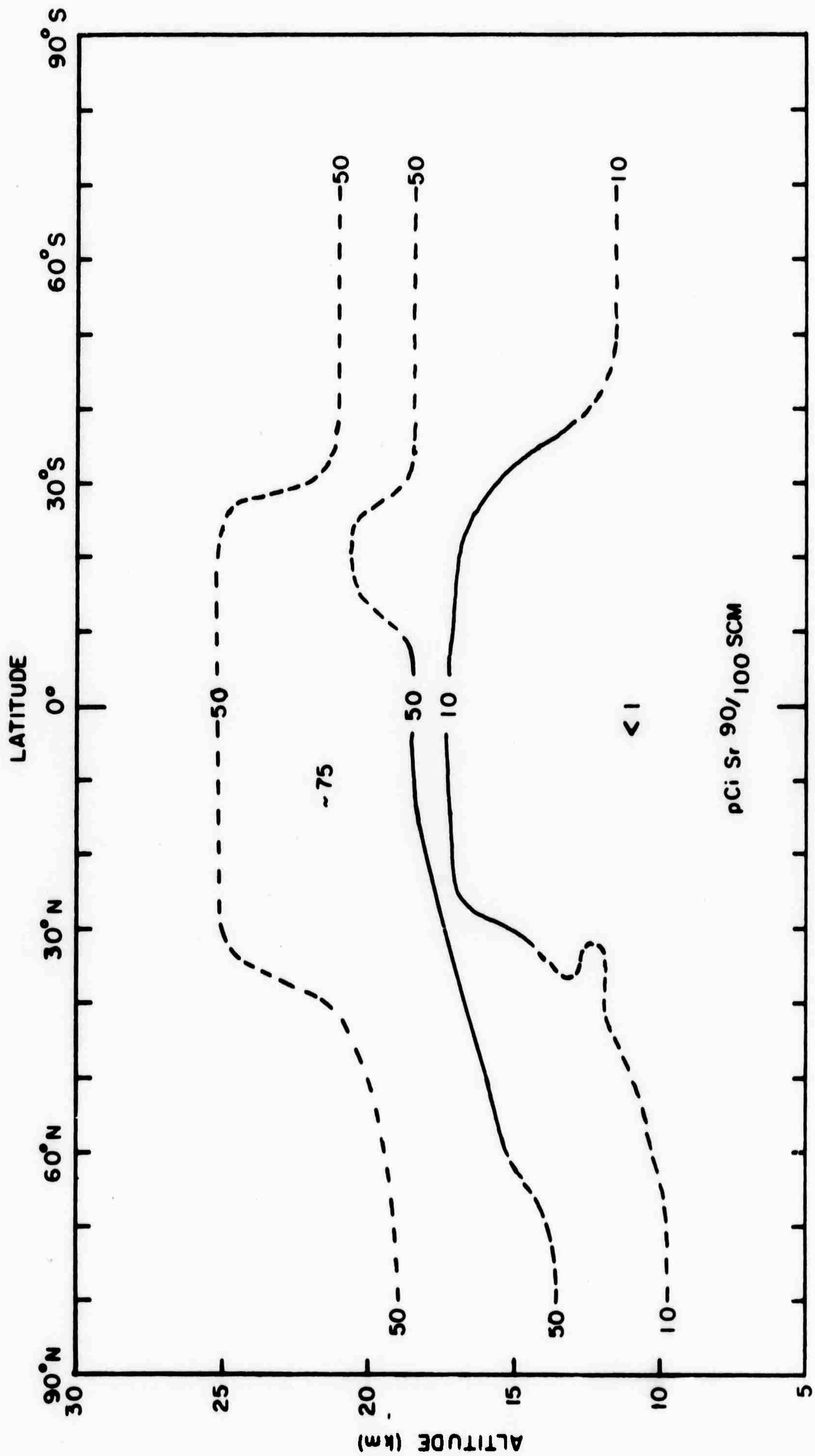

FIGURE 71. DISTRIBUTION OF Sr^{90} IN THE STARDUST SAMPLING CORRIDOR JAN - JUN 1967

debris from the tests at 30° to 40°N less than a week after the events. Except for occasions such as this, and then generally at lower altitudes, debris in the stratosphere was usually retained in equatorial regions very close to the latitude of injection. By mid-1962, concentrations in the Northern Hemisphere polar stratosphere rose significantly. The increase in strontium-90 content here is attributed to debris from high yield U.S.S.R. tests entering the STARDUST sampling corridors. The source of most of this material was identified as the U.S.S.R. tests on the basis of high values for the neutron activation products manganese-54 and iron-55 found in samples from these latitudes during the period (see discussion of activation products below). During late 1962 a series of high yield thermonuclear events performed by the U.S.S.R. injected large amounts of fission products into the northern polar stratosphere. As a result, extremely high concentrations of strontium-90 were found throughout the stratosphere of the Northern Hemisphere by December 1962 and January 1963.

During 1963 to 1967 concentrations decreased throughout the stratosphere. As had been observed previously, however, a layer of maximum concentration persisted, sloping from an altitude of 20 to 24 km in equatorial regions downwards to about 18 km in the polar regions of the Northern Hemisphere. The continuing removal of strontium-90 from the stratosphere resulted in lowering of concentrations in the northern polar stratosphere to the point where the highest values at these latitudes were comparable to those in the tropical stratosphere at altitudes greater than 20 km, and by 1966 the highest northern polar stratosphere values were significantly less than those in the tropical latitudes above 20 km.

High yield devices such as those tested during the late 1961 - 1962 series normally produce significant amounts of radionuclides by neutron activation of materials used in their construction. The principal nuclides produced by neutron activation which were measured and discussed here were manganese-54, iron-55 and antimony-124. Possible mechanisms for their production include:

$Fe^{54}(n,\gamma)\ Fe^{55}$ $\quad$ $Fe^{56}(n,2n)\ Fe^{55}$ $\quad$ $Sb^{123}(n,\gamma)\ Sb^{124}$

$Fe^{54}(n,p)\ Mn^{54}$ $\quad$ $Mn^{55}(n,2n)\ Mn^{54}$

Some of the devices tested in 1961 to 1962 produced especially large amounts of neutron activation products, as might be expected from high yield experiments, and many samples collected beginning in January 1962 contained high concentrations of manganese-54, iron-55 and antimony-124. This is in contrast to samples collected during October to December, 1961 which contained much fission debris from the early October U.S.S.R. tests but relatively little manganese-54 and iron-55, and no significant antimony-124. After April 1962, many samples from the north polar stratosphere contained high levels of neutron activation debris. This material in these samples has commonly been attributed to the very high yield devices tested on 23 October 1961 (about 25 megatons, and 30 October 1961 (55 - 60 megatons). It is noteworthy that only the 30 October 1961 event has been characterized as having a relatively small fission yield (see Table 32). This suggests that debris from this device should have a high ratio of activation products to fission products. When, however, high concentrations of activation products did appear in the STARDUST sampling corridor at the 20 km level in the first half of 1962, they were accompanied by only relatively small amounts of fission products. Tables 79 and 80 give vertical profiles of strontium-90 and activation products at 65°N on four dates in 1962 when high concentrations of activation products were intercepted. It may be seen that the peak concentration of activation products is at or above 18 km, but the strontium-90 maximum is below the 18 km level. If the 25 megaton device had a fusion/fission ratio similar to that which was typical of others in the series, it should have produced

TABLE 79. Vertical distribution of activation products and Sr^{90} (pCi/100 SCM corrected to 15 Oct 1961) at 65°N, 25 Jan 1962 and 23 Mar 1962

Altitude (Km)	25 Jan 1962		
	Sr^{90}	Mn^{54}	Fe^{55}
20.5	320	17,600	33,600
18.3	1,760	18,400	43,000
15.3	2,730	5,720	10,650
12.2	670	910	1,850

Altitude (Km)	23 Mar 1962			
	Sr^{90}	Mn^{54}	Fe^{55}	Sb^{124}
20.5	320	24,600	42,200	97,000
18.3	910	35,100	60,500	-
15.3	1,730	19,900	26,200	70,000
12.2	760	1,050	2,300	-

TABLE 80. Vertical distribution of activation products and Sr^{90} (pCi/100 SCM corrected to 15 Oct 1961) at 65°N, 24 Jul 1962 and 7 Dec 1962

Altitude (Km)	24 Jul 1962			
	Sr^{90}	Mn^{54}	Fe^{55}	Sb^{124}
20.2	540	34,200	56,400	121,000
18.3	720	32,600	50,100	119,000
16.8	940	20,200	30,800	66,000
15.3	1,340	11,100	17,100	43,800
12.2	290	1,270	1,560	-

Altitude (Km)	9 Dec 1962			
	Sr^{90}	Mn^{54}	Fe^{55}	Sb^{124}
19.5	1,710	38,200	43,700	82,700
16.8	3,320	34,600	60,500	145,000
13.7	2,940	23,800	36,600	123,000

TABLE 81. Vertical distribution of activation products and Sr^{90} (pCi/100 SCM corrected to 31 Dec 1962) at 65°N, 7 Dec 1962 and 16 Apr 1963

Altitude (Km)	7 Dec 1962			
	Sr^{90}	Mn^{54}	Fe^{55}	Sb^{124}
19.5	1,710	14,100	43,700	82,700
16.8	3,320	12,800	60,500	145,000
13.7	2,940	8,800	36,600	123,000

Altitude (Km)	16 Apr 1963			
	Sr^{90}	Mn^{54}	Fe^{55}	Sb^{124}
20.4	3,150	8,200	19,100	120,000
18.4	3,040	7,700	19,200	107,000
16.8	6,250	7,710	15,300	100,000
15.3	6,050	15,100	29,400	7,500
13.7	2,780	10,800	25,500	2,070
12.2	1,511	7,100	19,100	570

a significant portion of the fission products injected by the series. Therefore, the debris from the 23 October 1961 event should include high fission product concentration as well as high concentrations of products of neutron activation. The profiles shown in Tables 79 and 80 suggest, however, that the debris from this event could not have contributed much to the activation products found at the 20 km height or the fission product concentration would have been much higher. We might conclude that almost all the activation products at 20 km were the result of the event of 30 October. Since Fe^{55}/Mn^{54} and Sb^{124}/Mn^{54} ratios were fairly constant from one altitude to another, and independent of strontium-90 concentration, we might assume that most of the activation products at lower levels also were the result of the 30 October test. This would suggest that most of the debris from even this very high yield device was injected into the lower stratosphere, with much being deposited in the layer between 15 and 20 km. We would similarly conclude that most of the debris from the 23 October device was deposited in the region between 12 km and 19 km where the bulk of the strontium-90 from the 1961 tests was found. Prior to the 1962 test series, the ratio of Mn^{54}/Sr^{90} was fairly low (~ 1-2) in the lowest layer of the polar stratosphere, but high (50-100) at the 20 km level. It is this high Mn^{54}/Sr^{90} ratio which serves to distinguish debris produced by the very high yield event of 30 October 1961 from debris produced by other events which took place at about that time.

By December of 1962, (Tables 80 and 81), the U.S.S.R. test series of August to October 1962 had injected large amounts of fission products into the polar stratosphere of the Northern Hemisphere. The concentrations of manganese-54 and iron-55 were not greatly increasing during this time and it follows that production of these particular nuclides was not great. During early 1963, additional debris from the December 1962 tests was intercepted which contained high concentrations of antimony-124. It is concluded, therefore, that at least one high yield event in the December 1962 series was of such design as to produce this nuclide. Almost all debris from this particular test was intercepted at or above the 17 km level.

The data obtained in Project STARDUST should be helpful in indicating whether vertical mixing in the stratosphere changes in intensity with season. It might be expected that during the winter, the rate of eddy diffusion in a vertical direction would intensify. During the winter night at high latitudes the polar stratosphere receives no solar radiation, and temperatures drop to low values of around-80°C. This cooling decreases the stability of the polar stratosphere and should facilitate convection.

Comparing carbon-14 concentrations at various altitudes at 65°N as a function of season (Table 82) lends some support to this concept.

The ratio of the concentration at 15.2 km, compared to those at 18.3 km, did increase from 0.59 in November to December, 1963 to 0.78 in March to April, 1964. The ratio of concentrations at 13.7 km to those at 18.3 km increased from 0.25 to 0.83 during the same period. During September to October, 1964 the ratio of concentrations at 15.2 km to those at 18.3 km was 0.47. By January to February of 1965 the ratio had reached 0.80. These observations are consistent with an increase in the rate of vertical mixing during the winter.

The changing ratios of concentrations discussed above resulted in part from increasing concentrations at the lower altitudes, and especially at 13.7 km, but also from decreasing concentrations at the higher altitudes;specifically at 18.3 km. If these changes resulted from a downward transport of carbon-14, they should also have been accompanied by downward transport of particulate radioactive debris. In Table 83 are listed carbon-14 data and strontium-90 data for days when

TABLE 82. Relative concentrations of Carbon-14 at various altitudes at 65°N in the polar stratosphere

Time Interval	C^{14} concentrations, 10^5 atoms/g air					Ratios of C^{14} concentrations		
	13.7km	15.2km	16.8km	18.3km	20km	13.7km / 18.3km	15.2km / 18.3km	16.8km / 18.3km
Sep-Oct 1963	317 (3)	692 (7)	1098 (9)	1279 (9)	1406 (7)	0.25	0.54	0.86
Nov-Dec 1963	232 (1)	544 (8)	785 (7)	928 (7)	992 (8)	0.25	0.59	0.85
Jan-Feb 1964	556 (2)	681 (8)	844 (7)	1048 (6)	967 (7)	0.53	0.65	0.81
Mar-Apr 1964	674 (1)	632 (5)	632 (4)	811 (3)	922 (2)	0.83	0.78	0.78
May-Jun 1964	-	404 (3)	491 (3)	704 (3)	683 (1)	-	0.57	0.70
Jul-Aug 1964	-	300 (4)	420 (4)	442 (4)	608 (2)	-	0.68	0.95
Sep-Oct 1964	-	259 (4)	410 (5)	546 (1)	660 (2)	-	0.47	0.75
Nov-Dec 1964	-	371 (3)	483 (3)	492 (2)	-	-	0.75	0.98
Jan-Feb 1965	219 (1)	330 (4)	428 (2)	412 (2)	480 (2)	0.53	0.80	1.04
Mar-Apr 1965	230 (2)	222 (4)	351 (3)	450 (1)	463 (3)	0.51	0.49	0.78
May-Jun 1965	184 (1)	194 (3)	325 (1)	301 (2)	-	0.61	0.64	1.08
Jul-Aug 1965	147 (1)	163 (2)	-	353 (3)	-	0.42	0.46	-

(Number of samples represented by each average is indicated in parentheses)

TABLE 83. Relative concentrations of Carbon-14 and Strontium-90 at 65°N during late 1963 and early 1964

	15.2 km Altitude				18.3 km Altitude		
Date	$\frac{10^5 \text{ atoms } C^{14}}{\text{g air}}$	$\frac{\text{pCi } Sr^{90}}{100SCM}$	$\frac{Sr^{90} \text{ units}}{C^{14} \text{ units}}$	Date	$\frac{10^5 \text{ atoms } C^{14}}{\text{g air}}$	$\frac{\text{pCi } Sr^{90}}{100SCM}$	$\frac{Sr^{90} \text{ units}}{C^{14} \text{ units}}$
3 Sep 1963	399	847	2.1	3 Sep 1963	1367	2352	1.7
17 Sep 1963	428	995	2.3	5 Sep 1963	1427	2236	1.6
26 Sep 1963	505	1134	2.2	19 Sep 1963	1357	2310	1.7
				1 Oct 1963	1177	2487	2.1
10 Oct 1963	1032	1620	1.6	3 Oct 1963	1322	1617	1.2
24 Oct 1963	1011	1145	1.1	15 Oct 1963	1327	2406	1.8
29 Oct 1963	934	1644	1.8	17 Oct 1963	1028	2080	2.0
				29 Oct 1963	1143	1590	1.4
12 Nov 1963	625	1154	1.8	7 Nov 1963	1146	1943	1.7
14 Nov 1963	498	1426	2.9	12 Nov 1963	1098	2161	2.0
26 Nov 1963	872	1739	2.0	21 Nov 1963	595	1495	2.5
29 Nov 1963	615	1018	1.7	26 Nov 1963	1082	1747	1.6
12 Dec 1963	378	453	1.2	10 Dec 1963	673	1808	2.7
27 Dec 1963	528	1073	2.0	23 Dec 1963	878	1821	2.1
7 Jan 1964	883	1307	1.5	7 Jan 1964	857	1813	2.1
9 Jan 1964	913	855	0.9				
22 Jan 1964	504	1229	2.4	22 Jan 1964	1180	1262	1.1

TABLE 83. (continued)

Date	15.2 km Altitude: 10^5 atoms C^{14} / g air	15.2 km Altitude: pCi Sr^{90} / 100SCM	15.2 km Altitude: Sr^{90} units / C^{14} units	Date	18.3 km Altitude: 10^5 atoms C^{14} / g air	18.3 km Altitude: pCi Sr^{90} / 100SCM	18.3 km Altitude: Sr^{90} units / C^{14} units
23 Jan 1964	734	687	0.9				
6 Feb 1964	319	253	0.8	4 Feb 1964	1119	890	0.8
18 Feb 1964	604	785	1.3	13 Feb 1964	957	1078	1.1
20 Feb 1964	664	1094	1.6	18 Feb 1964	976	992	1.0
3 Mar 1964	873	1016	1.2	3 Mar 1964	833	1240	1.5
5 Mar 1964	562	752	1.3				
17 Mar 1964	788	1278	1.6	17 Mar 1964	866	1258	1.5
28 Apr 1964	446	703	1.6	28 Apr 1964	734	750	1.0
30 Apr 1964	493	827	1.7				

both types of samples were collected at 65°N during September 1963 to April 1964. The Sr^{90}/C^{14} ratio shows some variability and perhaps a tendency to decrease with time, but the ratio at 15.2 km remains consistent with that at 18.3 km.

