Sr$^{90}$ Concentration in Precipitation from Convective Showers$^1$

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ABSTRACT

Analysis has been made of seven spring and summer convective showers collected at State College, Pa. The data indicate that the ground-level Sr$^{90}$ concentration in the precipitation is dependent upon the extent of the vertical development of the clouds from which the precipitation originates and the distance of these clouds from the jet stream. These data are contrasted to the data obtained for precipitation resulting from large-scale uplift: where the generating level is essentially constant, and the ground-level Sr$^{90}$ concentration has been shown to be dependent upon the descent experience of the precipitation in falling from the cloud to the ground.

1. Introduction

An analysis of the meteorological influences on Sr$^{90}$ fallout concentration in ground-level precipitation resulting from large-scale uplift has been previously reported by Salter, Kruger, and Hosler (1962)$^4$ from studies being made of three types of precipitation-producing systems: 1) large-scale uplift, 2) convective showers, and 3) orographic storms. This report delineates the initial results obtained from the study by Kruger and Hosler$^4$ of seven spring and summer rains-storms resulting from convective activity and collected at State College, Pa. The program involves the combination of a meteorological analysis of individual storms with radiochemical analysis of the precipitation collected during consecutive intervals throughout the periods of precipitation.

The data given by Salter, Kruger and Hosler (1962) showed that for large-scale uplift where drop sizes are small, the Sr$^{90}$ concentration in precipitation at ground level was dependent upon the descent experience of the precipitation. High cloud bases resulted in high Sr$^{90}$ concentrations in rain reaching the ground due to large amounts of evaporation. It was also pointed out that significant debris removal requires that the debris be involved in the condensation process. Greenfield (1957)$^5$ has examined the rain scavenging of particulate matter and shows that debris-bearing aerosols are contained in the cloud droplets as condensation nuclei or collected by Brownian motion and vapor gradient deposition. Drevinsky et al., (1958)$^6$ data on the size distributions of aerosols in the stratosphere show a most probable size range of 0.1 to 0.5 micron which may be utilized in the nucleation process (Junge, 1958). Particles smaller than 0.05 micron may be captured in the cloud droplets according to the mechanism proposed by Greenfield if not utilized as condensation nuclei, since Greenfield, Langmuir (1948), and Vaughan and Perkins$^7$ have each shown that for aerosols smaller than a few microns, the collection efficiency of falling drops is extremely low. Further, Landsberg (1938)$^8$ has pointed out that the number of condensation nuclei decreases rapidly with height. Thus, each of the smaller number of particles in the higher levels of the clouds has a higher probability of being utilized as a condensation nucleus than if competing with all the particles of terrestrial origin in the lower levels. Since the Sr$^{90}$-bearing particles are known to be of stratospheric origin, we believe that removal of Sr$^{90}$-bearing debris results from condensation processes within the cloud and that direct capture below the cloud is relatively unimportant.

For the large-scale uplift storms, the height of the generating level and the nucleation and growth mechanisms in the cloud remained essentially constant during the period of precipitation over the stationary collection site. During convective storms, however, precipitation is the result of vertical motions within a cloud system which are of the same order of magnitude as the horizontal motions and where the height of the generating level and the precipitation process vary greatly and drop sizes are large. While evaporation below the cloud.

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$^3$ Also at the Pennsylvania State University, State College, Pa.


base may be important in some areas where cloud bases are very high, it is not considered important in Central Pennsylvania where the bases are usually low.

In convective clouds air is incorporated into the cloud system not only through the warm-moist updraft at the base of the cloud, but also by entrainment of drier air by mixing processes with the environment (Squires, 1958). By this latter phenomenon dry particulate debris may enter the precipitation generating levels at higher altitudes and be used as condensation nuclei.

The first radar echo usually appears in the cumulus stage as a shower develops, often extending downward at a speed greater than the rate of fall of the precipitation particles, suggesting an almost simultaneous growth of precipitation through a considerable thickness of cloud (Byers, 1959).

This suggests that the initial precipitation collected under convective shower conditions will originate in the lower parts of the cloud system and thereby utilize as condensation nuclei particles from the lower regions of the troposphere where nuclear debris air concentrations are low.

