# *RADIOACTIVE FALLOUT*

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I. *Introduction.*—The radioactivity produced by the detonation of nuclear weapons has been extensively studied and reported upon.[1-18] From this work we have learned about the amount of radioactive fallout which occurs and the mechanisms for its dissemination in a broad and general way. A few of these general points are as follows:

1. The stratosphere plays an extremely important role for the fallout from megaton-yield weapons, and the troposphere is the medium which disseminates the fallout from kiloton detonations; thus, speaking broadly, stratospheric debris is from megaton-yield detonations and the tropospheric fallout is from those of lower yield. It is not that the yield of the detonation is determinative but rather that the altitude to which the fireball rises before its average density is equalized with that of the surrounding air determines the fallout rates. The megaton-yield fireballs are so enormous that they stabilize at levels only above the tropopause—the imaginary boundary layer dividing the upper part of the atmosphere, the stratosphere, from the lower part, the troposphere—while the kiloton-yield fireballs stabilize below the tropopause. The tropopause normally occurs at something like 40,000–50,000 feet altitude, although it depends on season and location. In other words, low-yield bombs fired in the stratosphere would be expected to give the same slow fallout rates as high-yield weapons do when fired in the troposphere—or on the surface, if attention is focused on the part of the fallout which does not come down locally to form the oval-shaped pattern pointed in the downwind direction.

2. The stratospheric debris descends very slowly, unless, of course, it is so large as to fall in the first few hours. This paper is concerned only with the world-wide fallout—that is, the fallout which does not occur in the first few hours—and excludes the local fallout, which constitutes the famous elliptical pattern that is so hazardous because of its radiation intensity but which, in test operations, is carefully restricted to test areas. It is worth mentioning in passing that the local fallout may be the principal hazard in the case of nuclear war. Most serious attention should be paid to it in civilian defense programs.

The world-wide fallout from the stratosphere is literally world-wide in that the rate of descent of the tiny particles produced by the detonations is so small that something like 10 years or somewhat less probably is the average time they spend before descending to the ground, corresponding to an average annual rate of about 10 per cent of the amount in the stratosphere at any given time. It is not clear as to just how they do finally descend. It seems probable that general mixing of the stratospheric air with the tropospheric air, which occurs as the tropopause shifts with season and as it is brought about by the jet streams, constitutes the main mechanism and that the descent of the stratospheric fallout is never mainly due to gravity, but rather that the bulk mixing of stratospheric air with tropospheric air brings the radioactive fallout particles down from the stratosphere into the troposphere, where tropospheric weather finally takes over. The mechanism makes the percentage fallout rate the same for all particles too small to fall of their own

weight—and the same as would be expected for gases, provided that some means of rapidly removing the gases from the troposphere exists; hence the reverse process of troposphere to stratosphere transfer does not confuse the issue.

3. World-wide radioactive fallout in the troposphere is restricted to the general latitude of the detonations, for the reason that the residence time in the troposphere is about 30 days.[19-22] The lifetime of fine particles in the troposphere appears to be determined by the cleansing action of the water droplets in the clouds. For those particulates which are below 1 $\mu$ in diameter, Greenfield[21] calculates that the mean residence time of a 1-$\mu$ particle in a typical cloud of water droplets of 20 $\mu$ in diameter may vary between 50 and 300 hours, but that a particle of 0.04-$\mu$ diameter will last only 30–60 hours and that a particle of 0.01-$\mu$ diameter will last only 15–20 hours. The theory calculates the diffusion due to Brownian motion and says that it is just this motion induced by the collisions with the air molecules that makes possible the contact between the fallout particles and the cloud drops. Since this theory is based on first principles, with the single assumption that the fallout particle sticks to the water droplet on impact—an assumption so plausible as to be almost beyond doubt—it is no surprise to learn experimentally that the Greenfield theory appears to be correct.

There is essentially no world-wide fallout in the absence of rainfall—i.e., in desert regions—except for a little that sticks to tree leaves, blades of grass, and general surfaces, by the same type of mechanism as that Greenfield describes in the case of clouds. Thus we see that it is the moisture in the troposphere which assures the short lifetime of the world-wide fallout particles and that, when the stratospheric air, which contains essentially no moisture and therefore has no cleansing mechanism, descends into the troposphere, the tropospheric moisture proceeds to clean it up. On this model, we see that, for submicron fallout particles, weather phenomena are controlling and that the bombs which have insufficient energy to push their fireballs over the troposphere will have their world-wide fallout brought down in raindrops in a matter of about a month, in extreme contrast with the stratospheric material, which apparently stays aloft for something like 10 years, on the average. The contrast between these two lifetimes means that the concentration of radioactive fallout in the stratospheric air in terms of equal densities of air is always much higher than in tropospheric air. This has been experimentally observed to be true.[23] In fact, the stratospheric content is about 100-fold higher than that of the troposphere, corresponding to the much longer stratospheric residence time. Later in this paper, new data on the fallout content of the stratosphere are given.

It is inherent in the Greenfield mechanism that the total world-wide fallout will be proportional to rainfall if other factors are not allowed to vary. Thus we find that the Mediterranean basin[10] affords a good example of the truth of this principle. Other regions are northeastern United States, southeastern United States, northwestern United States, and southwestern United States.[24] It is now well established that desert areas have very little fallout.