Meteorologists have often suggested that a mean advection of air takes place from the lower tropical stratosphere into the lower polar stratosphere, it is desirable to determine whether such advection, rather than vertical eddy diffusion, could have introduced the increased concentrations of radioactive debris into the lower polar stratosphere during the winter of 1963 - 1964. In Table 84 the carbon-14, strontium-90 and manganese-54 concentrations at various locations in the stratosphere during September 1963 and March 1964 are compared. The ratio of manganese-54 to strontium-90 was fairly uniform, at about 3, throughout the lower stratosphere of the Northern Hemisphere at that time. The ratio of particulate debris to carbon-14, represented by the Mn^{54}/C^{14} ratio, increased toward lower latitudes, however. The Mn^{54}/C^{14} ratio in the samples collected at 13.7 km on 1 March 1964 was 6.5, slightly higher than that in overlying regions of the polar stratosphere, but lower than the values of 9.1 and 8.2 found in the samples collected at 16.8 km further south. This supports the argument that the increase in concentrations of particulate debris and carbon-14 at 13.7 km during the winter of 1963 - 1964 resulted from downward movement of debris by vertical mixing and not from poleward movement of debris by advection in the meridional direction.

The stratospheric distribution of radioactive debris from late 1962 USSR nuclear weapons tests was modified in late January-early February 1963 by changes in the circulation of the Northern Hemisphere stratosphere which accompanied a sudden warming of the northern polar stratosphere. This debris served as a tracer of the air motions which accompanied the warming, and some inferences may be drawn concerning the nature of those motions based on the STARDUST data for early 1963.

During December 1962 and early January 1963 the stratospheric circula-

TABLE 84. Relative concentrations of Manganese-54, Strontium-90 and Carbon-14 at various locations in late 1963 and early 1964

Latitude	Altitude (Km)	$\frac{\text{pCi } Mn^{54}}{\text{100 SCM}}$	$\frac{10^5 \text{ atoms } C^{14}}{\text{g air}}$	$\frac{Mn^{54}}{Sr^{90}}$	$\frac{Mn^{54} \text{ units}}{C^{14} \text{ units}}$
17 September 1963					
70° - 65°N	20.1	5645	1275	2.7	4.4
"	16.8	7028	1257	3.3	5.6
"	13.7	1477	346 *	3.1	4.3
32° - 20°N	20.4	6408	740	2.7	8.7
"	17.1	2465	285	3.2	8.6
20° - 9°N	20.4	7998	647	3.4	12.4
"	17.1	754	148	3.0	5.1

*C^{14} value is average for samples collected on 22 and 24 Sep 1963

Latitude	Altitude (Km)	$\frac{\text{pCi } Mn^{54}}{\text{100 SCM}}$	$\frac{10^5 \text{ atoms } C^{14}}{\text{g air}}$	$\frac{Mn^{54}}{Sr^{90}}$	$\frac{Mn^{54} \text{ units}}{C^{14} \text{ units}}$
3 March 1964					
70° - 65°N	19.7	2703	485	2.8	5.6
"	16.8	4547	803	3.0	5.7
"	13.7**	4404	674	3.1	6.5
32° - 20°N	19.8	2942	378	2.9	7.8
"	16.8	2894	318	2.8	9.1
20° - 9°N	16.8	367	45	3.2	8.2

** Samples at 70° - 65°N, 13.7 km collected on 1 March 1964 tion of the Northern Hemisphere displayed the normal winter configuration of intense cyclonic circulation around a cold (-80°C) low centered about over the pole. The warmest air at the 50 mb level (about 20km alt.) was located in a belt at mid-latitude surrounding the cold low. A warm center (-45C) was situated over the western Pacific, near Japan. The circulation around the pole tended to be nearly circular in pattern during most of December 1962 and early January 1963.

About 15 January 1963, the circumpolar circulation began to evolve into an elliptical configuration, with its long axis extending from North America, across the pole and over western Asia. At the same time, temperatures began to increase in the warm center over the Atlantic, reaching -50°C on 16 January, -40°C on 19 January and -35°C on 25 January at the 50 mb level. Meanwhile this warm center gradually moved westward and then northward across the North American continent. The polar cold center then split into two cold centers. One migrated southward across western North America and the other southward across eastern Europe. By 31 January 1963 the warm cells over North America and the western Pacific had merged, and on 3 February 1963 the warm center, with a miximum temperature above -35°C, was situated over the pole at the 50 mb level. Remnants of the cold center were located over southern California and European USSR. The altitude of the 50 mb surface at the center of the deep low on 11 January 1963 had been at 18.7 km, but as this low filled during late January, the level of the 50 mb surface within it rose, reaching 19.5 km by 3 February 1963.

Commonly this period of rapid warming of the polar stratosphere is attributed to adiabatic heating of air undergoing subsidence as circumpolar circulation weakens and the circumpolar low filled. Maximum rates of subsidence of about 8 cm sec^{-1} at the 10 mb level were estimated by Finger and Teweles. Rates of subsidence at the 50 mb level were presumably less. Since the warm centers did not move in the streamline directions, air leaving regions of subsidence evidently entered other regions where it underwent lifting and adiabatic cooling. Yet, since the net change during late January 1963 was one of warming, the amount of subsidence must have exceeded the amount of lifting experienced by an average parcel of air. Perhaps the subsidence resulted mainly from veritcal motion within the polar stratosphere, with poleward advection at higher levels bringing in air from the tropical stratosphere to replace subsiding air. Possibly, however, the net subsidence was part of a downward and poleward quasihorizontal flow. This latter alternative would attribute the sudden warming to an intensification of the poleward component of the normal quasihorizontal eddy diffusion found between the polar stratosphere and the tropical stratosphere, implying that tropical air might have undergone advection into the polar stratosphere at all levels which experienced the sudden warming, and not just at the highest level. If this were true, advected tropical air might be encountered even at 50 mb, and not just at 30 mb or 10 mb, where warming was more intense.

Table 85 lists total beta activity, strontium-90 and managanese-54 data for samples collected before and after arrival of warm air in the STARDUST sampling corridor. On 22 and 24 January 1963, effects of the stratospheric warming were still restricted to eastern North America at the 50mb level. High levels of debris were encountered from 70°N to 9°N, but concentrations decreased south of 43°N. By 5 and 6 February 1963, the warm cell at 50 mb was centered over northern Alaska, and relatively low concentrations of debris were found between 65° and 61°N. A cold cell had moved southward to about 40°N over western North America and samples from within it showed high activity. By 19-21 February 1963, a widespread warm region lay over the pole, and temperatures decreased equatorward. Samples collected at high latitudes contained low concentrations of debris but samples from farther south in the cold air still contained high concentrations. Evidently the warm air which spread poleward during late January 1963 contained relatively little debris from the 1962 USSR test series, and probably was advected into the polar stratosphere from lower latitudes and from altitudes above 70 km. Arrival of this air in the sampling corridor as a component of the first warm air to reach it suggests that it was derived from relatively low levels in the tropical stratosphere. This supports the concept of the warming being produced by

TABLE 85. Comparison of the meridional distribution of strontium-90 and manganese-54 at 20 km preceding and following the January 1963 sudden warming of the polar stratosphere

A. Preceding arrival of warm air in STARDUST sampling corridor:

Collection Date	Latitude Range	Altitude (Km)	pCi Total B / 100 SCM	pCi Sr^{90} / 100 SCM	pCi Mn^{54} / 100 SCM
22 Jan 1963	70°-65°N	20.7	3,940,000	5,260	-
24 Jan 1963	65°-49°N	19.2	3,470,000	4,440	15,660
24 Jan 1963	49°-43°N	20.4	12,590,000	6,900	-
24 Jan 1963	43°-37°N	20.7	6,630,000	5,183	-
24 Jan 1963	37°-31°N	20.7	2,340,000	3,990	-
22 Jan 1963	32°-19°N	20.7	1,580,000	2,900	-
22 Jan 1963	20°-13°N	20.7	1,460,000	2,830	-
22 Jan 1963	13°- 9°N	20.7	502,000	2,810	-

B. Following arrival of warm air in STARDUST sampling corridor:

Collection Date	Latitude Range	Altitude (Km)	pCi Total B / 100 SCM	pCi Sr^{90} / 100 SCM	pCi Mn^{54} / 100 SCM
5 Feb 1963	70°-65°N	19.2	1,320,000	1,830	5,790
6 Feb 1963	65°-61°N	20.4	402,000	1,030	-
6 Feb 1963	61°-53°N	20.4	1,590,000	2,850	-
6 Feb 1963	53°-45°N	20.4	5,900,000	5,720	-
6 Feb 1963	45°-32°N	19.8	3,130,000	4,200	-
5 Feb 1963	31°-19°N	20.4	1,540,000	2,750	-
5 Feb 1963	20°-15°N	20.4	1,485,000	2,670	-
5 Feb 1963	15°- 9°N	20.7	388,000	1,426	-
5 Feb 1963	10°- 7°N	20.1	305,000	986	-
19 Feb 1963	70°-64°N	20.1	550,000	1,010	4,120
21 Feb 1963	64°-55°N	20.7	88,900	335	-
21 Feb 1963	55°-49°N	20.1	410,000	930	-
21 Feb 1963	49°-44°N	20.7	5,900,000	4,400	8,940
21 Feb 1963	44°-36°N	21.0	2,260,000	2,000	4,960
21 Feb 1963	36°-31°N	21.4	806,000	1,390	-
19 Feb 1963	31°-25°N	21.0	2,180,000	2,930	-
19 Feb 1963	25°-19°N	21.0	987,000	2,540	11,600
19 Feb 1963	20°-15°N	20.7	1,350,000	2,380	-
19 Feb 1963	15°- 9°N	20.7	698,000	2,190	9,750

rapid quasihorizontal motion rather than vertical motion within the polar stratosphere.

Data from project HASP indicated that during late 1959 an acceleration in the rate of transport of debris from the Northern Hemisphere into the Southern Hemisphere occurred. Data from project STARDUST,(Table 86) show a similar acceleration during mid to late 1963. At the equator, concentrations of strontium-90 and manganese-54 approximately doubled between the first and last thirds of 1963. At 30°S during this same period, the strontium-90 concentration more than doubled and the manganese-54 concentration increased seven-fold. Table 47 shows this transport of radioactive debris into the Southern Hemisphere in the second half of 1963 raised the Mn^{54}/Sr^{90} ratio in that region, but left it well below the ratio found in the Northern Hemisphere. It seems likely, therefore, that much of the debris transported into the Southern Hemisphere at that time originated from low rather than high latitude injections of 1961 and 1962, which had been characterized by high Mn^{54}/Sr^{90} ratios.

As previously noted, and illustrated in Table 88, the ratio of carbon-14 to particulate radioactivity decreased from the pole toward the equator at stratospheric altitudes. Presumably this results from carbon-14 being carried to higher altitudes during equatorward transport by the quasihorizontal eddy diffusion, while particle settling causes the particulate debris to settle into lower layers as the air which originally contained them rises. The result of this separation during trans-equatorial transport of air is illustrated in Table 89. While strontium-90 and manganese-54 concentrations at 40°S increased substantially during late 1963, carbon-14 concentrations did not. This suggests that the transport of air between hemispheres, which occurred during late 1963 was more or less restricted to the lower stratosphere, perhaps to the region between the tropopause and 21 or 22 km. Higher levels, where maximum C^{14} concentrations would be found, apparently were not involved.

TABLE 86: Horizontal profiles of Sr^{90} and Mn^{54} (pCi/100 SCM) at 20 Km, 1963 - 1966

Time Interval	70°N Mn^{54}	70°N Sr^{90}	60°N Mn^{54}	60°N Sr^{90}	50°N Mn^{54}	50°N Sr^{90}	40°N Mn^{54}	40°N Sr^{90}
Jan - Apr 1963	9260	3450	11,550	2942	11,300	3560	12,800	3275
May - Aug 1963	7900	2530	7,560	2464	7,560	2512	8,430	2624
Sep - Dec 1963	5230	1765	5,710	1776	5,710	1776	6,400	2156
Jan - Apr 1964	2960	855	3,610	916	3,610	1127	4,330	1136
May - Aug 1964	2010	666	2,130	685	2,430	777	2,730	901
Sep - Dec 1964	2580	577	1,080	610	1,840	630	2,160	676
Jan - Apr 1965	1380	388	2,050	509	1,780	463	1,780	463
May - Aug 1965	-	421	-	-	1,100	331	1,100	356
Sep - Dec 1965	520	312	1,190	229	850	266	850	266
Jan - Apr 1966	-	-	549	164	670	182	710	188
May - Aug 1966	-	-	-	-	-	164	-	164
Sep - Dec 1966	-	-	-	-	-	137	-	132

Time Interval	30°N Mn^{54}	30°N Sr^{90}	20°N Mn^{54}	20°N Sr^{90}	10°N Mn^{54}	10°N Sr^{90}	0° Mn^{54}	0° Sr^{90}
Jan - Apr 1963	12,600	3132	10,800	2560	10,900	1610	2,410	500
May - Aug 1963	7,570	2560	7,140	2131	6,600	2035	3,040	585
Sep - Dec 1963	6,770	1900	6,630	1817	6,610	1709	4,710	1003
Jan - Apr 1964	4,560	1199	4,340	1150	3,500	1113	2,310	695
May - Aug 1964	2,770	809	2,620	766	2,620	766	2,370	693
Sep - Dec 1964	-	719	2,220	612	2,220	612	1,940	525
Jan - Apr 1965	2,230	483	2,380	536	2,380	536	1,130	326
May - Aug 1965	1,390	365	1,190	237	1,190	219	710	224
Sep - Dec 1965	712	273	652	248	652	248	645	211
Jan - Apr 1966	590	156	576	165	576	165	246	82
May - Aug 1966	500	147	-	-	-	-	-	134
Sep - Dec 1966	-	123	-	123	-	123	-	127

TABLE 86. (Continued)

Time Interval	10°S		20°S		30°S		40°S	
	Mn^{54}	Sr^{90}	Mn^{54}	Sr^{90}	Mn^{54}	Sr^{90}	Mn^{54}	Sr^{90}
Jan - Apr 1963	1600	378	154	203	130	197	-	162
May - Aug 1963	3040	578	370	235	264	215	360	215
Sep - Dec 1963	3700	1003	1100	585	990	518	1030	504
Jan - Apr 1964	2310	695	1100	391	780	377	760	331
May - Aug 1964	2370	693	938	347	938	347	760	347
Sep - Dec 1964	1940	525	1000	221	986	221	630	205
Jan - Apr 1965	1130	326	361	253	574	253	410	153
May - Aug 1965	714	224	369	175	587	175	350	130
Sep - Dec 1965	432	211	300	132	477	132	470	167
Jan - Apr 1966	246	82	411	101	411	101	-	-
May - Aug 1966	-	-	-	100	-	100	-	80
Sep - Dec 1966	-	127	-	-	-	88	-	58

	50°S	
Jan - Apr 1963	-	-
May - Aug 1963	-	-
Sep - Dec 1963	970	485
Jan - Apr 1964	740	261
May - Aug 1964	-	-
Sep - Dec 1964	-	-
Jan - Apr 1965	330	122
May - Aug 1965	350	130
Sep - Dec 1965	466	167
Jan - Apr 1966	-	-
May - Aug 1966	-	80
Sep - Dec 1966	-	58

TABLE 87. Horizontal profiles of Mn^{54}/Sr^{90} ratios at 20 Km, 1963 - 1966

Time Interval	70°N	60°N	50°N	40°N	30°N	20°N	10°N	0°
Jan - Apr 1963	2.68	3.92	3.17	3.60	4.02	4.22	6.77	4.82
May - Aug 1963	3.12	3.07	3.01	3.21	2.96	3.35	3.24	5.20
Sep - Dec 1963	2.96	3.22	3.22	2.97	3.56	3.64	3.87	4.71
Jan - Apr 1964	3.46	3.94	3.20	3.81	3.80	3.77	3.14	3.32
May - Aug 1964	3.02	3.11	3.13	4.14	3.42	3.42	3.42	3.42
Sep - Dec 1964	4.47	1.77	2.92	3.20	-	3.63	3.63	3.70
Jan - Apr 1965	3.55	4.03	3.84	3.84	4.62	4.44	4.44	3.46
May - Aug 1965	-	-	3.32	3.20	3.81	5.02	5.43	3.18
Sep - Dec 1965	1.67	5.20	3.20	3.20	2.61	2.63	2.63	3.06
Jan - Apr 1966	-	3.35	3.68	3.78	3.78	3.49	3.49	3.00

Time Interval	10°S	20°S	30°S	40°S
Jan - Apr 1963	4.23	0.76	0.66	-
May - Aug 1963	5.26	1.57	1.23	1.67
Sep - Dec 1963	3.70	1.88	1.91	2.04
Jan - Apr 1964	3.32	2.87	2.07	2.30
May - Aug 1964	3.42	2.70	2.70	2.19
Sep - Dec 1964	3.70	4.52	4.46	3.07
Jan - Apr 1965	3.47	1.43	2.27	2.68
May - Aug 1965	3.19	2.11	3.35	2.69
Sep - Dec 1965	2.05	2.27	3.61	2.81
Jan - Apr 1966	3.00	4.07	4.07	-

TABLE 88. Horizontal profiles of C^{14}/Sr^{90} ratios at 20km, 1963 - 1966

Time Interval	70°N	60°N	50°N	40°N	30°N	20°N	10°N
May-Aug 1963	0.71	0.60	0.53	0.52	-	0.32	0.36
Sep-Dec 1963	0.72	0.66	0.66	0.52	0.50	0.39	0.34
Jan-Apr 1964	1.09	1.16	0.83	0.77	-	0.47	0.26
May-Aug 1964	0.95	1.08	0.85	0.73	-	0.51	0.42
Sep-Dec 1964	1.14	0.66	0.89	0.90	-	0.49	0.41
Jan-Apr 1965	1.23	0.94	1.06	0.95	0.91	0.60	0.24
May-Aug 1965	1.09	-	1.24	1.20	0.96	0.80	0.93
Sep-Dec 1965	-	1.66	1.62	1.28	1.24	0.66	0.58
Jan-Apr 1966	-	2.01	3.11	1.70	-	1.27	0.87
May-Aug 1966	-	-	2.57	1.11	1.11	-	-