During the mature stage of a shower when the most intense rain occurs, the cloud may extend to more than 60,000 ft, penetrating the tropopause, although more often the maximum height reached is from 40,000 to 45,000 ft (Byers, 1959). The precipitation is falling from higher levels; and even though the precipitation rate is greater and accompanied by less volume reduction of the larger elements by evaporation below the cloud, the air concentration of nuclear debris is much greater at these higher levels; and, therefore, the Sr\textsuperscript{90} concentration in precipitation reaching the ground would be expected to be greater. In addition, as the downdraft develops during this stage, some of the water moving downward must evaporate to keep the air saturated. This results in an even greater enhancement of the debris concentration in the precipitation finally falling from the cloud. This effect will be in proportion to the height of the storm and the intensity of the downdraft.

With penetration of the tropopause by the cloud tops, the Sr\textsuperscript{90} concentration may be expected to rise even further because of the much larger reservoir of nuclear debris in the stratosphere. In general, therefore, it is expected that during the mature stage of a cell the peak value of Sr\textsuperscript{90} concentration in precipitation will be coincident with the maximum height developed by the cloud tops.

When a cell is dissipating, the updraft disappears and the downdraft spreads over the entire area of the cell. As the updraft is cut off, the mass of water available to accelerate the descending air diminishes, so the downdraft also weakens. At this stage the convective system dissipates completely or only stratified clouds remain. Further precipitation is expected to be less intense, of smaller elements, and evaporation effects below the cloud may again become important. The Sr\textsuperscript{90} concentration in this precipitation is likely to diminish but may be influenced by descent experience as noted for large-scale uplift.

In summary, for convective showers the Sr\textsuperscript{90} concentration in collected precipitation should increase during the development of the convective cells, reach a peak value at the time precipitation from maximum cloud top development reaches the ground, and diminish as the dissipating stage begins.

A further consideration for understanding the absolute Sr\textsuperscript{90} levels in precipitation resulting from convective showers is the location of the cloud system to regions of high air concentrations of nuclear debris. It has been suggested by Machta and List\textsuperscript{4} that the jet stream break is a region of preferential stratospheric removal. This area is characterized by intense vertical gradients of debris concentration. Concentration gradients may also exist within the troposphere within well-developed cyclonic storm systems due to injections of stratospheric air (Danielesen, 1959). Since precipitation is considered to be the major process for removing Sr\textsuperscript{90} particles from high altitudes to the ground, the following factors must be important for determining the Sr\textsuperscript{90} levels in the precipitation as it is formed:

1) The location of the precipitation generating level with respect to the regions of high dry air concentration;
2) The rate with which the cloud air is mixing with the environment, that is, the rate of entrainment;
3) The moisture content of the air supporting the precipitation.

A further possible factor may be that particles containing the Sr\textsuperscript{90} may be attached to freezing nuclei and, therefore, be selectively removed at some particular temperature. If such mechanism takes place, then the degree to which the Bergeron-Findeisen mechanism is responsible for the generation of precipitation and the temperature at which it is operating may play a role in determining the Sr\textsuperscript{90} concentration in the precipitation at the generating level.

2. Data

The collection equipment and methods used to obtain the precipitation samples have been described previously by Salter, Kruger and Hosler (1962). After sampling the 8 March 1961 storm at Pittsburgh, Pa., the collectors were moved to State College, Pa., where 3-cm vertically-pointing radar coverage with an M33C radar apparatus was made available. The samples were shipped to the Nuclear Science and Engineering Corporation laboratories in Pittsburgh, Pa., for radiochemical analysis.

### Table 1. Precipitation collection and Sr\(^{90}\) concentration data: 8 March 1961.

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<td>Time of precip (hours)</td>
<td>Volume collected (liters)</td>
<td>Average precip rate (liters/hr)</td>
<td>\textbf{Sr} (^{90}) (dpm/sample)</td>
<td>\textbf{Sr} (^{90}) conc. (dpm/liter)</td>
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<td>to Day Time</td>
<td>Time of precip (hours)</td>
<td>Volume collected (liters)</td>
<td>Average precip rate (liters/hr)</td>
<td>\textbf{Sr} (^{90}) (dpm/sample)</td>
<td>\textbf{Sr} (^{90}) conc. (dpm/liter)</td>
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<td>15.1</td>
<td>17</td>
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<td>3.47 ± 0.11</td>
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### Table 3. Precipitation collection and Sr\(^{90}\) concentration data: 9 May 1961.

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<td>Time of precip (hours)</td>
<td>Volume collected (liters)</td>
<td>Average precip rate (liters/hr)</td>
<td>\textbf{Sr} (^{90}) (dpm/sample)</td>
<td>\textbf{Sr} (^{90}) conc. (dpm/liter)</td>
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<tr>
<td>9 May 1530</td>
<td>1555</td>
<td>0.084</td>
<td>24.6</td>
<td>290</td>
<td>85.4 ± 2.7</td>
<td>3.47 ± 0.11</td>
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<td>1955</td>
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<td>3.47 ± 0.11</td>
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### Table 4. Precipitation collection and Sr\(^{90}\) concentration data: 24 July 1961.

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<td>to Day Time</td>
<td>Time of precip (hours)</td>
<td>Volume collected (liters)</td>
<td>Average precip rate (liters/hr)</td>
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<td>81</td>
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<th>Sr$^{90}$ conc. (dpm/liter)</th>
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<td>Rinse</td>
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### Table 6. Precipitation collection and Sr$^{90}$ concentration data: 14 September 1961.

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<th>Time</th>
<th>to Day</th>
<th>Time</th>
<th>Time of precip. (hours)</th>
<th>Volume collected (liters)</th>
<th>Average precip. rate (liters/hr)</th>
<th>Sr$^{90}$ (dpm/sample)</th>
<th>Sr$^{90}$ conc. (dpm/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Sept.</td>
<td>1800</td>
<td>1910</td>
<td>0.25</td>
<td>Rinse</td>
<td>2.62</td>
<td>10.5</td>
<td>0 ±1.0</td>
<td>0 ±0.45</td>
</tr>
<tr>
<td></td>
<td>1920</td>
<td>1924</td>
<td>0.067</td>
<td>7.94</td>
<td>118</td>
<td>0 ±1.2</td>
<td>0 ±0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1924</td>
<td>1929</td>
<td>0.084</td>
<td>11.04</td>
<td>131</td>
<td>3.73±0.84</td>
<td>0.34±0.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1929</td>
<td>1931</td>
<td>0.033</td>
<td>10.78</td>
<td>237</td>
<td>3.62±0.76</td>
<td>0.34±0.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1931</td>
<td>1933</td>
<td>0.033</td>
<td>5.92</td>
<td>178</td>
<td>0 ±0.88</td>
<td>0 ±0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1933</td>
<td>1942</td>
<td>0.15</td>
<td>7.68</td>
<td>51</td>
<td>1.37±0.57</td>
<td>0.18±0.07</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1942</td>
<td>1945</td>
<td>0.05</td>
<td>1.40</td>
<td>28</td>
<td>2.16±0.68</td>
<td>1.55±0.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2052</td>
<td>2113</td>
<td>0.35</td>
<td>4.42</td>
<td>12.6</td>
<td>2.18±0.73</td>
<td>0.49±0.17</td>
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</tr>
<tr>
<td></td>
<td>2130</td>
<td>2235</td>
<td>1.084</td>
<td>2.62</td>
<td>2.4</td>
<td>0 ±0.93</td>
<td>0 ±0.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2249</td>
<td></td>
<td>—</td>
<td>Rinse</td>
<td>0</td>
<td>±1.3</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