TABLE 89. Trends with time in the concentrations of Sr^{90}, Mn^{54}, and C^{14} at 20 Km, 40°N and 40°S

Time Interval	40°N Sr^{90} pCi/100SCM	40°N Mn^{54} pCi/100SCM	40°N C^{14} 10^5 atom/gm air	40°S Sr^{90} pCi/100SCM	40°S Mn^{54} pCi/100SCM	40°S C^{14} 10^5 atom/gm air
Jan-Apr 1962	286(9)	79,500(2)	-	138(2)	-	-
May-Aug 1962	500(11)	26,300(4)	-	-	-	-
Sep-Dec 1962	1600(3)	44,100(7)	-	226(2)(35°)	360(2)(35°)	-
Jan-Apr 1963	3280(9)	13,800(4)	1475(10)	162(8)	132(2)	123(8)
May-Aug 1963	2620(11)	8,440(2)	1220(12)	215(4)	326(4)	123(6)
Sep-Dec 1963	2160(5)	6,850(5)	1107(22)	505(9)	1025(7)	140(6)
Jan-Apr 1964	1140(9)	4,450(5)	814(21)	331(9)	772(7)	132(6)
May-Aug 1964	902(4)	2,730(4)	557(15)	348(4)	849(4)	133(8)
Sep-Dec 1964	676(3)	2,670(1)	465(15)	205(3)	773(5)	159(8)
Jan-Apr 1965	463(4)	1,950(5)	413(9)	153(5)	406(5)	156(7)
May-Aug 1965	357(2)	1,360(2)	382(3)	130(4)	497(2)	162(9)
Sep-Dec 1965	266(4)	817(1)	319(7)	167(3)	465(2)	154(8)
Jan-Apr 1966	187(4)	710(3)	310(4)	100(1)	341(1)(19km)	174(4)
May-Aug 1966	164(2)	-	275(4)	80(1)	-	150(6)
Sep-Dec 1966	132(2)	-	237(1)	69(2)	-	-
Jan-May 1967	54(2)	-	203(5)	53(3)	-	137(3)

(Number of samples represented by each average given in parenthesis)

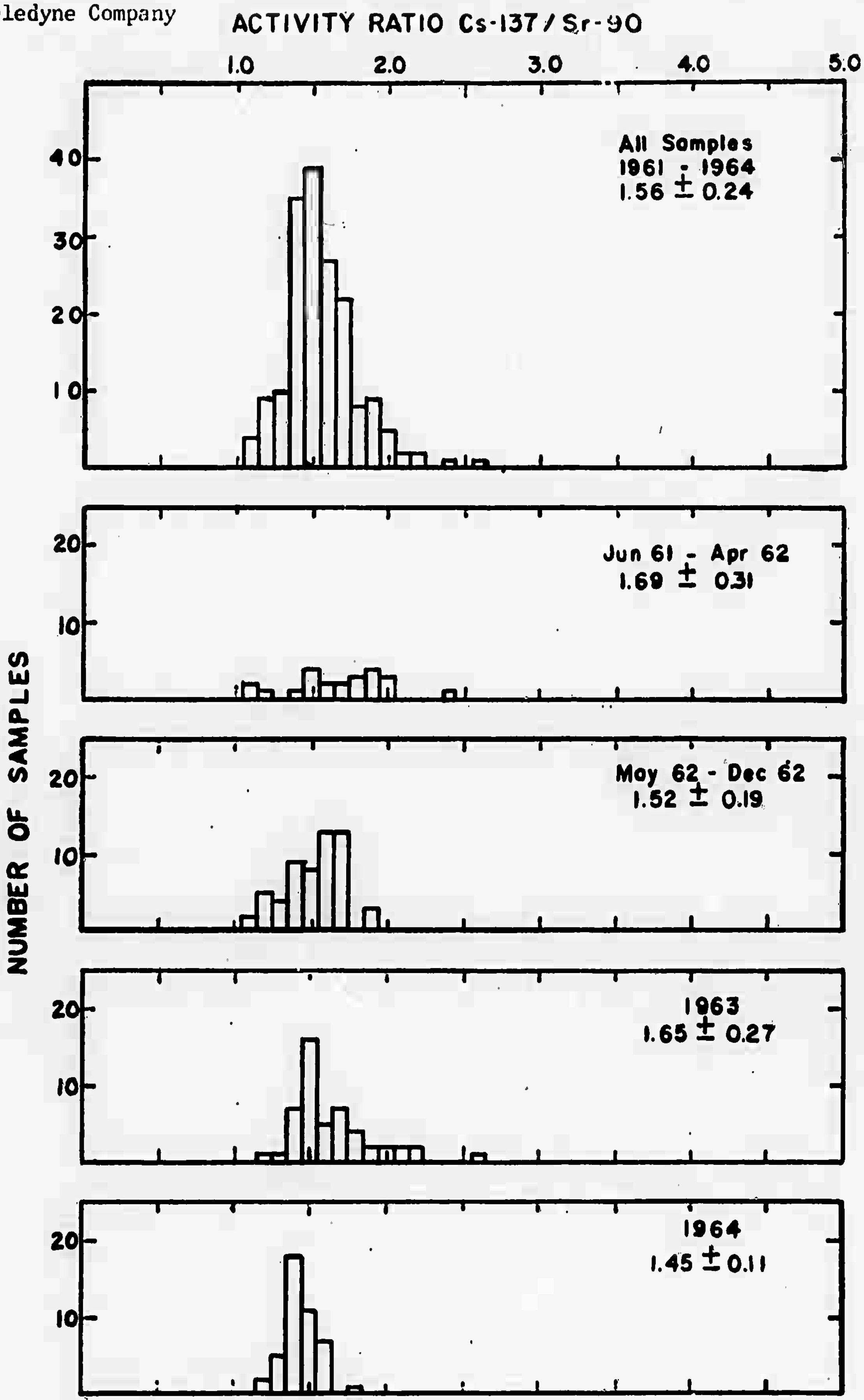

FIGURE 72. FREQUENCY OF Cs-137/Sr-90 RATIOS IN STARDUST SAMPLES

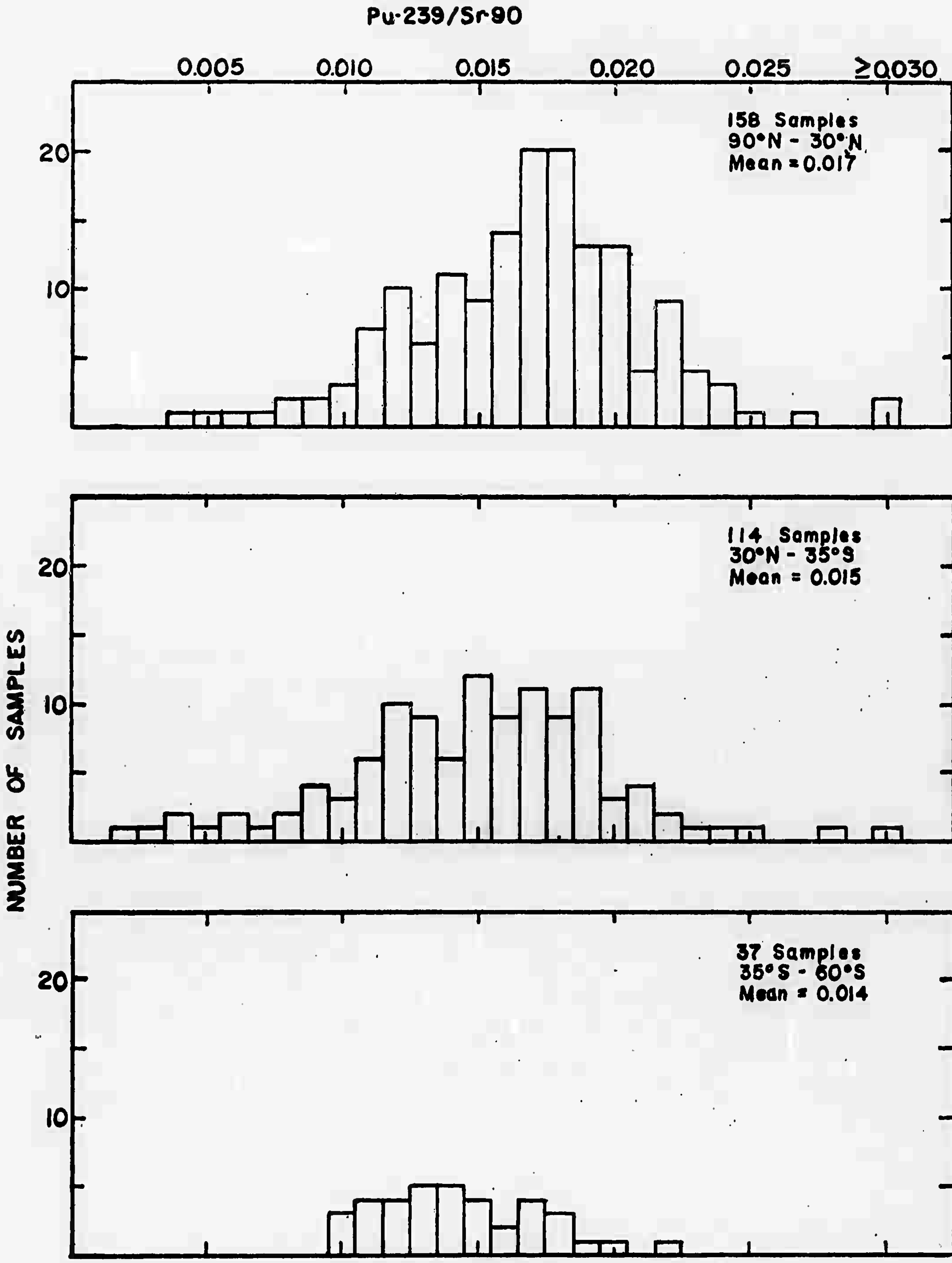

FIGURE 73. FREQUENCY OF Pu-239/Sr-90 RATIOS IN STARDUST SAMPLES ACCORDING TO LATITUDE OF COLLECTION

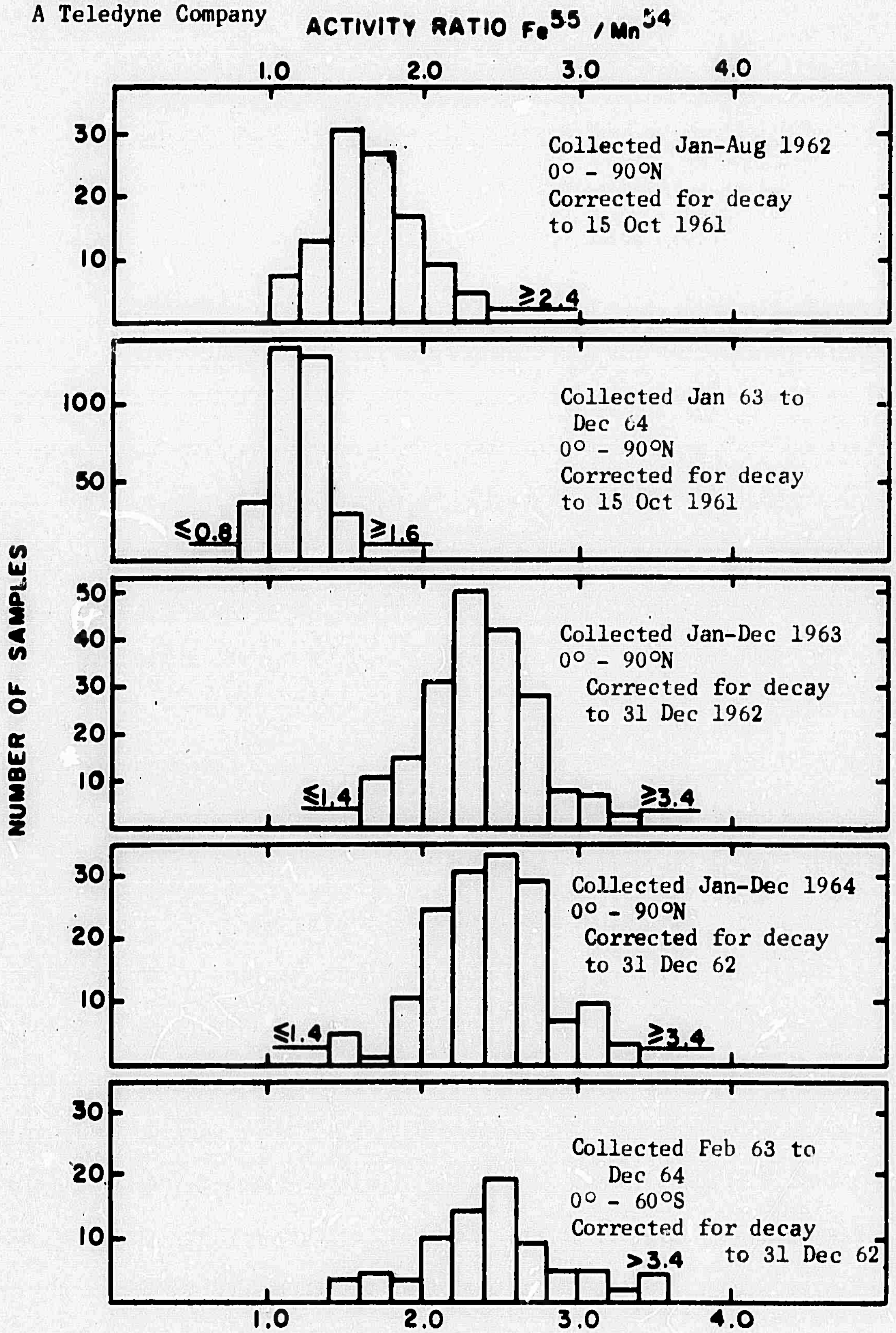

FIGURE 74. FREQUENCY OF Fe^{55}/Mn^{54} ACTIVITY RATIOS IN STARDUST SAMPLES

7.6 Transport of Particulate Radioactivity from High Altitude Bursts

It has been estimated that between 100 and 400 kilocuries of cadmium-109 were produced by the Starfish Prime event of Dominic series of nuclear weapons tests [116,117]. This event, which took place at a height of about 400 km in the vicinity of Johnston Island (about 17°N latitude) on 9 July 1962, had a reported yield of 1.4 megatons. Much of the cadmium-109 was, no doubt, injected into the upper atmosphere by this event, but some may have been ejected from the atmosphere. Fission fragments in the debris would be self-ionizing and would be trapped in the magnetosphere, but his may not have been true of the non-fission fragment components containing the cadmium [117]. Thus, less than 100 kilocuries of cadmium-109 may have remained in the atmosphere following the explosion of the Starfish Prime device.

Cadmium-109 from the Starfish Prime event was first detected in the stratosphere by the USAEC high altitude balloon sampling program. A sample collected at 32 km in the vicinity of Mildura, Australia (34°S latitude) on 13 December 1962 contained a high concentration of this nuclide.

At 32 km at 34°S, subsequent to the first interception of cadmium-109 in December 1962, still higher concentrations were intercepted during March and April, 1963. In May and July, 1963 samples collected at this location contained virtually no cadmium-109, however, indicating that this tracer nuclide was still far from being distributed uniformly within the upper stratosphere of the Southern Hemisphere. All samples collected at this location between August, 1963 and late 1965 contained significant cadmium-109 activities, but there was a considerable decrease in the average concentrations between late 1963 and late 1964, and again between late 1964 and late 1965. At 24 km at 34°S cadmium-109 concentrations increased during late 1963 and, during the first two thirds of 1964, were consistently higher than the concentrations at 32 km at that latitude. During late 1964 and during 1965, however, comparable concentrations were found at both levels. (Table 90)

Cadmium-109 concentrations at 32 km and 24 km at 31°N underwent a significant increase during 1964, with concentrations at 32 km at this latitude reaching higher values than were present at a comparable altitude at 34°S. By 1965, however, concentrations at both of these altiutdes were similar to each other and to those found at comparable altitudes at 34°S vicinity of the lower limit of detection of this nuclide. Data (Table 93) reported for balloon samples collected during late 1965 and early 1966 have included large variations in cadmium-109 concentrations together with an increasing number of samples in which activities were less than the counting error in the measurement.

Cadmium-109 data for the lower stratosphere, obtained by analysis of Stardust filter samples, also indicate that during the past few years a gradual equalization of concentrations between the Southern and Northern Hemispheres has taken place. In Table 94 are listed results for samples collected at 20 km at 25°S, at 17 and 20 km at 45°S, 17 and 20 km at 65°N, during 1962 to 1966.

Cadmium-109 from the Starfish Prime event first reached the lower stratosphere towards the end of 1963 in the Southern Hemisphere, and at about the beginning of 1964 in the Northern. Low concentrations of cadmium-109, presumably produced by some events in the 1962 USSR weapons tests series, were found in the Northern Hemisphere during late 1962 and early 1963. During 1964 the concentrations found in the Southern Hemisphere far exceeded those found in the Northern, but by mid-1965 activity levels in the Southern Hemisphere had decreased significantly, and less difference remained between the activities in the two hemispheres. (Table 94)

Observed changes in the vertical profiles of cadmium-109 concentrations suggest that the vertical distribution of this tracer, as well as its distribution between hemispheres, was becoming more uniform during 1963 to 1965. Vertical profiles for 1963, 1964, and 1965 obtained by combining data from the AEC balloon program and from Project STARDUST, are shown in Tables 90-92. At 34°S the highest concentrations at first were found at about 34 km and the concentration profile between 34 and 21 km was very steep in April 1963, less steep in September 1963, and apparently reversed in direction by March 1964, with the highest concentration by then occurring at 21 km. By October-November 1965, concentrations were much lower, and the maximum was found at 16 km. At 31°N the concentrations were low and the profile quite gentle in March 1963 and October 1963. The concentrations were considerably higher in March 1964 with the maximum at the highest altitude sampled, but the profile was still gentle. By July 1965, concentrations had decreased at the higher altitudes and the maximum was found at 20 km.

Vertical profiles of cadmium-109 activity in the lower stratosphere during 1963 to 1965, as deduced from Project STARDUST data, are shown in Tables 91 and 92. At 40°S both the concentrations and the steepness of the gradient between 20 and 17 km increased from May 1963 to November 1963 to April 1964. By December 1964, however, concentrations had decreased at 20 km. By September 1965 they had decreased still further at that altitude, and had decreased at the lower altitudes as well. During both December 1964 and September 1965 a maximum in the vertical profile was found in the lower stratosphere, below 20 km.

At 65°N (Table 92) some cadmium-109 was present in the lower stratosphere during January 1963, before the cadmium-109 from the Starfish Prime event had reached even the regions of the upper stratosphere sampled by the AEC balloon program. Perhaps a small amount of this nuclide was produced by one or more low altitude nuclear weapons tests during late 1962. The cadmium-109 concentrations in the lower northern polar stratosphere decreased rapidly during the first half of 1963, soon reaching values near the lower limit of detection of this nuclide. In any case, in June 1963 there was no detectable cadmium-109 attributable to the Starfish Prime event present in the lower stratosphere of the Northern Hemisphere. By February 1964, however, cadmium-109 from this source had reached the 20 km level at this latitude. By January, 1965 there had been a considerable increase in concentrations above the 12 km level, and a steep concentration gradient had been established between 19 km and 12 km. In September 1965 a steep gradient still existed between 18 km and 13 km but very similar cadmium-109 activities were found at 18 and 20 km.

The vertical profiles in the Northern Hemisphere (Table 92) indicate that during 1963 to 1965 significant quantities of this tracer were appearing at lower and lower altitudes. Presumably then, the vertical distribution of cadmium-109 was becoming progressively more uniform during these years, especially if the observed downward movement resulted from eddy diffusion. The vertical profiles in the Southern Hemisphere (Table 91) indicate that there, this movement progressed much more rapidly than it did in the Northern Hemisphere. They also suggest that by the end of December 1964 there existed a fairly uniform vertical distribution of cadmium-109 between the upper stratosphere and levels as low as 15 km in the lower stratosphere and further, that a layer of maximum concentration may have begun to form at about 20 km. At altitudes of 15 km and higher there was a significant drop in concentrations of this nuclide in both hemispheres during mid-1965 to early 1966. This indicates that the fallout of cadmium-109 to the

TABLE 90. Vertical profiles of Cd^{109} concentrations (pCi/100SCM corr.to 9 July 1962) at 34°N and 31°S, 1963 - 1965

Altitude (Km)	34°S					31°N			
	Apr 1963	Sep 1963	Mar 1964	Oct 1965	Nov 1965	Mar 1963	Oct 1963	Mar 1964	Jul 1965
32	14.2	79.5	41.8	2.1	-	9.5	5.6	27.5	11.9
27	12.7	22.3	46.1	4.8	-	4.0	6.4	21.0	11.4
24	16.1	12.1	58.8	6.4	-	-	4.5	16.1	12.7
20	-	6.8	27.5	-	12.6	-	-	4.9	12.5
17	-	2.4	< 1.6	-	14.6	-	-	1.6	< 4.8

TABLE 91. Vertical profiles of Cd^{109} concentrations (pCi/100SCM decay corr.to 9 July 1962) in the lower Stratosphere at 40° - 50°S Latitude

Altitude (Km)	May 1963	Nov 1963	Apr 1964	Dec 1964	Sep 1964
20	<1.0	9.5	48.9	19.5	14.3
17	<1.0	2.1	2.4	22.3	12.7
12	-	-	-	4.1	-

TABLE 92. Vertical profiles of Cd^{109} concentrations (pCi/100SCM decay corr. to 9 July 1962) in the lower Stratosphere at 55° - 65°N, 1963 - 1965

Altitude (Km)	Jan 1963	Jun 1963	Feb 1964	Jan 1965	Sep 1965
20	4.0	1.4	3.6	-	12.4
17	3.3	1.3	1.2	6.0	9.4
14	1.1	1.4	1.0	2.5	1.8
11	-	< 1	< 1	< 1	1.2

TABLE 93. Variations with time in Cd^{109} concentrations (pCi/100SCM) in balloon samples

Time Interval	31°N 32Km	31°N 24Km	34°S 32Km	34°S 24Km
1962 Oct	≤ 2.20	-	-	-
Nov	≤ 1.59	-	-	≤ .65
Dec	2.62	-	98.6	≤ .96
1963 Jan	-	-	-	-
Feb	-	-	-	≤ .32
Mar	16.8	-	145	2.85
Apr	-	-	140	1.91
May	5.25	≤ 3.8	4.14	3.98
Jun	7.31	≤ 1.27	-	5.57
Jul	7.31	-	6.84	-
Aug	3.18	-	-	25.5
Sep	5.89	-	47	12.4
Oct	6.20	4.77	78	21.6
Nov	4.05	8.11	96	19.4
Dec	10.0	-	33.1	38.0
1964 Jan	31.8	9.21	-	-
Feb	-	-	-	-
Mar	28.0	19.1	40.7	55.6
Apr	-	-	19.6	-
May	31.2	23.5	8.05	26.1
Jun	33.7	11.6	-	30.2
Jul	-	-	7.8	30.0
Aug	38.2	13.9	8.9	-
Sep	-	10.2	-	-
Oct	46.1	9.60	-	11.7
Nov	-	-	12.4	-
Dec	-	-	-	-
1965 Jan	12.2	11.5	-	23.4
Feb	-	9.29	-	12.9
Mar	7.23	4.10	9.9	21.5
Apr	-	15.9	6.44	39.0
May	-	10.2	-	18.0
Jun	-	-	19.7	-
Jul	11.6	11.5	8.88	9.41
Aug	-	10.9	8.88	9.10
Sep	-	11.2	1.96	7.65
Oct	-	20.0	1.45	5.92
Nov	-	8.36	5.54	5.89
Dec	-	3.90	-	6.23
1966 Jan	-	4.56	-	9.93
Feb	-	2.22	-	7.27
Mar	-	7.20	-	-

TABLE 93. (continued)

Time Interval	31°N 32Km	31°N 24Km	34°S 32Km	34°S 24Km
1966 Apr	-	8.79	-	-
May	-	-	-	-
Jun	-	-	-	3.15
Jul	-	-	-	1.94
Aug	-	5.35	-	5.06
Sep	-	-	-	-
Oct	-	-	-	-
Nov	-	-	-	-
Dec	-	-	-	-

TABLE 94. Variations with time in Cd^{109} concentrations (pCi/100 SCM corrected to 9 July 1962) in STARDUST samples

Time Interval		65° N 20km	65°N 17km	45°S 20km	45°S 17km	25°S 20km
1962	Aug	≤ 0.75	-	-	-	-
	Oct	-	-	-	-	≤ 0.78
	Dec	2.99(2)	≤ 1.12	-	-	≤ 0.54
1963	Jan	4.64	3.21	-	-	-
	Feb	1.96	1.94	-	-	≤ 1.00
	Mar	1.31(2)	1.73(2)	-	-	-
	Apr	1.68	3.56	-	-	≤ 0.79
	May	1.07	1.30	-	-	≤ 0.31
	Jun	≤ 1.56	-	-	-	≤ 0.43
	Jul	≤ 2.15	≤ 0.60	2.96	-	0.30
	Aug	≤ 1.06	-	-	-	1.28
	Sep	-	-	-	2.62	4.45(2)
	Oct	-	-	-	≤ 0.45	-
	Nov	1.57	0.99	8.54	2.05	4.01
	Dec	≤ 3.72	≤ 2.58	18.8	2.62	4.69
1964	Jan	3.23(2)	-	37.0	0.68	22.3
	Feb	4.36	1.15	33.2	2.45	-
	Mar	4.61	-	26.4	-	7.79
	Apr	6.54(2)	5.52(2)	48.5	2.29	22.5(3)
	Jun	9.20(2)	2.86(2)	32.9	3.37	24.5
	Aug	11.2(2)	5.07	-	19.1	23.5
	Sep	12.9	-	-	-	22.4
	Oct	11.7	2.54	24.0	24.3	-
	Nov	-	-	21.6	-	-
	Dec	5.98	6.88	22.3	19.1	20.8
1965	Jan	13.4	5.88	-	18.9	29.1
	Feb	-	10.6	41.0	18.4	23.2
	Mar	11.2(2)	12.0(2)	10.2	3.05	-
	Apr	-	-	15.2	-	-
	May	-	5.69	16.4	7.38	-
	Jul	11.0	8.36	18.4	13.9(2)	14.6
	Sep	12.2	11.2	15.6	-	14.2
	Nov	10.5(2)	6.12	12.8	13.9(2)	13.4
1966	Feb	6.31	3.44	-	-	-
	Mar	-	8.48	11.3	9.10	10.8
	Apr	-	-	-	6.56	-
	Aug	-	5.67	6.22	7.55	7.49
	Dec	-	4.97	6.09	4.60	5.38

Numbers in parentheses indicate number of samples averaged.

troposphere during late 1965 far exceeded its downward flux from the high altitude source region. It would appear that by mid-1965 cadmium-109 should have begun to show a relatively rapid rate of fallout, similar to that displayed during and after 1963 by radioactive debris injected into the lower stratosphere by the low altitude bursts in the 1961 and 1962 nuclear weapon tests. As is indicated below, however, this expected rapid rate of fallout of cadmium-109 had not developed by early 1966.

7.7 Stratospheric Burdens and Residence Times of Particulate Radioactivity

The stratospheric distributions of strontium-90 shown in Figures 65 to 71, and listed in Tables 72 to 78 have been used as the basis for calculating the stratospheric burden of strontium-90 from 1961 to 1967. Data from the Atomic Energy Commission's balloon sampling program have been used to extrapolate the STARDUST data to altitudes above 30 km, and additional data from WU-2 sampling during 1961 have been used for extrapolating 1961 STARDUST data to high northern latitudes. The results of these calculations are presented in Table 95 and Figure 76.

As a result of the 1961 and 1962 nuclear weapon tests, the stratospheric burden of strontium-90 increased from about 0.9 megacurie in mid-1961 to over 6 megacuries by the beginning of 1963. Since that time the stratospheric burden has decreased at a rate equivalent to a residence half-time of approximately 10 months. By mid-1965 this decrease had brought the stratospheric burden back down to about 0.9 megacurie. By early 1967 the burden had diminished to only 0.2 megacuries (200 kilocuries). It might have been expected that the apparent residence half-time of strontium-90 would have slowly lengthened with time during 1963 to 1967 as the lower stratosphere was gradually depleted by continued fallout. It has been suggested [20] that its failure to do so may be attributed to the continued downward flux of debris from the upper to the lower stratosphere during

TABLE 95. Trends with time in the Stratospheric Burden of Sr^{90} (in megacuries) 1961 - 1967

Time Interval	Northern Hemisphere	Southern Hemisphere	Total Burden
Jun - Sep 1961	0.4 ± 0.1	~ 0.5	~ 0.9
Oct - Dec 1961	~ 1.6	0.5 ± 0.2	~ 2.1
Jan - Apr 1962	1.6 ± 0.3	0.4 ± 0.1	2.0 ± 0.3
May - Aug 1962	2.5 ± 0.5	~ 1.0	~ 3.5
Sep - Oct 1962	2.2 ± 0.7	1.0 ± 0.3	3.2 ± 0.8
Nov - Dec 1962	5.6 ± 1.9	0.8 ± 0.3	6.4 ± 1.9
Jan - Apr 1963	5.8 ± 1.5	0.7 ± 0.2	6.5 ± 1.5
May - Aug 1963	4.3 ± 1.1	0.8 ± 0.3	5.1 ± 1.2
Sep - Dec 1963	2.8 ± 0.6	1.0 ± 0.3	3.8 ± 0.7
Jan - Apr 1964	2.3 ± 0.4	0.7 ± 0.3	3.0 ± 0.5
May - Aug 1964	1.5 ± 0.4	0.6 ± 0.3	2.1 ± 0.5
Sep - Dec 1964	1.1 ± 0.4	0.6 ± 0.3	1.7 ± 0.5
Jan - Apr 1965	0.9 ± 0.3	0.4 ± 0.2	1.3 ± 0.3
May - Aug 1965	0.6 ± 0.3	0.3 ± 0.2	0.9 ± 0.4
Sep - Dec 1965	0.5 ± 0.1	0.3 ± 0.1	0.8 ± 0.2
Jan - Apr 1966	0.4 ± 0.1	0.2 ± 0.1	0.6 ± 0.1
May - Aug 1966	0.3 ± 0.1	0.2 ± 0.1	0.5 ± 0.1
Sep - Dec 1966	0.21 ± 0.07	0.17 ± 0.06	0.38 ± 0.08
Jan - May 1967	0.14 ± 0.05	0.10 ± 0.03	0.24 ± 0.06

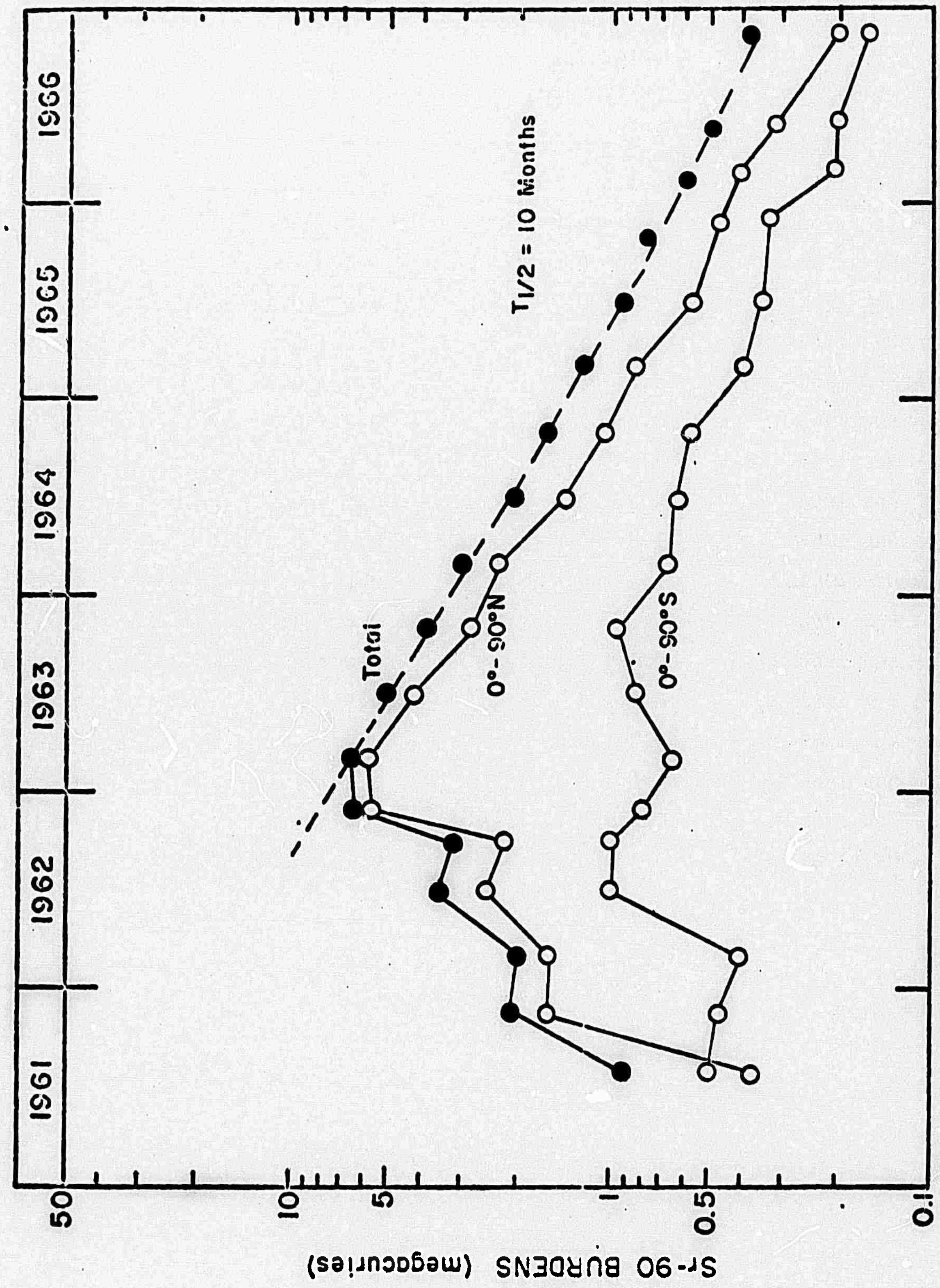

FIGURE 76 STRATOSPHERIC BURDENS OF STRONTIUM-90

1963-1965 as a result of particle settling.

The distributions of manganese-54 in the stratosphere during January 1962 to mid-1966 are presented in Tables 79 to 81,86 and 89. These distributions have been extrapolated into the upper atmosphere using data from the USAEC high altitude balloon sampling program, and the stratospheric burdens at intervals during the period have been calculated. These burdens are summarized in Table 96 and plotted in Figure 77. During early 1963 almost all of the manganese-54 produced by the 1961 and 1962 weapon tests was still present in the stratosphere of the Northern Hemisphere. A southward movement of debris occurred during 1963 and 1964, however, and by mid-1964 the manganese-54 burden of the stratosphere of the Northern Hemisphere was only twice that of the stratosphere of the Southern Hemisphere. By the first half of 1966, fallout of manganese-54 had reduced the burdens in each hemisphere to one third the burdens present in mid-1964, and the Northern Hemisphere stratosphere still contained twice as much manganese-54 as did that of the Southern Hemisphere. As with strontium-90, the fallout rate of manganese-54 during 1963 to 1966 was equivalent generally to a stratospheric residence half time of about 10 months.