### Table 7. Summary of meteorological and radiochemical data for the convective showers.

<table>
<thead>
<tr>
<th>Date (1961)</th>
<th>Tropopause Height (ft)</th>
<th>Temp. (°C)</th>
<th>3-cm radar echo tops Ave. (ft)</th>
<th>Max. (ft)</th>
<th>Dist. to jet stream (+) mil N (-) mi S</th>
<th>Freezing level (ft)</th>
<th>Precipitable water (inches)</th>
<th>Showalter stability index</th>
<th>Synoptic type</th>
<th>Average Sr$^{90}$ conc. (dpm/l)</th>
<th>Peak Sr$^{90}$ conc. (dpm/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Mar.</td>
<td>23,500</td>
<td>— 33</td>
<td>20,000</td>
<td>29,000</td>
<td>+ 75</td>
<td>8,500</td>
<td>0.86</td>
<td>+6</td>
<td>occlusion passage</td>
<td>8.8</td>
<td>51.0</td>
</tr>
<tr>
<td>8 May</td>
<td>41,800</td>
<td>— 69</td>
<td>20,000</td>
<td>20,000</td>
<td>— 400</td>
<td>10,500</td>
<td>1.04</td>
<td>+2</td>
<td>pre-cold frontal</td>
<td>0.39</td>
<td>0.4</td>
</tr>
<tr>
<td>9 May</td>
<td>38,900</td>
<td>— 61</td>
<td>35,000</td>
<td>41,000</td>
<td>— 400</td>
<td>10,500</td>
<td>1.04</td>
<td>+2</td>
<td>pre-cold frontal</td>
<td>6.1</td>
<td>6.7</td>
</tr>
<tr>
<td>24 July</td>
<td>44,500</td>
<td>— 62</td>
<td>38,000</td>
<td>40,000</td>
<td>— 300</td>
<td>13,800</td>
<td>1.70</td>
<td>+1</td>
<td>squall line</td>
<td>5.6</td>
<td>9.9</td>
</tr>
<tr>
<td>25 Aug.</td>
<td>42,000</td>
<td>— 62</td>
<td>32,000</td>
<td>38,000</td>
<td>— 190</td>
<td>13,000</td>
<td>1.60</td>
<td>+1</td>
<td>cold frontal</td>
<td>0.25</td>
<td>0.8</td>
</tr>
<tr>
<td>14 Sep.</td>
<td>48,000</td>
<td>— 67</td>
<td>33,000</td>
<td>36,500</td>
<td>— 450</td>
<td>14,800</td>
<td>1.07</td>
<td>+5</td>
<td>cold frontal</td>
<td>0.21</td>
<td>1.6</td>
</tr>
</tbody>
</table>
For each storm the following data were obtained:

1) Storm description;
2) Surface chart and upper air analysis;
3) Sounding for tropopause location;
4) Radar observations for echo tops;
5) Sample collection periods;
6) Quantity and rate of precipitation;
7) Quantity and concentration of Sr$^{90}$ in the samples.

These data are given following the description of each storm. The surface analysis shows the prevailing weather. Tropopause data and the 35,000-ft streamline analysis were used to locate the jet stream relative to Pittsburgh or State College. The collection and radiochemical data for each storm are given in Tables 1–6, respectively. Pertinent meteorological data are summarized in Table 7. The average precipitation rate was obtained from the total volume collected and the time duration of precipitation during each sampling period.

The concentrations of Sr$^{90}$ collected as a function of time during the storms are shown in Fig. 3. The horizontal bars show the period of collection and the vertical bar, the standard deviation of concentration due to the counting error.

8 March 1961. An intense frontal system moved eastward through the Central Plains during the morning of 8 March, 1961. Light precipitation falling from layer clouds had spread widely in advance of the rapidly developing system. During the early afternoon, scattered thunderstorms developed in the warm air just ahead of the cold front, and the system began to occlude as it approached the Ohio Valley. As the occlusion process proceeded, the warm, moist air which was supporting showers was lifted farther and farther aloft, causing the showers to extend to increasing altitudes.

Figs. 1a and 1b show the surface chart and the upper air analysis for 1900E. An occluded front extended from western Pennsylvania to a secondary low-pressure center which developed along the New Jersey coast. As the secondary low proceeded to intensify, the occluded portion of the front underwent frontalysis. The location of the jet stream core is not well defined for this period. A broad zone of strong winds is located between Washington, D. C., and Pittsburgh. The tropopause has several leaves in this region; and there appear to be two cores, one near Washington, D. C., and the other about 75 miles east of Pittsburgh.