The distributions of cadmium-109 in the lower stratosphere during 1962 and during the first half of 1966 are shown in Tables 90-94. The stratospheric burdens calculated for these intervals, extrapolating the distributions in these tables into the upper stratosphere with the help of available balloon data, are included in Table 97, and plotted in Figure 78. In addition to the total burden in each hemisphere, the table indicates the burden above the 40 mb level (about 22 km) and the burden between the 40 mb level and the tropopause. It would appear that by mid-1964 more than half of the cadmium-109 in the stratosphere of the Southern Hemisphere had reached the lower stratosphere. In the Northern

TABLE 96. Trends with time in the Stratospheric Burden of Mn^{54} (Megacuries corrected for decay to 31 December 1962), 1963 - 1966

Time Interval	Northern Hemisphere	Southern Hemisphere	Total Burden
Jan - Apr 1963	22.8 ± 8.0	1.2 ± 0.8	24.0 ± 8.0
May - Aug 1963	13.6 ± 3.5	1.6 ± 1.0	15.2 ± 3.6
Sep - Dec 1963	9.4 ± 2.5	2.5 ± 1.2	11.9 ± 2.8
Jan - Apr 1964	7.7 ± 2.0	2.0 ± 1.0	9.7 ± 2.2
May - Aug 1964	4.2 ± 1.4	2.1 ± 1.0	6.3 ± 1.7
Sep - Dec 1964	3.7 ± 1.2	2.1 ± 1.0	5.8 ± 1.6
Jan - Apr 1965	3.4 ± 1.1	1.0 ± 0.5	4.4 ± 1.2
May - Aug 1965	2.0 ± 0.9	1.0 ± 0.5	3.0 ± 1.0
Sep - Dec 1965	1.6 ± 0.8	0.9 ± 0.4	2.5 ± 0.9
Jan - Jun 1966	1.4 ± 0.7	0.7 ± 0.3	2.1 ± 0.7

TABLE 97. Trends with time in the Stratospheric Burden of Cadmium-109 (Kilocuries corrected for decay to 9 July 1962) 1964 - 1966

Time Interval	Northern Hemisphere			Southern Hemisphere			Total Burden
	0-40mb	Below 40mb	Total	0-40mb	Below 40mb	Total	
Jan - Apr 1964	15 ± 10	5 ± 3	20 ± 10	28 ± 15	17 ± 10	45 ± 18	65 ± 21
May - Aug 1964	18 ± 10	7 ± 3	25 ± 10	21 ± 15	29 ± 12	50 ± 19	75 ± 22
Sep - Dec 1964	15 ± 10	9 ± 4	24 ± 11	17 ± 12	34 ± 15	51 ± 19	75 ± 22
Jan - Apr 1965	10 ± 6	12 ± 4	22 ± 7	12 ± 8	27 ± 13	39 ± 15	61 ± 17
May - Aug 1965	8 ± 4	15 ± 4	23 ± 6	9 ± 6	21 ± 10	30 ± 12	53 ± 13
Sep - Dec 1965	8 ± 4	13 ± 3	21 ± 5	7 ± 4	19 ± 10	26 ± 11	47 ± 12
Jan - Jun 1966	5 ± 3	12 ± 3	17 ± 4	6 ± 4	15 ± 7	21 ± 8	38 ± 9

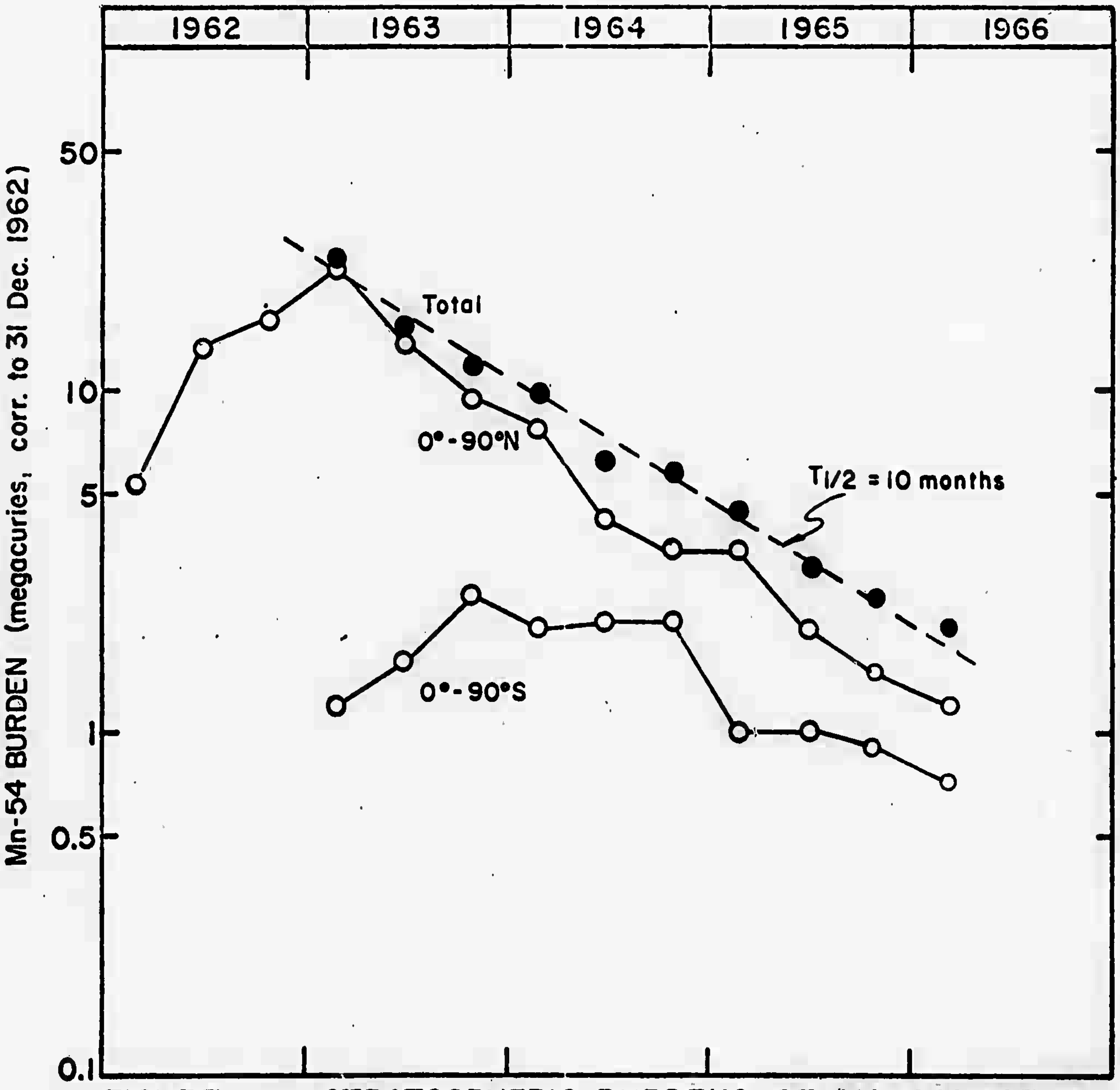

FIGURE 77 STRATOSPHERIC BURDENS OF MANGANESE-54

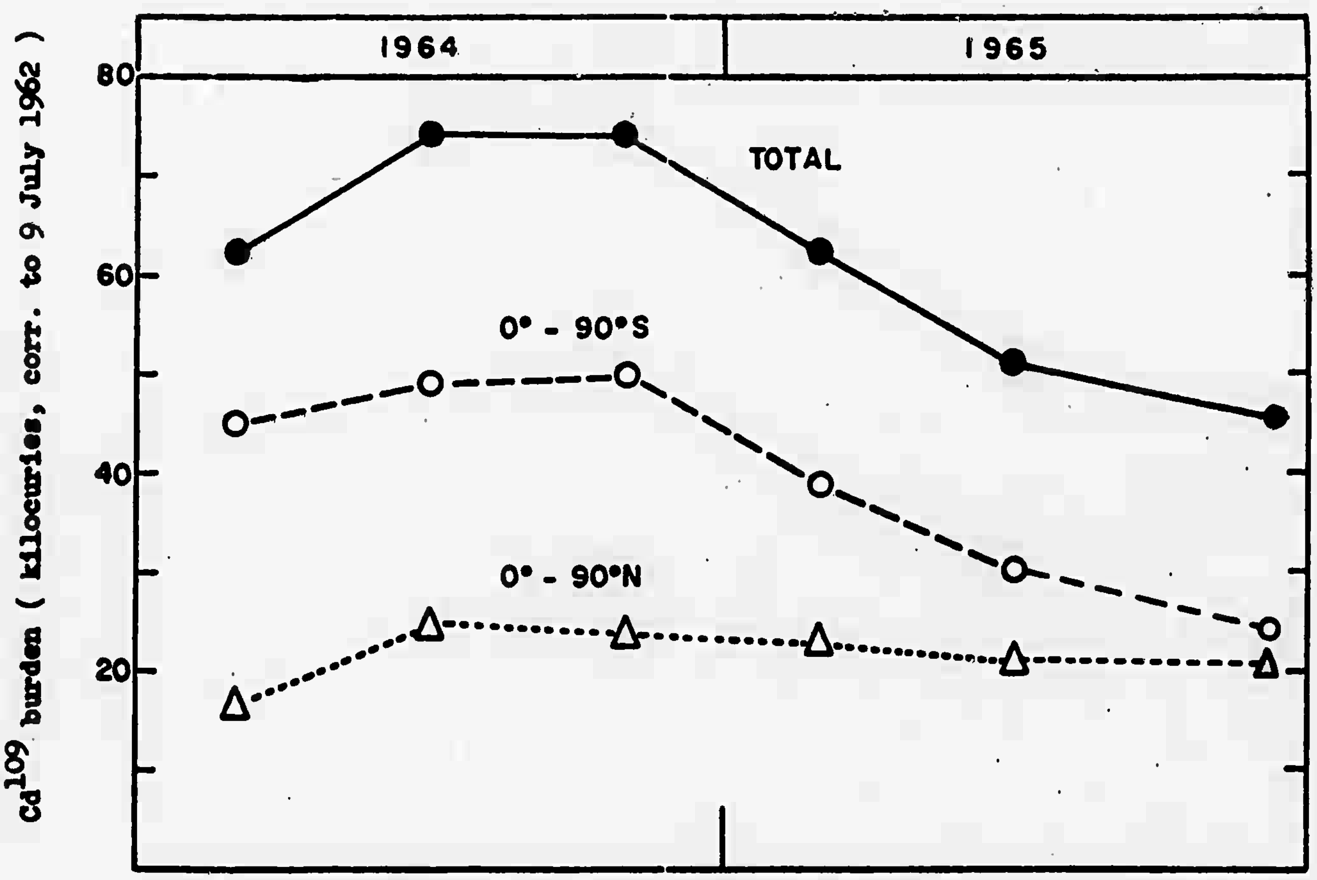

FIGURE 78. STRATOSPHERIC BURDENS OF CADMIUM - 109 DURING 1964 AND 1965

Hemisphere it was not until early 1965 that more than half of the cadmium-109 burden was found below the 40 mb level.

Between late 1964 and the first half of 1966 the burden in the 0-40 mb layer decreased with a residence half time of about 11 months, the burden in the lower stratosphere (below 40 mb) decreased with a residence half-time of about 25 months, and the total burden decreased with a residence half-time of 17.5 months. This rate of decrease is slower than we had predicted on the basis of experience with particulate debris from low altitude nuclear weapon tests. Perhaps this debris from a high altitude source has displayed a relatively long residence half time because it is carried by finer particles than is the debris from low altitude bursts, and thus is less susceptible to gravitational concentration in the lower stratosphere.

7.8 Summary and Conclusions

In addition to permitting the original objective of development and testing of a numerical model of stratospheric transportation processes which had begun in Project HASP, abundant data was accumulated in STARDUST which provided a firmer base for estimates of stratospheric burdens and residence times. The greatest effort of Project STARDUST was directed toward measurement of the massive injections of radioactive debris which resulted from the nuclear weapons test series of 1961 to 1962. It was data obtained from these measurements that provided most of the information gained during the project.

Interception of fresh debris from specific events provided information on the trajectories followed by the "clouds" of debris and their rates of movement around the earth, as well as their rate of distribution throughout the stratosphere. Measurements of neutron activation products such as manganese-54, iron-55, and antimony -124 produced in high yield events indicated that debris from even this type of event stabilized mainly below about 20 km in the polar stratosphere. That little debris from the USSR series penetrated into the Southern Hemisphere is evidence that the tropical stratosphere is generally a region of slow mixing in the meridional direction. Short periods of rapid interhemispheric exchange do, however, occasionally take place as was evidenced by short term changes of concentrations of debris in the STARDUST sampling corridors such as that which took place during the summer of 1963. Most particulate radioactive debris injected into the lower and middle layers of the stratosphere appears to migrate, probably because of gravitational settling, into the layer between the tropopause and about 20 km. The difference between the behavior of particulate debris of which strontium-90 is typical, and that of gaseous material, typified by carbon-14 as carbon dioxide, provides reinforcement for this observation.

On the basis of data obtained in Project STARDUST, particulate debris exhibits a stratospheric residence half-time of about 10 months. The expectation that this residence half-time would increase gradually with the passage of time was not borne out by the data. The peak in the vertical distribution of radioactive debris continued to be found near or below the 20 km level throughout 1963 to 1967, presumably because fallout into the troposphere was compensated by gravitational settling from above. This combination of processes appeared to maintain the residence half-time of the debris in the stratosphere at about 10 months. On the other hand, the residence half-time of carbon-14 in gaseous carbon dioxide did not remain constant during this period, but gradually lengthened as a result both of depletion of the lowest layers of the stratosphere and buildup of carbon-14 concentrations within the trosphere.

CHAPTER 8. INFORMATION DERIVED FROM MEASUREMENTS OF RADIOACTIVITY FROM THE 1966 CHINESE AND FRENCH NUCLEAR WEAPON TESTS

Several of the nuclear weapon tests performed during 1966, including the 9 May 1966 Chinese test and a few of the French tests, injected radioactivity into the lower stratosphere. Fission products from these nuclear events have been detected by various programs of fallout measurement in a variety of sample types, including filter samples of stratospheric air collected by RB-57F aircraft as part of Project STARDUST. These injections have provided an additional opportunity for the use of radioactive debris as a tracer for the movement of masses of stratospheric air.

8.1 The Distribution in the Atmosphere of Radioactivity from the 9 May 1966 Chinese Nuclear Weapon Test

A nuclear device was exploded by the Chinese on 9 May 1966. According to the U.S. Atomic Energy Commission, this nuclear event, which was China's third, had an energy yield "in the lower end of the intermediate yield range (equivalent to the force of 200 kilotons to 1 megaton of TNT)."

The first STARDUST sampling mission flown after 9 May 1966 took place on 25 May, and involved the collection of a series of samples at 15.2 km between 36°N and 9°N. Samples collected between 36°N and 16°N contained debris from the weapon test. The next sampling mission, flown on 27 May, collected a series of samples at 16.8 km between 7°N and 12°S, and at 18.3 km between 13°S and 31°S. The samples collected between 7°N and 9°S also contained debris. During 25 May - 5 June the Chinese debris was intercepted at 15.2 km between

64°N and 16°N, at 16.8 km between 35°N and 9°S, and at about 18.3 km between 19°N and 3°N. A number of samples collected during July and August 1966 contained radioactive debris from this event.

Prior to the 9 May 1966 nuclear explosion the concentrations of short-lived fission products, such as strontium-89, were too low within the stratosphere to be detected. All strontium-89 found in STARDUST samples collected during May to July 1966 can thus be attributed to the 9 May 1966 event, and it is possible to use the measured concentrations of this nuclide to indicate the distribution within the stratosphere of radioactive debris from that event. Strontium-89 found in STARDUST samples collected in the stratosphere of the Northern Hemisphere during August 1966 can also be attributed exclusively to that event, but some samples collected in the Southern Hemisphere during August contained debris recently injected into the stratosphere by the French nuclear weapon tests of July 1966. In order to calculate the amount of Chinese debris in the Southern Hemisphere during August 1966, therefore, it was necessary to extrapolate southward the strontium-89 concentrations found in the northern tropical stratosphere, assuming that the variation of concentrations with latitude during August was similar to that observed during July 1966.

The apparent distribution of strontium-89 within the stratosphere, as determined by sampling missions flown for Project STARDUST, is portrayed for the periods 25 May to 4 June 1966, 10 to 18 June 1966, and 21 to 30 June 1966 in Figure 79 and for July 1966 and August 1966 in Figure 80. In these figures isolines of strontium-89 concentration, expressed as picocuries per cubic meter of air at standard temperature and pressure (pCi/SCM), are drawn

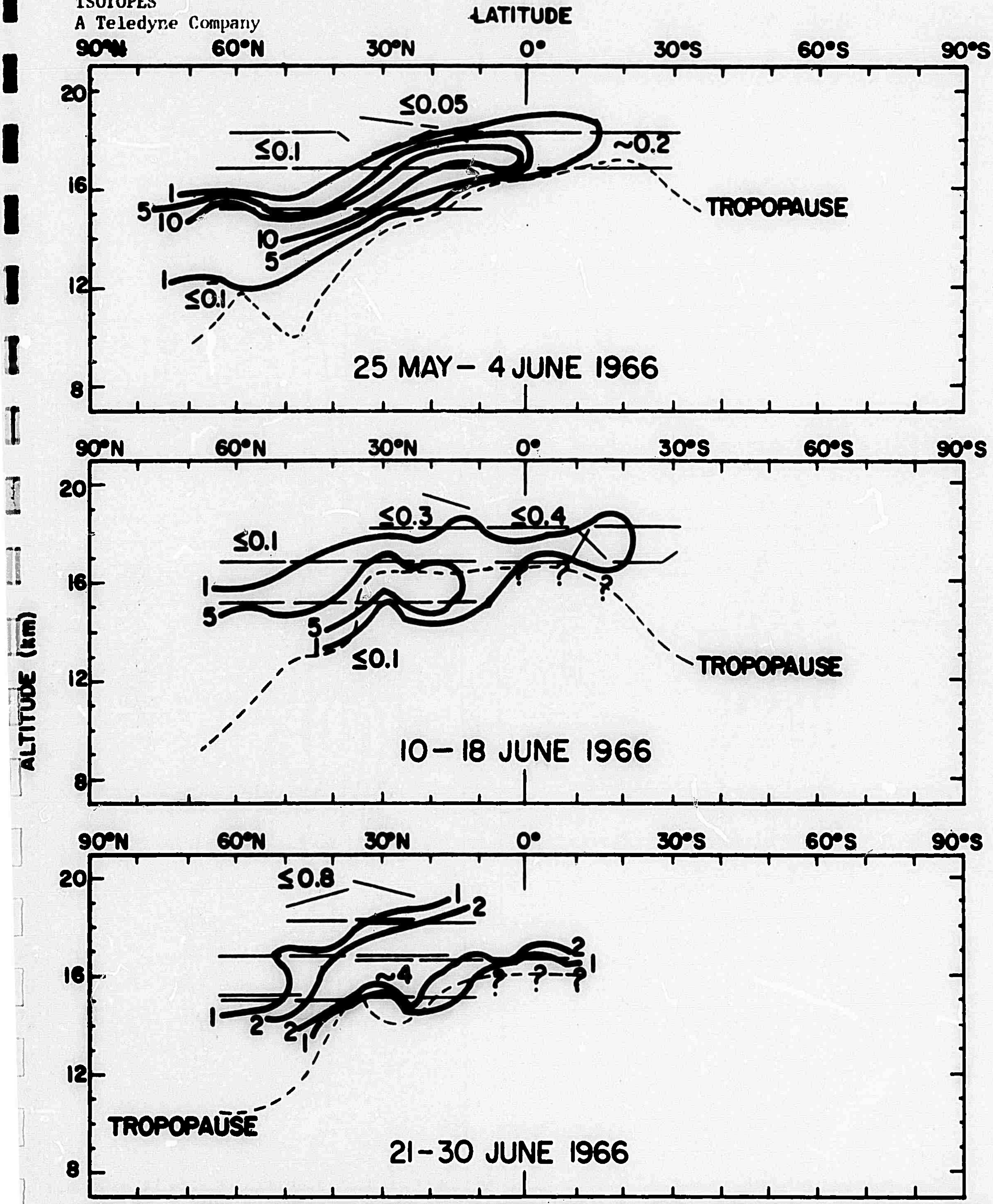

FIGURE 79. THE DISTRIBUTION OF STRONTIUM-89 (pCi/SCM CORRECTED TO 9 MAY 1966) DURING JUNE 1966

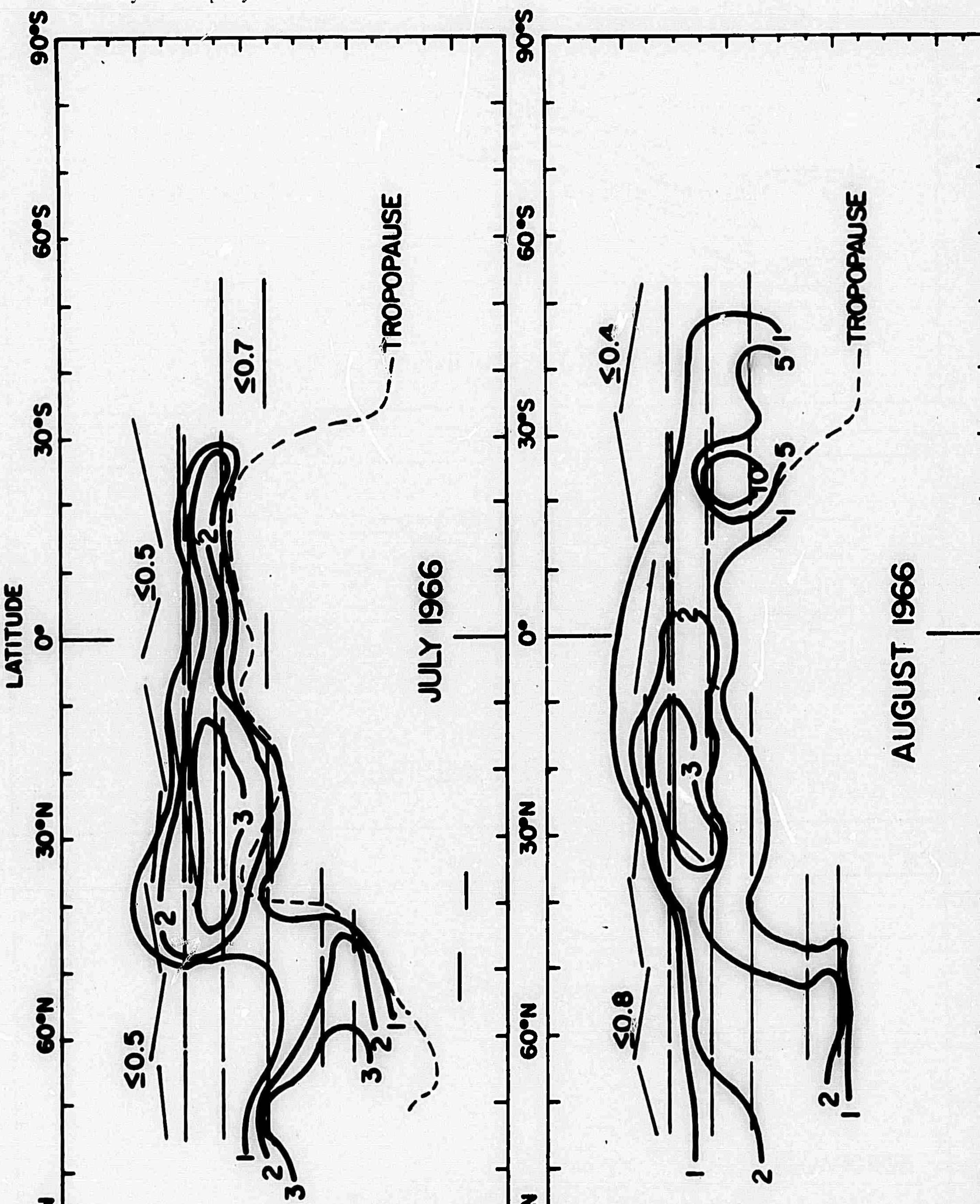

FIGURE 80. THE DISTRIBUTION OF STRONTIUM-89 (pCi/SCM CORRECTED TO 9 MAY 1966) DURING JULY AND

on a meridional section of the atmosphere. The strontium-89 data are all corrected for radioactive decay to 9 May 1966. The flight tracks of the sampling aircraft are plotted on the figure as thin horizontal lines, and the approximate position of the tropopause is shown as a dashed line.

It appears from Figures 79 and 80 that in the stratosphere the major portion of the cloud of debris from the Chinese test, as intercepted, was restricted to the lowest layers - below 17 km in the northern polar stratosphere and below 20 km in the tropical stratosphere. The configuration of the Chinese cloud is consistent with the observation that meridional transport of radioactive debris within the stratosphere occurs by eddy diffusion along surfaces which slope gently downward from the equator toward the poles [19,21].

It is especially interesting that the debris, injected at about 40°N on 9 May 1966, was intercepted as far south as 5° - 9°S on 27 May, and as far south as 12° - 17°S on 17 June. Some of the debris had moved southward about 45° of latitude, or about 5,000 km, in 18 days or less.

There is a mean mass transport of air from the summer hemisphere to the winter hemisphere [44]; however, the rate of this seasonal mean circulation (~0.003 knots) is too small for it to account for the observed rate of meridional transport of the Chinese debris. Also the southward transport of the debris cannot be attributed to eddy diffusion. Assuming a value of 10^9 $cm^2\ sec^{-1}$ for the horizontal exchange coefficient [1], (Ky in the diffusion equation), and assuming the β-activity at the point of injection on 1 June 1966, to be 8,000 pCi/100 SCM (ten times higher than the highest concentration observed anywhere in the STARDUST corridor), about 5 months would be required for concentrations as high as those observed at 5°S (more than 50 pCi/100 SCM) to reach that point by eddy diffusion alone. A value of 10^{10} cm^2 sec^{-1}, which seems excessive, particularly in the low latitudes, would have to be assumed for K_y to explain the observed transport by eddy diffusion. It may be possible, however, to explain the observed meridional transport by advection southward by the upper tropospheric (or lower stratospheric) return circulation of the southwest monsoon which develops during May. This upper air return flow of the monsoon at about 15 km has southward velocities of about 5-10 knots[42]. Between 120°E and 150°E longitude, the flow may extend sufficiently far south of the equator to bring the debris into the westerly zonal flow of the Southern Hemisphere where it would be advected across the Pacific. A detailed investigation of the upper air circulation during May and June 1966 should provide evidence on the mechanism involved in the southward movement of the Chinese debris.

A number of filter samples collected during May and June 1966 were analyzed for barium-140 as well as for strontium-89, and a few were analyzed also for zirconium-95 and cerium-141. Table 98 contains data on the collection sites of these samples as well as the measured strontium-89 concentrations and the activity ratios Ba^{140}/Zr^{95}, Ce^{141}/Zr^{95}, Sr^{89}/Zr^{95} and Ba^{140}/Sr^{89}. The mean values for the ratios reported in Table 98 are compared in Table 99 with expected production ratios in megaton yield nuclear weapons [35] and with fission product ratios reported in samples of surface air collected by Brar, et al.[31] at Argonne, Illinois and by the U.S. Atomic Energy Commission[44] at a few sites in the continental United States and in Hawaii and Puerto Rico. The concentrations of strontium-89 and zirconium-95 measured at all of the

TABLE 98. Fission Product Ratios in May – June 1966 STARDUST Samples, Corrected to 9 May 1966

Sample Number	Collection Date	Latitude	Altitude (km)	pCi Sr^{89} / 100 SCM	Ba^{140}/Zr^{95}	Ce^{141}/Zr^{95}	Sr^{89}/Zr^{95}	Ba^{140}/Sr^{89}
SF-7876	25 May 66	36° – 33°N	15.2	1,880	–	–	–	5.03
SF-7877	27 May 66	7°N – 9°S	16.8	800	22.5	5.18	5.26	4.27
SQ-7807	2 Jun 66	64° – 55°N	15.2	2,870	–	–	–	5.00
SF-7879	2 Jun 66	64° – 55°N	15.2	2,790	–	–	–	5.11
SF-7881	2 Jun 66	43° – 37°N	15.2	780	29.2	4.02	4.48	6.51
SF-7882	3 Jun 66	35° – 27°N	16.8	442	21.6	2.88	3.62	5.96
SQ-7812	3 Jun 66	27° – 20°N	16.8	1,070	–	–	–	5.47
SF-7883	3 Jun 66	27° – 20°N	16.8	1,100	26.7	3.70	5.03	5.31
SF-7884	3 Jun 66	20° – 10°N	16.8	631	32.6	5.40	6.35	5.13
SQ-7861	10 Jun 66	36° – 23°N	16.8	733	–	–	–	3.75
SQ-7864	10 Jun 66	23° – 10°N	18.3	262	–	–	–	4.29
SF-7874	14 Jun 66	9° – 13°S	17.5	569	–	–	–	5.12
SX-7837	14 Jun 66	13° – 32°S	18.3	130	–	–	–	3.55
SQ-7867	15 Jun 66	64° – 49°N	15.2	324	–	–	–	4.01
SQ-7868	15 Jun 66	49° – 37°N	15.2	481	–	–	–	4.20
SF-7875	17 Jun 66	9° – 17°S	17.0	325	–	–	–	4.76
SX-7847	24 Jun 66	36° – 16°N	16.8	572	–	–	–	4.27
SX-7849	25 Jun 66	49° – 37°N	15.2	162	–	–	–	5.78
SX-7851	25 Jun 66	36° – 23°N	15.2	465	–	–	–	3.00
Mean of May – June 1966 Samples					26.5	4.2	5.0	4.8

TABLE 99. Production Ratios of Fission Products and Ratios in Stratospheric and Surface Air, Corrected for Radioactive Decay to 9 May 1966

	$\frac{Ba^{140}}{Zr^{95}}$	$\frac{Ce^{141}}{Zr^{95}}$	$\frac{Sr^{89}}{Zr^{95}}$	$\frac{Ba^{140}}{Sr^{89}}$
Production Ratios:				
Megaton yield events (Harley, et al[14])	5.2	1.8	0.65	8.0
May-June 1966 STARDUST Samples	26.5	4.2	5.0	4.8
Surface Air, Argonne, Illinois (Brar, et al[19])				
17 May - 7 June 1966	2.7	1.2	-	-
8 June - 30 June 1966	6.4	2.3	-	-
Surface Air, May 1966 (Krey[21])				
New York, N. Y.	-	1.2	0.57	-
Sterling, Virginia	-	1.2	0.71	-
Miami, Florida	-	4.3	1.74	-
Mauna Loa, Hawaii	-	3.5	1.37	-
San Juan, Puerto Rico	-	1.4	0.45	-
Surface Air, June 1966 (Krey[21])				
New York, N. Y.	-	3.8	0.98	-
Sterling, Virginia	-	1.8	0.84	-
Miami, Florida	-	1.8	0.88	-
Mauna Loa, Hawaii	-	2.1	0.90	-
San Juan, Puerto Rico	-	1.5	0.59	-

USAEC sites are listed in Table 100.

The relative amounts of the various fission products produced by a nuclear event depend upon the fissionable materials used and upon the energy spectrum of the neutrons causing the fission reaction. In many instances the ratios between fission products in samples of debris from a nuclear event will be different from their production ratio, and may vary from sample to sample. This "fractionation" of fission products occurs mainly when certain nuclides are preferentially condensed onto particles present in the cooling fireball from the nuclear explosion. Nuclides such as zirconium-95 and cerium-144, which are mainly present as "refractory elements" during the first minute or so following the explosion, will be selectively condensed onto particles, while nuclides such as strontium-89, strontium-90 and barium-140, which are present to a large extent as isotopes of the rare gases, krypton and xenon, will not be condensed. The "refractory" fission products will tend to condense onto the particles which are present in the cooling fireball, and these will tend to grow to larger sizes than the particles which form subsequently. In this circumstance the "refractory" fission products will be enriched in the relatively coarse particles which settle out of the cloud early in its history, while the "volatile" fission products and those with rare gas precursors will be enriched in the relatively fine particles which remain suspended in the cloud. Fractionation effects will be most pronounced for ground bursts over land, for large quantities of soil or rock may be drawn up into the fireball. The local fallout from such events will be enriched in "refractory" fission products, while the long-range fallout will be depleted in them. Fractionation of debris from air bursts is also

TABLE 100. Concentrations of Strontium-89 and Zirconium 95, corrected to 9 May 1966, in USAEC Surface Air Samples

Station	Latitude	Longitude	Altitude (m)	pCi Sr^{89} / 100 SCM May 1966	pCi Sr^{89} / 100 SCM Jun 1966	pCi Zr^{95} / 100 SCM May 1966	pCi Zr^{95} / 100 SCM Jun 1966
Thule, Greenland	76° 36'N	68° 35'W	259	n.d.	-	3.13	-
Charlie Ocean Station	57° 00'N	35° 30'W	0	n.d.	-	0.58	-
Bravo Ocean Station	56° 30'N	51° 00'W	0	0.24	0.81	0.29	1.08
Moosonee, Ontario	51° 16'N	80° 39'W	10	n.d.	3.60	0.93	3.56
Delta Ocean Station	49° 00'N	41° 00'W	0	n.d.	2.39	0.94	4.03
Seattle, Washington	47° 36'N	122° 20'W	3	n.d.	0.71	5.34	2.24
New York, New York	40° 48'N	73° 58'W	38	2.75	7.63	4.83	7.79
Sterling, Virginia	38° 58'N	77° 25'W	76	2.12	9.23	2.98	10.7
Echo Ocean Station	35° 00'N	48° 00'W	0	(0.07)	-	4.13	-
Miami, Florida	25° 49'N	80° 17'W	4	10.3	14.5	5.92	16.4
Mauna Loa, Hawaii	19° 28'N	155° 36'W	3401	10.3	48.4	7.56	53.8
San Juan, Puerto Rico	18° 26'N	66° 00'W	10	4.01	10.6	8.83	17.9
Balboa, Panama Canal Zone	08° 58'N	79° 34'W	23	1.80	1.38	1.48	2.08
Guayaquil, Ecuador	02° 10'S	79° 52'W	7	n.d.	0.41	n.d.	1.32
Lima, Peru	12° 06'S	77° 01'W	134	0.57	0.82	0.55	0.81
Chacaltaya, Bolivia	16° 21'S	68° 07'W	5220	n.d.	4.86	0.33	6.00
Antofagasta, Chile	23° 37'S	70° 16'W	519	n.d.	-	0.12	-
Portillo, Chile	32° 50'S	70° 08'W	2850	0.75	n.d.	4.04	3.52
Santiago, Chile	33° 27'S	70° 42'W	520	n.d.	n.d.	n.d.	n.d.
Puerto Montt, Chile	41° 27'S	72° 57'W	5	n.d.	n.d.	n.d.	n.d.
Punta Arenas, Chile	53° 08'S	70° 53'W	3	0.08	n.d.	n.d.	n.d.

n.d. = no detectable activity

possible, however, since particles form as the materials of the casing of the device and of the supporting structures condense in the cooling fireball.

If we assume that the production ratios of fission products from the 9 May 1966 Chinese nuclear explosion should be similar to those in debris from nuclear weapons of megaton yield, we may conclude that the stratospheric radioactivity measured in the STARDUST samples is enriched in strontium-89 by about a factor of 7.5, in barium-140 by about a factor of 5, and in cerium-141 by about a factor of 2.3 relative to zirconium-95. Fractionation of the extent observed is possible in debris from air bursts, but is probably more likely in debris from surface bursts.