Figure 2a is the 1900E sounding taken at Pittsburgh. The sounding shows a double tropopause with the lower one at about 23,500 ft and the upper at 44,400 ft. The temperature at the lower tropopause was $-33^\circ$C. The showers sampled during the afternoon and evening of 8 March had echo tops which were from 20,000 ft to 29,000 ft, with the later showers reaching the higher altitudes.

The precipitation collection and Sr$^{90}$ radiochemical data are listed in Table 1.

8 May 1961. On 8 May a frontal system moved eastward through the Mississippi Valley. Fig. 1c shows the surface chart for 2200E. The surface winds were light and from the south; the surface temperatures were near 70°F; and the dew points, in the low 60's. The upper air analysis, Fig. 1d, locates the jet stream with maximum winds of about 125 knots just north of the Great Lakes. Thus, the showers sampled were at a considerable distance south of the jet (approximately 400 miles). Fig. 2b is the 1900E sounding taken at Pittsburgh.

Two separate showers were sampled. The first was an individual decaying shower which moved over the site and had echo tops near 20,000 ft. The second collection was from a thunderstorm which developed as part of a meso-scale system in western Pennsylvania and moved eastward across central Pennsylvania with the characteristics of a squall line. The echo tops of these cells varied from 35,000 ft to 41,000 ft.

The precipitation collection and Sr$^{90}$ radiochemical data are listed in Table 2.

9 May 1961. On 9 May a frontal wave was located in western Ohio and a north-south cold front extended from Canada to the Gulf of Mexico. Fig. 1e shows the 1300E surface chart. Over central Pennsylvania the surface temperatures were in the high 70's, the dew points about 60°F, and there was strong southerly flow at the surface.

The upper wind analysis, Fig. 1f, shows the jet stream near Erie, Pa., approximately 150 miles northwest. The maximum winds in the jet were 90 to 100 knots. The 1900E Pittsburgh sounding, Fig. 2c, locates the tropopause at 38,900 ft and at a temperature of $-61^\circ$C.

The shower sampled was a large cell which was part of a squall line that later extended the full length of the frontal system. This portion of the line developed 35 miles southwest of the site, and the most intense cell passed directly over the collection area. The echo tops of this storm were 35,000 to 40,000 ft. Surface winds up to 80 mph were recorded near the site.

The precipitation collection and Sr$^{90}$ radiochemical data are listed in Table 3.

24 July 1961. On 24 July a cold front was moving eastward across Lake Erie with scattered showers occurring in Ohio and western Pennsylvania. The surface analysis for 1300E is shown in Fig. 1g. The surface winds were southerly, the temperatures in the low 80's and the dew points were in the mid-70's throughout the area ahead of the front.

The wind analysis for the 35,000-ft level is given in Fig. 1h. The jet stream was located near Toledo, Ohio, (approximately 300 miles northwest of the site) and the maximum winds in the jet were 75 knots. The 1900E Pittsburgh sounding, Fig. 2d, locates the tropopause at 44,800 ft and at a temperature of $-62^\circ$C.

The shower sampled was part of a line which de-
developed from scattered showers 30 miles west of the site. The echo tops of these cells were near 40,000 ft. This line had the characteristics of a squall line and was still in the developing stage as it passed the site.

The precipitation collection and Sr\(^{90}\) radiochemical data are listed in Table 4.

25 August 1961. On 25 August a high-pressure ridge covered the eastern third of the United States, and a frontal system moved eastward across the North-Central Plains. Fig. 1i shows the surface chart for 1300E. The surface flow was light and from the south. The temperatures in central Pennsylvania were in the high 70's; and the dew points, in the high 60's.

The flow at 35,000 ft is shown in Fig. 1j. The jet stream is located over Lake Erie, 190 miles northwest of the collection site. Fig. 2e is the Pittsburgh sounding taken at 1900E. The tropopause was at a height of 42,000 ft and at a temperature of \(-62^\circ\C\).

The shower collected developed as part of a line west of the site and moved slowly eastward across the area. The echo tops of the cells varied from 32,000 to 38,000 ft. The precipitation collection and Sr\(^{90}\) radiochemical data are listed in Table 5.