It is rather interesting to compare the apparent fractionation of the Chinese debris encountered in the stratosphere with the apparent fractionation of the debris encountered in the troposhere. The Chinese debris which reached Argonne, Illinois in surface air during 17 May to 7 June 1966 (see Table 99) was depleted in barium-140 by almost 50 percent and in cerium-141 by about 33 percent relative to zirconium-95. On the other hand, the radioactive debris which reached Argonne during 8 to 30 June 1966 was enriched slightly in barium-140 and cerium-141 relative to zirconium-95. This suggests that the fission products were not distributed uniformly within the cloud from the Chinese explosion, and that the more "volatile" fission products, including those with rare gas precursors, were concentrated in the upper portions of the cloud, in the upper troposphere and lower stratosphere. Presumably the low portions of the cloud were enriched in the "refractory" fission products, such as zirconium-95, as a result of gravitational settling of the particles which formed first during the cooling of the fireball from the Chinese nuclear event, and grew to relatively large size compared to the particles which formed later. It may be hypothesized that these lower portions of the cloud contributed most of the fission products which reached Argonne during the first month after the explosion, but that subsequently a large fraction of the Chinese debris sampled at Argonne was derived from the upper portions of the cloud.

Results of measurements of fission products performed during the USAEC surface air sampling program(44), some of which are included in Table 99 and Table 100, are of particular interest when considered in the light of the distributions of the Chinese debris in the stratosphere, as shown by Figures 79 and 80. The three USAEC surface air stations which collected the highest concentrations of strontium-89 and zirconium-95 during May and June 1966 were Miami, Mauna Loa and San Juan (see Table 100), all lying between 30° and 15°N. More northerly and more southerly stations collected significantly lower concentrations. Indeed, stations north of Seattle (48°N) collected quite low concentrations, especially during May 1966. This situation is consistent with the hypothesis that the distribution of the Chinese debris was strongly affected by the return circulation of the southwest monsoon. The relatively high values of the activity ratios Ce^{141}/Zr^{95} and Sr^{89}/Zr^{95} at Miami and Mauna Loa during May 1966 suggest that debris from the upper portions of the Chinese radioactive cloud, and perhaps from the stratospheric portion, reached those stations during May. These activity ratios decreased at those two stations by June 1966, but they increased at most of the other stations in the Northern Hemisphere, as exemplified by New York, Sterling and

San Juan in Table 99. This suggests that radioactive debris from the upper portion of the Chinese radioactive cloud either was mixing downward from the upper troposphere, or was spreading laterally from low latitudes.

It may be quite significant that the middle cross-section in Figure 79 representing the period 10-18 June 1966, shows that a large portion of the cloud of Chinese debris in the region between 35° and 5°N was located below the tropopause. Danielson(45) pointed out that within the thermal structure of the atmosphere, there often are numerous isentropic laminae which may be traced from regions of the atmosphere which lie above the tropopause, as it is generally defined, into other regions which lie below the tropopause. Some of these extend from the polar stratosphere, through the "tropopause gap" region, and into the tropical troposphere. It may be hypothesized that the Chinese radioactive debris which was encountered in the upper troposphere in mid-May had been carried southward and eastward along such layers by the zonal flow, and as a result, had moved from the stratosphere into the troposphere. The injection of portions of the Chinese debris into the troposphere in this manner may have occurred repeatedly at a number of different locations as it was carried around the globe in the lower stratosphere. Some of the radioactivity which entered the troposphere in this manner may subsequently have re-entered the stratosphere, but most of it probably remained within the troposphere. This transfer process would preferentially inject material from the stratospheric portion of the Chinese debris, which was enriched in strontium-89, barium-140 and cerium-141, into the troposphere in the region between 39° and 15°N. Such injections could have resulted in the high concentrations of Chinese debris, and the enrichment of this debris in "volatiles", which characterized surface air samples collected at Miami and Mauna Loa during May 1966.

As stated above, the yield of the 9 May 1966 nuclear event has been described as being between 200 kilotons and one megaton. If this event involved purely a fission reaction, an energy yield of about 200 kilotons should have produced about 22 kCi of strontium-90[43]. If the event was an air burst, between 80 and 100 percent of the radioactive debris produced may have been injected into the stratosphere, but if it was a ground surface burst the stratosphere injection may have been much less, perhaps between 0 and 50 percent, depending on the yield[47]. Thus if the 9 May event was an air burst, we might expect it to have injected about 20 kCi of strontium-90 into the stratosphere, while if it was a ground burst less than 10 kCi was probably injected.

The strontium-89 burdens represented by each of the five distributions shown in Figures 79 and 80 have been calculated, assuming that each of these distributions is representative of all meridians during the period covered. Of the strontium-89 in the Southern Hemisphere during August 1966, only that which could be attributed to the Chinese event was included in the calculation of the burden for that month. The equivalent strontium-90 burden has been estimated from each strontium-89 burden assuming an initial value of 147 for the activity ratio, Sr^{89}/Sr^{90}, in the debris from the Chinese test[35], and assuming that these two nuclides were not separated by fractionation effects in the cooling radioactive cloud from the explosion. These calculated stratospheric burdens are summarized in Table 101.

It is probable that the zonal distribution of the Chinese debris within the stratosphere was not yet uniform during May and June 1966, and that the actual stratospheric burdens of strontium-89 and strontium-90 were significantly

TABLE 101. Apparent Stratospheric Burdens of Strontium-89 and Strontium-90 from the 9 May 1966 Chinese Nuclear Explosion

Sampling Period	Sr^{89} Burden (corrected to 9 May 1966)	Sr^{90} Burden (0.0068 X Sr^{89} Burden)
25 May - 4 June 1966	800 kCi	5.4 kCi
10-18 June 1966	510	3.5
21-30 June 1966	350	2.4
July 1966	520	3.5
August 1966	470	3.2

different from those summarized in Table 101. It is likely that the most concentrated sections of the radioactive cloud from the Chinese event were carried through the STARDUST sampling corridor either before 25 May 1966 or during the period 25 May - 4 June 1966. In either event, the concentrations encountered in the STARDUST corridor during the periods 10-18 June and 21-30 June would probably be lower than the mean value for the whole stratosphere, and the burdens calculated from them would be lower than the true values. It is reasonable to expect that by July and August 1966 the zonal distribution of the Chinese debris was much more uniform, and that the burdens calculated for these months are fairly accurate. It is safe to assume also that during May and June a significant fraction of the debris injected into the stratosphere on 9 May 1966 reentered the troposphere. On the basis of these assumptions it is possible to estimate only very approximately the stratospheric injection by the Chinese event. It is unlikely that the residence half time of the Chinese debris in the stratosphere was longer than six months or shorter than two months. Accordingly, at least 600 kilocuries of strontium-89 must have been injected or the burden of this nuclide would have been significantly below 520 kilocuries by July 1966. On the other hand, less than 1000 kilocuries must have been injected or the burden during July 1966 would have been significantly above 520 kilocuries. It is, therefore concluded that the 9 May 1966 nuclear event injected into the stratosphere 800 $\pm$ 200 kilocuries of strontium-89, equivalent ot about 5.5 $\pm$ 1.5 kilocuries of strontium-90.

It is possible to estimate very roughly the tropospheric burden of strontium-89 during June 1966 using the USAEC surface air measurements. For performing this calculation, the troposphere may be divided arbitrarily into a lower layer between the surface and 700 mb (about 3 km), and an upper layer between 700 mb and the tropopause (at 300 mb from 90° to 30° and at 100 mb from 30° to 0°). The surface air measurements at low elevation stations (sea level to 600 meters) may be used to calculate the burden in the lower layer, and measurements of STARDUST tropospheric samples and of surface air samples from high elevation stations (above 3 kilometers) may be used to calculate the burden in the upper layer. The mean concentrations used and burdens calculated are summarized in Table 102. If we assume that the Sr^{89}/Sr^{90} production ratio in debris from the Chinese weapon was 147, the ratio typical of debris from megaton yield nuclear explosions[35], and that these nuclides would not be separated by fractionation processes, for they both have important rare gas precursors, we may estimate that the total tropospheric burden of about 570 kilocuries of strontium-89 was associated with a strontium-90 burden of about 4 kilocuries. Comparison of this result with data in Table 101 suggests that during June 1966 the debris from the 9 May 1966 event was roughly equally divided between the stratosphere and the troposphere.

TABLE 102. Apparent Tropospheric Burdens of Strontium-89 and Strontium-90 during June 1966 from the 9 May 1966 Chinese Nuclear Explosion (All concentrations and burdens are corrected to 9 May 1966)

Latitude Band	Sr^{89} Concentrations (pCi/100 SCM) Below 700 mb	Sr^{89} Concentrations (pCi/100 SCM) Above 700 mb	Sr^{89} Burdens (kilocuries) Below 700 mb	Sr^{89} Burdens (kilocuries) Above 700 mb
90° - 45°N	0.9	27	3	130
45° - 30°N	3.8	27	10	94
30° - 0°N	3.7	22	24	277
0° - 30°S	0.3	2.2	2	28

Burden of Sr^{89} = 570 kCi

Burden of Sr^{90} = 4 kCi

8.2 The Distribution in the Stratosphere of Radioactivity from the July, September and October 1966 French Nuclear Weapon Test

Figures 81 and 82 portray the distribution of strontium-89 within the stratosphere during August, October, November and December 1966. These figures are similar to Figures 79 and 80, except that the strontium-89 concentrations are corrected for radioactive decay to 4 October 1966, the date of the last event in the French series of nuclear weapon tests.

Several samples collected south of 10°S, along the western coast of South America, on 15 and 16 August 1966 contained small quantities of recently produced radioactive debris. Comparison of the rate of decay of their total beta activity with the rates expected for mixed fission products at various times after production[45] indicates an apparent age of 3 to 4 weeks at the time of collection. The French government announced[14] that a plutonium fission device of "tactical" size was exploded on 2 July 1966 near Mururoa atoll (21°S), and that a device of low yield, dropped from an airplane, was exploded in the same area on 19 July 1966. The apparent age of the radioactive debris intercepted by STARDUST missions indicates that the second of these two events was the source. It is surprising that radioactivity from a low yield device, which presumably exploded at a fairly low altitude, penetrated the stratosphere. Perhaps the thermal structure of the atmosphere over the French test site at the time of detonation permitted the fireball to rise to an unusually high altitude, or perhaps part of the radioactive cloud became involved in a circulation of air between the stratosphere and troposphere, and was carried into the stratosphere subsequent to its stabilization in the upper troposphere.

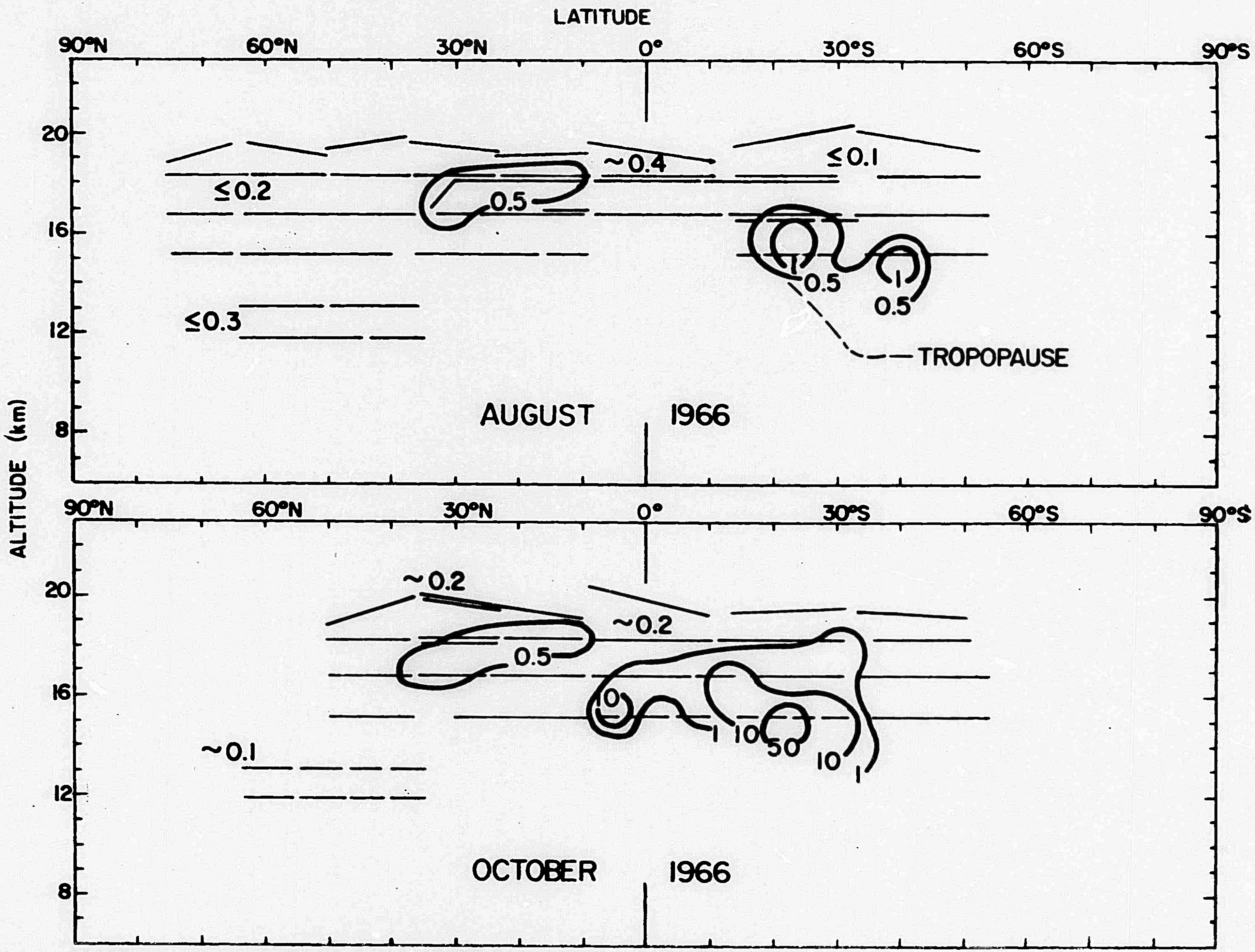

FIGURE 81. THE DISTRIBUTION OF STRONTIUM-89 (pCi/SCM CORRECTED TO 4 OCTOBER 1966) DURING AUGUST

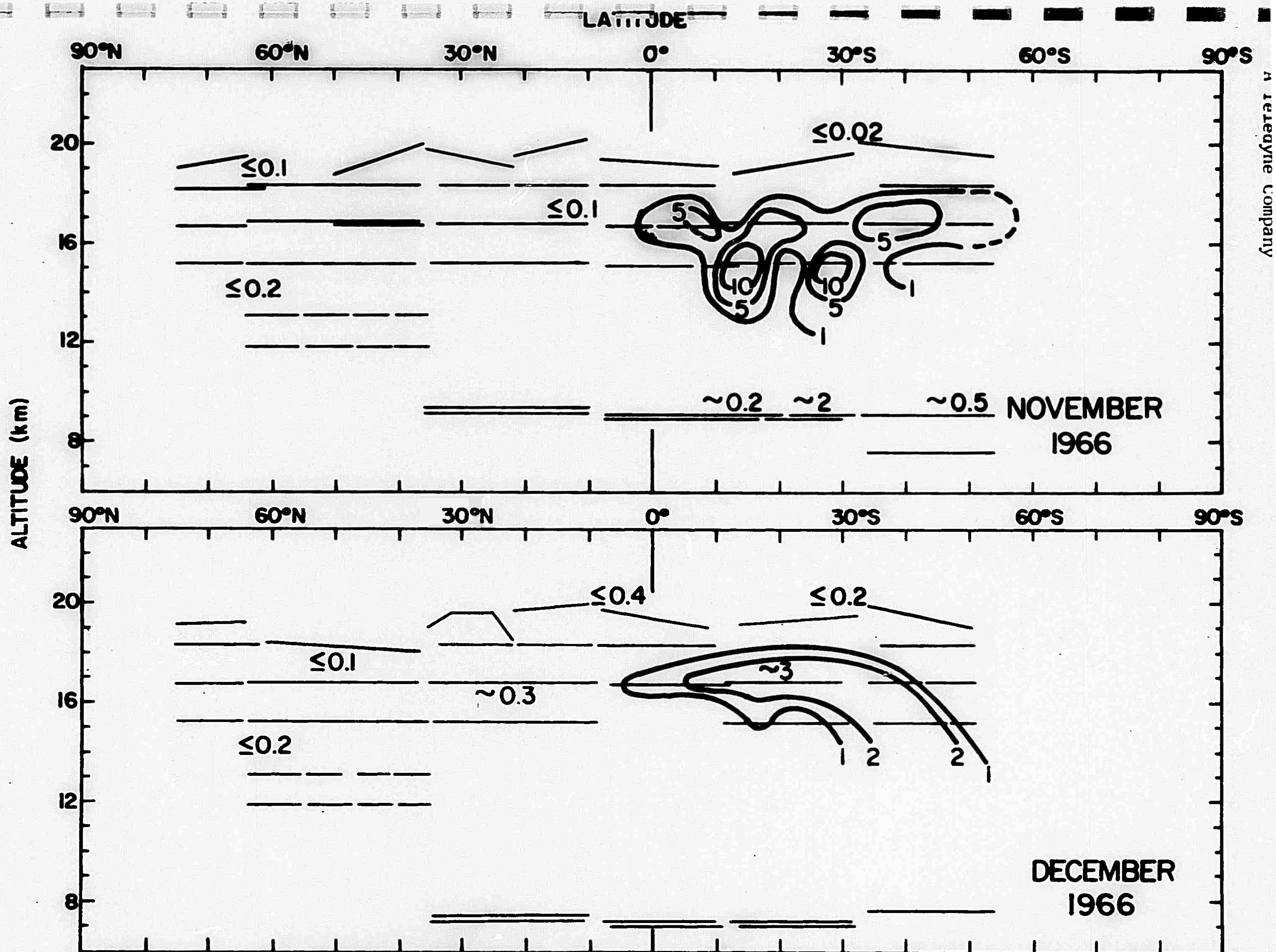

FIGURE. 82. THE DISTRIBUTION OF STRONTIUM-89 (pCi/SCM CORRECTED TO 4 OCTOBER 1966) DURING NOVEMBER AND DECEMBER 1966

During August the French debris was intercepted close to the normal winter position of the Southern Hemisphere jet stream (about 30°S). The presence of this debris over South America 3 to 4 weeks after its injection, in a region of the atmosphere normally characterized by strong westerly winds during July and August, suggests that it had passed completely around the world once and was being carried over South America for the second time when it was intercepted. The distance around the earth at a latitude of 23° is 3.7×10^7 meters. It would appear that between 19 July and 15 August (2.33×10^6 seconds), this debris had travelled about 4.4×10^7 meters, indicating a velocity of about 19 meters per second. In the core of the Southern Hemisphere jet stream, velocities in excess of 50 meters per second may be found, but at 23°S velocities of about 20 meters per second are common at 15 to 17 km during July and August[46]. The region in which these high wind velocities are found is normally part of the troposphere, however.