14 September 1961. On 14 September a north-south cold front moved through Ohio into western Pennsylvania. Behind the cold front a large high-pressure ridge with temperatures in the low 50's covered most of the central United States. The surface chart for 1900E is shown in Fig. 1k.

In Pennsylvania the air mass ahead of the front, being the northern extension of the sub-tropical high, was very stable. Thus, the instability needed to generate the
showers was available only at the leading edge of the frontal surface. The showers, consequently, did not attain very great heights or intensity.

The flow at 35,000 ft is shown in Fig. 11. The Pittsburgh sounding at 1900E is shown in Fig. 2f. The tropopause was at 48,000 ft and at a temperature of –67°C. The jet stream was over the northern part of Lake Michigan about 450 miles northwest of the site. The highest echo tops measured in these cells were about 36,000 ft.

The precipitation collection and Sr⁹⁰ radiochemical data are listed in Table 6.

3. Evaluation

The analysis of the Sr⁹⁰ concentration for the seven storms collected during the report period was made in terms of the convective nature of these storms. From the considerations given in the Introduction, it was anticipated that the aliquot of highest Sr⁹⁰ concentration would originate from a generating zone near the maximum altitude of the cloud tops or near the lowest vertical distance from the jet stream.

A summary of the meteorological and radiochemical data are given in Table 7. The peak Sr⁹⁰ concentrations taken from Tables 1 to 6 are compared to the average Sr⁹⁰ concentration which would be observed if the rain were collected from the total storm and analyzed as a single sample. In five of the seven storms the peak Sr⁹⁰ concentration was a factor of two or more greater than the average Sr⁹⁰ concentration for the storm as a whole. The peak Sr⁹⁰ concentration generally occurred after the onset of precipitation at the collection site,
suggested that the cells were still developing vertically when the first precipitation began to reach the ground-level stationary collectors, and later precipitation fell from the greater height achieved at the peak of vertical development. Sufficient detail was not available for these storms to determine whether the individual Sr$^{90}$ concentration peaks came from individual cells since several cells in close proximity were contributing water at any time. We also noted that cells in various stages of development passed over our collection site. We determined the height of the highest cell in the group during collection and used this value as the peak height.

The number of showers that show increases in Sr$^{90}$ concentration after the onset of precipitation indicates that mechanical removal of dry debris below the cloud and evaporation are playing insignificant roles here. Both of these processes would tend to yield decreasing Sr$^{90}$ concentrations with time due to cleansing on the one hand and gradual decrease in low-level evaporation on the other.

A preliminary analysis has been made of the correlation of the peak Sr$^{90}$ concentration with the extent of vertical development of the cloud and distance to the jet stream. These data are shown in Fig. 3 on a normalized plot prepared by Giles$^7$ of atmospheric Sr$^{90}$ concentrations derived from high-altitude sampling programs. The air concentrations are given in dpm per $10^3$ scf. [Disintegrations per minute per $10^3$ standard cubic feet, where standard is a pressure of 1 atmosphere and a temperature of 15°C.] On this plot the observed peak Sr$^{90}$ concentration, in dpm $l^{-1}$, is placed in relation to both the relative distance of the cloud tops from the tropopause and the distance from the jet stream. Two observations may be made from Fig. 3. The peak Sr$^{90}$ concentration value is shown to be strongly dependent on the relative location of the shower, both vertical and horizontal, with respect to the jet and the tropopause. Further, even though no a priori quantitative correlation is inferred between airborne concentration in dpm

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FIG. 3. Sr\(^{90}\) concentration in precipitation aliquots from the six storms studied.

FIG. 4. Peak Sr\(^{90}\) concentration (dpm l\(^{-1}\)) in convective shower precipitation plotted at relative position of maximum cloud tops and distance from jet core. Data are superimposed on air concentration plot (dpm per 10\(^{9}\) scf) from Giles (1961).
per 10^3 scf and precipitation concentration in dpm l^-1, a good over-all fit is, indeed, observed. This fit may be completely fortuitous or may indicate some quantitative process of dry and moist air being mixed throughout the vertical development of the shower with a possible dependence of precipitation concentration upon the Sr^86-attached particulate "reservoir" available for nucleation.

The penetration of the tropopause by convective clouds may be a significant method of transport of stratospheric debris into the troposphere and to the ground. Fig. 4 shows our highest observed concentration value of 51 dpm/liter, which occurred in the 8 March 1961 rain during the "spring peak." This value occurred during the time period, according to our observations, when a thunderstorm developed under one of the "leaves" of the tropopause and penetrated to the vicinity of the jet. US Weather Bureau radar reports gave the echo top at 29,000 ft, which places the actual cloud top well into the mixing zone. The pressure jump at the surface indicates that this was a very intense thunderstorm with a well-developed downdraft, and the height given by radar may actually be underestimated.

Several models have been delineated for accounting for the spring peak. For example, Machta and List suggest that vertical downward flow of air at the polar tropopause carries the nuclear debris through at this time of year. Our data, however, indicate that convective clouds penetrating the tropopause may be a significant method of removal working in concert with the large-scale mechanisms. Such penetration is most probable during the spring months and, therefore, is likely to be coincident with a larger-scale downward flow through the break in the tropopause in the vicinity of the jet. It is anticipated that direct attention will be given to this possibility during the continuation of our studies of convective storms.

Casual observation of virga under high- and middle-cloud conditions reveals that precipitation falling from these levels and evaporating into drier air below may also be a strong contributor to downward transport of nuclear debris in the troposphere. The fall velocities of the Sr^86-bearing particulates themselves, as well as large-scale vertical velocities in the troposphere, are of the order of 1 cm sec^-1 or less; whereas, the virga or evaporating precipitation falls at a minimum of 100 cm sec^-1 and as much as 1000 cm sec^-1. Thus, wide-spread precipitation not reaching the ground could greatly accelerate the downward transport of Sr^86 to the lower layers of the troposphere. The combination of convective clouds reaching the tropopause with the resultant removal of debris from the stratosphere and the downward transport by the ensuing precipitation and later by other low-level precipitating systems may, therefore, determine the rate at which nuclear debris reaches the ground.

4. Conclusions

From our observations and analysis in terms of the simple description of convective cells, we feel that the Sr^86 concentration in precipitation reaching the ground is influenced by the vertical development of the convective clouds and the distance of the clouds from large air concentrations of debris, such as found at the tropopause or the jet core. In summary, for simple, one-celled, non-pulsating, stationary convective systems, the Sr^86 concentration should increase during the development of the convective cell, reach a peak value during maximum development (the absolute value being in relation to the maximum height reached by the cloud tops and the air particulate concentration at these levels) and diminish as the dissipating stage begins (unless the system degenerates to stratiform conditions).

For the storms studied during this period, we have been able to relate the peak Sr^86 concentration to the highest development of the precipitating cloud and to its position relative to the tropopause and the jet axis.

However, it is obvious from these data and examination of the problem that our consideration of a convective cell is too simple for the type of convective showers that occur in nature. This is because there is no clear break between the decay of an old cell and the development of a new one. A more detailed examination of the time variations within the life cycle of a given convective shower is required to understand the influences of convective showers upon the transport of nuclear debris from the atmosphere to the ground by precipitation. Some of the meteorological considerations which require examination are:

1) The ratio of low-level to high-level entrainment;
2) The change in this ratio during the life cycle of the shower;
3) The degree of constancy or periodicity of the entrainment process and the showers with respect to the collection station;
4) The stage or stages of the convective cells from which precipitation reaches the collection site;
5) The rate of movement of the shower compared to the rate of change of the shower itself.

We anticipate examining these considerations in greater detail during our continued studies of Sr^86 concentration in precipitation resulting from convective showers.

Acknowledgments. The authors appreciate the assistance of Larry Davis and Ray Boeker of State College, Pa., who participated in the convective shower collections and the preparation and evaluation of the meteorological data. Mr. Carl Wilson and Miss Nan Norris of Nuclear Science and Engineering Corporation participated in the radiochemical analysis of the samples.
REFERENCES