It is interesting that the French debris apparently did not spread very far northward at 15 and 17 kilometers during the first month following its injection, and that the highest concentrations were found very close to the latitude of injection. It is unfortunate that no data are available at 15 kilometers between 9°N and 14°S for mid-August, but the relatively low activity found in the sample collected at 15 km between 14° and 18°S does suggest that the cloud of French debris did not spread significantly toward the north. It is evident that the cloud had spread toward the south, however, and that it had reached at least about 45°S. Since the debris was probably moving to lower altitudes as it spread southward[15,19], it may have reached high southern latitudes at an altitude below the levels sampled for Project STARDUST.

If we assume that the distribution of strontium-89 during August 1966 which is shown in the upper half of Figure 81 was representative of all meridians, we may calculate that the stratospheric burden of strontium-89 from the French Test, corrected for decay to 19 July 1966, was about 125 kCi. This is equivalent to a strontium-90 burden of 0.9 kCi, if the Sr^{89}/Sr^{90} production ratio in the French debris was 147. It is possible, of course, that the distribution of strontium-89 shown in the upper half of Figure 81 is not representative of the entire stratosphere, and that these calculated burdens are too high or too low.

The short-lived fission products barium-140, cerium-141 and zirconium-95, as well as strontium-89, were measured in three pairs of filter samples containing radioactive debris from the July 1966 French event. The results are summarized in Table 103 in the form of strontium-89 concentrations and the activity ratios, Ba^{140}/Zr^{95}, Ce^{141}/Zr^{95}, Sr^{89}/Zr^{95} and Ba^{140}/Sr^{89}. Production ratios of these fission products by megaton yield nuclear weapons are included in the table for comparison. If it is assumed that the production ratios in the French debris were similar to those in debris from megaton weapons, it may be concluded that the material sampled in the stratosphere was enriched in strontium-89, barium-140 and cerium-141 by about a factor of 3.5 compared to zirconium-95. It may be concluded further that the debris intercepted at 15.2 km on 16 August 1966 was less enriched in strontium-89, barium-140 and cerium-141 than was the debris intercepted at 16.8 km on that day, or the debris intercepted on the preceding day farther south at 15.2 km. This appears to indicate that even the portion of the radioactive cloud, produced by the 19 July 1966 French Test, which stabilized in the stratosphere

TABLE 103. Fission Product Ratios in August 1966 STARDUST Samples Corrected to 19 July 1966

Sample Number	Collection (Date)	Latitude	Altitude (km)	$\frac{pCi\ Sr^{89}}{100\ SCM}$	$\frac{Ba^{140}}{Zr^{95}}$	$\frac{Ce^{141}}{Zr^{95}}$	$\frac{Sr^{89}}{Zr^{95}}$	$\frac{Ba^{140}}{Sr^{89}}$
SF-7954	15 Aug 1966	34° - 43°S	15.2	364	20	-	2.7	7.4
SF-8088	15 Aug 1966	34° - 43°S	15.2	336	21	7.5	2.3	9.0
SF-7955	16 Aug 1966	18° - 27°S	15.2	463	14	3.1	1.4	10.1
SF-8089	16 Aug 1966	18° - 27°S	15.2	429	12	4.0	1.4	9.0
SF-7956	16 Aug 1966	18° - 27°S	16.8	656	20	6.9	2.7	7.1
SF-8091	16 Aug 1966	18° - 27°S	16.8	633	15	5.9	2.4	6.2
Mean Value of August 1966 Samples:					17 ± 4	5.8 ± 1.9	2.2 ± 0.6	8.1 ± 1.3
Production Ratios:								
Megaton yield events (Harley et al( ))					5.2	1.8	0.65	8.0

was not uniform in composition. Probably nuclides such as strontium-89 and barium-140, which have rare gas precursors, were most concentrated in the highest portions of the radioactive cloud, at about 17 km. Subsequent poleward movement of this debris would be accompanied by its subsidence to lower altitudes[16,19]. Thus the radioactive debris intercepted at 15.2 km between 34° and 43°S on 15 August 1966 may represent debris initially injected at about 17 km at about 21°S, the latitude of the French test site.

The French government announced the performance of additional tests of nuclear weapons at its South Pacific Test Site[21] on 11 September, 24 September and 4 October 1966. No samples were collected for Project STARDUST during September 1966, but when sampling was resumed in October 1966 radioactive debris from these tests was encountered at 15.2 and 16.8 km in the region between 10°N and 35°S, and at 18.3 km near 30°S. The half-lives of the total beta activities of most of the October 1966 samples which contained fresh French debris were quite short, indicating that most of the debris encountered had originated in the most recent nuclear event, that of 4 October 1966. The half-lives of two samples were somewhat longer, however, suggesting that the most recent debris they contained had come from the September 1966 French tests.

The rate of decay of the total beta activity of sample SF-8094, collected at 18.3 km near 30°S on 11 October 1966, indicated an apparent age of one month, suggesting that the recent radioactive debris which it contained had been produced by the 11 September 1966 event. A filter collected between 7° and 4°N at 15.2 km on 10 October 1966, from which samples SF-8087 and SF-8092 were prepared, contained debris which decayed with a half-life equivalent to an age of about two weeks at the time of collection, indicating that it contained predominantly radioactivity from the 24 September 1966 French

Test. The results of radiochemical analyses of these samples, which are summarized in Table 104 are consistent with these dates of origin. In the table strontium-89 concentrations and some fission product activity ratios are given. If it is assumed that the nuclide production ratios for these events were similar to those for megaton yield events, it may be concluded that the debris from these two nuclear events apparently underwent relatively little fractionation of the fission products.

Molybdenum-99 was measured in three samples collected during October 1966, and fairly precise determinations may be made of the dates of origin of fission products in those samples. Both 66-hour molybdenum-99 and 65-day zirconium-95 are "refractories", and would not be expected to undergo significant fractionation relative to each other during the cooling of a fireball. The Mo^{99}/Zr^{95} activity ratios in the three samples measured for molybdenum-99 are given in Table 105. The zirconium-95 concentrations and the activity ratios are corrected for decay to the dates of the three French events during September and October 1966. Production ratios for megaton yield events are given for comparison. The results indicate that the origin of the bulk of the short-lived fission products in sample SF-8087 can best be attributed to the 25 September 1966 event, while the fission products in the other two samples listed in Table 105 can best be attributed to the 4 October 1966 event.

Strontium-89 concentrations and fission product activity ratios for several samples collected in the Southern Hemisphere during October 1966, which appeared to contain radioactive debris from the 4 October 1966 French event, are listed in Table 106. If we assume that the production ratios of fission products from that event were similar to those for megaton yield events, we may conclude that relatively little fractionation occurred in the debris from that

TABLE 104. Fission Product Ratios in Samples Apparently Containing Radioactive Debris from the 11 September and 24 September 1966 Events

Sample Number	Collection Date	Latitude	Altitude (km)	$\frac{pCi\ Sr^{89}}{SCM}$	$\frac{Ba^{140}}{Zr^{95}}$	$\frac{Ce^{141}}{Zr^{95}}$	$\frac{Sr^{89}}{Zr^{95}}$	$\frac{Ba^{140}}{Sr^{89}}$
Debris from the 11 September 1966 event, with data corrected to that date:								
SF-8094	11 Oct 1966	27° - 31°S	18.3	3.7	6.5	2.7	0.75	8.6
Debris from the 25 September 1966 event, with data corrected to that date:								
SF-8087	10 Oct 1966	7° - 4°N	15.2	19.2	6.9	1.4	0.47	14.6
SF-8092	10 Oct 1966	7° - 4°N	15.2	22.8	7.4	(0.8)	0.61	12.1
Production Ratios:								
Megaton yield events (Harley et al[14]):					5.2	1.8	0.65	8.0

TABLE 105. The Mo^{99}/Zr^{95} Activity Ratios in Three October 1966 Samples

				Corrected to 11 Sep 1966		Corrected to 25 Sep 1966		Corrected to 4 Oct 1966	
Sample Number	Collection Date	Latitude	Altitude (km)	$\frac{pCi\ Zr^{95}}{SCM}$	$\frac{Mo^{99}}{Zr^{95}}$	$\frac{pCi\ Zr^{95}}{SCM}$	$\frac{Mo^{99}}{Zr^{95}}$	$\frac{pCi\ Zr^{95}}{SCM}$	$\frac{Mo^{99}}{Zr^{95}}$
SF-8087	10 Oct 1966	7° - 4°N	15.2	47.5	432	40.6	15.2	36.9	1.8
SF-8121	10 Oct 1966	14° - 32°S	15.2	119	5450	101	191	92.2	22
SF-8117	27 Oct 1966	7° - 15°S	16.8	14.8	4890	12.7	168	11.5	20

Expected Mo^{99}/Zr^{95} Ratios:

Megaton yield events (Harley, et al, 1965): 26.5

TABLE 106. Fission Product Ratios in October 1966 Samples Apparently Containing Radioactive Debris from the 4 October 1966 Event, with Data Corrected to that Date

Sample Number	Collection Date	Latitude	Altitude (km)	pCi Sr^{89} / SCM	Ba^{140}/Zr^{95}	Ce^{141}/Zr^{95}	Sr^{89}/Zr^{95}	Ba^{140}/Zr^{95}
Samples collected at 15.2 km								
SF-8093	10 Oct 1966	4° - 10°S	15.2	2.6	4.3	1.7	0.49	8.5
SF-8122	10 Oct 1966	14° - 18°S	15.2	24.0	4.1	2.1	0.31	13
SF-8123	10 Oct 1966	18° - 23°S	15.2	50.5	3.7	2.4	0.38	9.7
SF-8124	10 Oct 1966	23° - 27°S	15.2	35.0	6.1	2.4	0.42	9.8
SF-8125	10 Oct 1966	27° - 32°S	15.2	13.7	5.3	2.8	0.61	8.7
SF-8121	10 Oct 1966	14° - 32°S	15.2	29.4	4.9	(0.8)	0.32	15
Mean values of ratios:					4.7±0.9	2.3±0.4	0.42±0.11	11±2.8
Samples collected at 16.8 km								
SF-8118	27 Oct 1966	9°N - 7°S	16.8	4.7	6.2	2.8	0.92	6.7
SF-8117	27 Oct 1966	7° - 15°S	16.8	10.9	7.5	3.2	0.94	7.9
SF-8119	27 Oct 1966	15° - 31°S	16.8	2.4	4.7	2.7	0.88	5.3
Mean values of ratios:					6.1±1.4	2.9±0.3	0.91±0.03	6.6±1.3
Mean values of ratios for all samples:					5.2±1.2	2.5±0.5	0.59±0.28	9.4±3.0
Production Ratios:								
Megaton yield events (Harley et al[14])					5.2	1.8	0.65	8.0

event, though there is evidence of some enrichment of strontium-89 relative to zirconium-95 in the highest portion of the radioactive cloud, which was intercepted at 16.8 km, and a corresponding depletion of strontium-89 relative to zirconium-95 in the somewhat lower portion of the cloud intercepted at 15.2 km. Barium-140 and cerium-141 may show similar, though less pronounced, enrichment and depletion relative to zirconium-95 at these two altitudes. Thus the data for debris attributed to the 4 October 1966 nuclear event suggest that a slight separation of the "volatile" and "refractory" fission products occurred within the radioactive cloud produced by this event. In general, however, the extent of fractionation in this event and in the two which occurred during September 1966 was so slight that there appears to be little hope of using the extent of fractionation to distinguish between debris initially injected into the stratosphere and debris initially injected into the troposphere.

During November and December 1966 (Figure 82) only those STARDUST missions flown at altitudes below 18 km intercepted radioactive debris from the 1966 French events. Strontium-89 concentrations and fission product ratios for fifteen filter samples collected during these months and analyzed for several fission products are presented in Table 107. A few samples collected below 10 km, and clearly in the troposphere, are included in the list. With each passing month the activities of the samples were lower and the measurements were correspondingly more subject to error. Nevertheless the fission product ratios given in Table 107 are in reasonable agreement with those given in Table 106 suggesting that in the calculations which follow, in which an arbitrary mean date of origin must be assigned to all French debris, 4 October 1966 may be used as the approximate date of origin for the French debris collected during the last half of 1966.

TABLE 107. Fissic Product Ratios in November 1966 and December 1966 STARDUST Samples, Corrected to 4 October 1966

Sample Number	Collection Date	Latitude	Altitude (km)	pCi Sr^{89} / SCM	Ba^{140}/Zr^{95}	Ce^{141}/Zr^{95}	Sr^{89}/Zr^{95}	Ba^{140}/Zr^{95}
SF-8134	11 Nov 1966	9°N - 30°S	8.8	0.72	4.5	3.0	0.68	6.7
SF-8135	11 Nov 1966	21° - 32°S	9.1	2.47	7.2	4.0	0.94	7.7
SF-8142	13 Nov 1966	9°N - 30°S	8.5	0.28	5.7	2.7	0.64	8.9
SF-8139	12 Nov 1966	30° - 54°S	8.2	0.51	4.9	2.5	0.69	7.0
SF-8132	10 Nov 1966	7° - 14°S	15.2	6.0	7.4	3.6	0.86	8.6
SF-8137	12 Nov 1966	11° - 19°S	15.2	11.0	6.6	3.2	0.71	9.4
SF-8138	12 Nov 1966	23° - 31°S	15.2	11.3	9.1	3.5	1.03	8.8
SF-8133	10 Nov 1966	1° - 9°S	16.8	4.6	3.4	1.9	0.44	7.6
SF-8141	13 Nov 1966	15° - 31°S	16.8	5.2	4.7	2.1	0.56	8.5
SF-8136	11 Nov 1966	33° - 46°S	16.8	7.0	6.3	3.2	0.92	6.9
Mean values of ratios for all November samples:					6.0±1.7	3.0±0.7	0.75±0.18	8.0±1.0
SF-8197	5 Dec 1966	9°N - 35°S	7.0	0.15	8.7	3.9	0.74	11.8
SF-8194	7 Dec 1966	33° - 54°S	7.3	0.18	11.0	5.1	0.91	12.0
SF-8195	7 Dec 1966	35° - 47°S	15.2	4.7	8.0	4.1	0.88	9.1
SF-8193	6 Dec 1966	7°N - 12°S	16.8	1.9	8.1	3.6	0.77	10.5
SF-8196	9 Dec 1966	11° - 30°S	16.8	3.5	7.4	3.6	0.78	9.5
Mean values of ratios for all December samples:					8.6±1.4	4.1±0.6	0.82±0.07	10.6±1.3

We have corrected strontium-89 activities of samples collected during the second half of 1966 to the reference date, 4 October 1966, and have calculated the apparent stratospheric burdens of French strontium-89 for August, October, November and December 1966. These are summarized in Table 108 together with corresponding strontium-90 burdens, calculated assuming a Sr^{89}/Sr^{90} production ratio of 147 for the French events. The French strontium-89 burden in August, attributable to the 19 July 1966 event, was quite small compared to those during later months, so the strontium-89 found in the stratosphere during October to December 1966 may be attributed almost completely to the September-October events. The calculated apparent burden during October is almost certainly higher than the actual stratospheric burden at that time. Many October samples were collected within a week following the 4 October 1966 event, and the radioactive cloud from that event was intercepted before it had had time to diffuse thoroughly in the zonal direction. The calculated apparent burdens during November and December 1966 are probably reasonably close in value to the actual stratospheric burdens during those months. It is quite likely that the French debris experienced a relatively short stratospheric residence time, for it was injected into the lower stratosphere in close proximity to the tropopause. Using the results in Table 108 and assuming that the French debris would experience a residence half-time in the stratosphere of between two and six months, it may be estimated that the total injection of strontium-89 into the stratosphere by the 1966 French tests was less than 1300 kCi, but more than 700 kCi, giving a best estimate of 1000 $\pm$ 300 kCi. This is equivalent to an injection of strontium-90 of 7 $\pm$ 2 kCi.

It is noteworthy that the French debris was confined almost entirely to the Southern Hemisphere. Some debris from the 24 September 1966 event had

TABLE 108. Apparent Stratospheric Burdens of Strontium-89 and Strontium-90 from the 1966 French Nuclear Events

Sampling Interval	Sr^{89} Burden (corrected to 4 October 1966)	Sr^{90} Burden ($0.0068 \times Sr^{89}$ Burden)
August 1966	44 kCi	0.30 kCi
October 1966	1270	8.6
November 1966	573	3.9
December 1966	326	2.2

entered the equatorial region of the Northern Hemisphere by mid-October (see Figure 81 and Table 108), and some French debris was still encountered in the equatorial region during November and December 1966. Nevertheless, there was no indication that any substantial portion of the French debris had moved north of 10°N by December. Some of the strontium-89 found in the region between 10° and 30°N at 15.2 and 16.8 km during December probably originated from the French tests, however, and it may be estimated that between 5 and 10 percent of the French debris still present in the stratosphere in December 1966 may have been situated north of the equator.

8.3 Radioactivity from the Chinese Nuclear Tests of October and November 1966

Measurements of filter samples collected during October 1966 to March 1967 failed to indicate the presence in the stratosphere of any radioactive debris attributable to the Chinese nuclear explosions of 27 October 1966 (which is reported[47] to have had a yield of 20 to 200 kilotons), or of 28 December 1966 (which is reported[48] to have had a yield of a few hundred kilotons).

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