4. After falling to the ground in the form of rain or being picked up on the surface of the leaves of grass or trees by the same type of Brownian-motion accretion mechanism that causes cloud-drop pickup, the radioactive fallout may enter the biosphere by normal biological processes. Radioactive strontium-90 and radio-

active cesium-137 are the two principal isotopes which have this facility, are produced in high yield by the fission reaction, and are of long enough lifetimes to be disseminated world-wide, particularly by the stratospheric mechanism—about 28 years half-life for each. Strontium-90 is produced at a level equivalent to about 1 millicurie of strontium-90 per square mile of the earth's surface for every 2 megatons of fission energy, and radiocesium is produced at about 50 per cent higher yield. Of the two isotopes, strontium-90, because of its chemical similarity to calcium, collects in human bone, where it is held for years and where its radiations might then cause deleterious effects on the health of the individual, such as leukemia or bone cancer. It is interesting that strontium-90 constitutes a relatively less important genetic hazard because of the short range of its radioactive radiation and the fact that it is not held in the reproductive organs. Radiocesium stays in the human body only 6 or 8 months, on the average, because it has no permanent structure like the bone for which it has a natural affinity. As a result, the amount of radiation occurring from internally ingested radiocesium is much less and most likely is subject to palliative measures calculated to reduce its time in the body. Strontium-90 taken into the bone, however, appears to be stored for many years, the exact time not being known very well.[25] Radiostrontium is taken into the body because of its similarity to calcium, but there is a definite difference in chemical behavior which causes animal organisms to prefer calcium. Thus the radiostrontium content of newly deposited bone calcium is less than that for food calcium. In many countries the principal source of calcium is milk products; hence the fact that cow's milk has only one-seventh the strontium in it per gram of calcium that the cow's food has and that milk taken into the human body similarly deposits calcium in the bones with only half the strontium-90 content of the milk itself means that human beings naturally have a lower strontium-90 to calcium ratio for new bone than for the food source by something like a factor of 15 for dairy products. On the other hand, vegetation containing strontium-90 also deposits its strontium relatively inefficiently, with a factor of something like 4 less strontium in the bone from these sources than is carried in the vegetable food itself—all relative to calcium. In some countries where calcium in the human diet comes principally from vegetables, other sources of calcium contribute, some of which contain essentially no strontium-90—namely, sea food. Because fallout is diluted so quickly by the action of the waves in the ocean, the concentration of the radioactive strontium in the sea calcium is very much lower than it is in the soil of the land in which the grass and vegetable crops grow. This difference becomes even larger when the effects of direct leaf and stem base pickup are considered. This perhaps accounts for the high values reported by Ogawa[26] for rice in Japan. Hence, fish from the sea are naturally at the lowest level in radiostrontium and sea food should be the lowest source of calcium among ordinary human foods. With all these factors taken together, the world populations assimilate calcium at a much lower radiostrontium content than is exhibited by land plants. Eckelmann, Kulp, and Schulert[18] have given a detailed sample calculation recently, based on their extensive measurements on human bone, and Comar has given the general principles for this type of calculation.[27]

5. The biological hazard from the radioactive fallout from weapons-testing is not well known, and, like many biological problems, the determination of the

hazard in any exact way seems to be almost impossibly difficult. Fortunately, however, it is possible to compare the radiation from radioactive fallout with the intensities of natural radiation to which we are always exposed. For example, it is clear that the present level of the radiostrontium in the bones of young children, which are, of course, closest to being in equilibrium with the fallout, since adults have had their bones some time even before there was any radioactive fallout, is about 2 milliroentgens per year as compared to an average natural dosage of 150–200 milliroentgens per year, about 1–2 per cent of the dosage from natural sources to the bones, depending upon location. Natural radioactivity present in the ground, building materials, and even our own bodies gives us an average total dose at sea level of about 150 milliroentgens per year, and medical X-rays add something like another 150 milliroentgens. The radiocesium taken into the body and the penetrating radiations from non-assimilable radioactive fallout contribute perhaps another 3 or 4 per cent to the whole-body dosage. Thus the total dosage to freshly formed human bone is, at most, 5 per cent of the natural dosage. Furthermore, we do know that the variations in natural background dosages from place to place are enormous in magnitude as compared to the average value and, of course, as compared to the fallout dosage. For example, it has been found[28] that exposure rates from external radiation rise from a value of about 90 milliroentgens per year at sea level to something like 150 milliroentgens per year at 5,000–6,000 feet altitude in the United States. These numbers are considerably larger than those expected on the basis of earlier calculations and measurements,[3,29–31] the increase apparently being due to the cosmic rays and their increase with altitude. In addition, the effects of radioactivity in the soil and in building materials made of stone or soil are considerable, amounting in some instances to 50 or 100 per cent of the average natural background dose at sea level, and the magnitude of the medical exposures to X-rays approximates, on the average, those due to all natural sources.[32]

We see, therefore, that, whatever the extent of our ignorance of the biological effects of radiation, we do know that these effects are not unexperienced by the human species, even from the genetic point of view, since it is clear now that persons living at high altitudes on granitic rocks always have received extra radiation many times greater than is contained in the radioactive fallout from the testing of nuclear weapons and that even those living on certain sedimentary rocks at sea level always have received about ten to twenty times the present fallout dose.

Of course, this does not mean that any of the effects from radioactive fallout are in any way negligible, and it does not mean that certain numbers of people will not be injured by radioactive fallout radiations, even though these numbers be very small relative to the total population of the world. However, the problem is bounded, and common sense and good judgment can be brought to bear on the extent of the biological hazards, even though they are not now known exactly and probably will not be well understood for many years. Researches to increase this understanding are being done, in the United States and United Kingdom and other countries. Information on radioactive fallout and all its aspects, both physical and biological, is collected and collated by the United Nations Scientific Committee on the Effects of Atomic Radiation, which is drafting its first report at the present time.

6. From our study of radioactive fallout from testing, we have learned much of

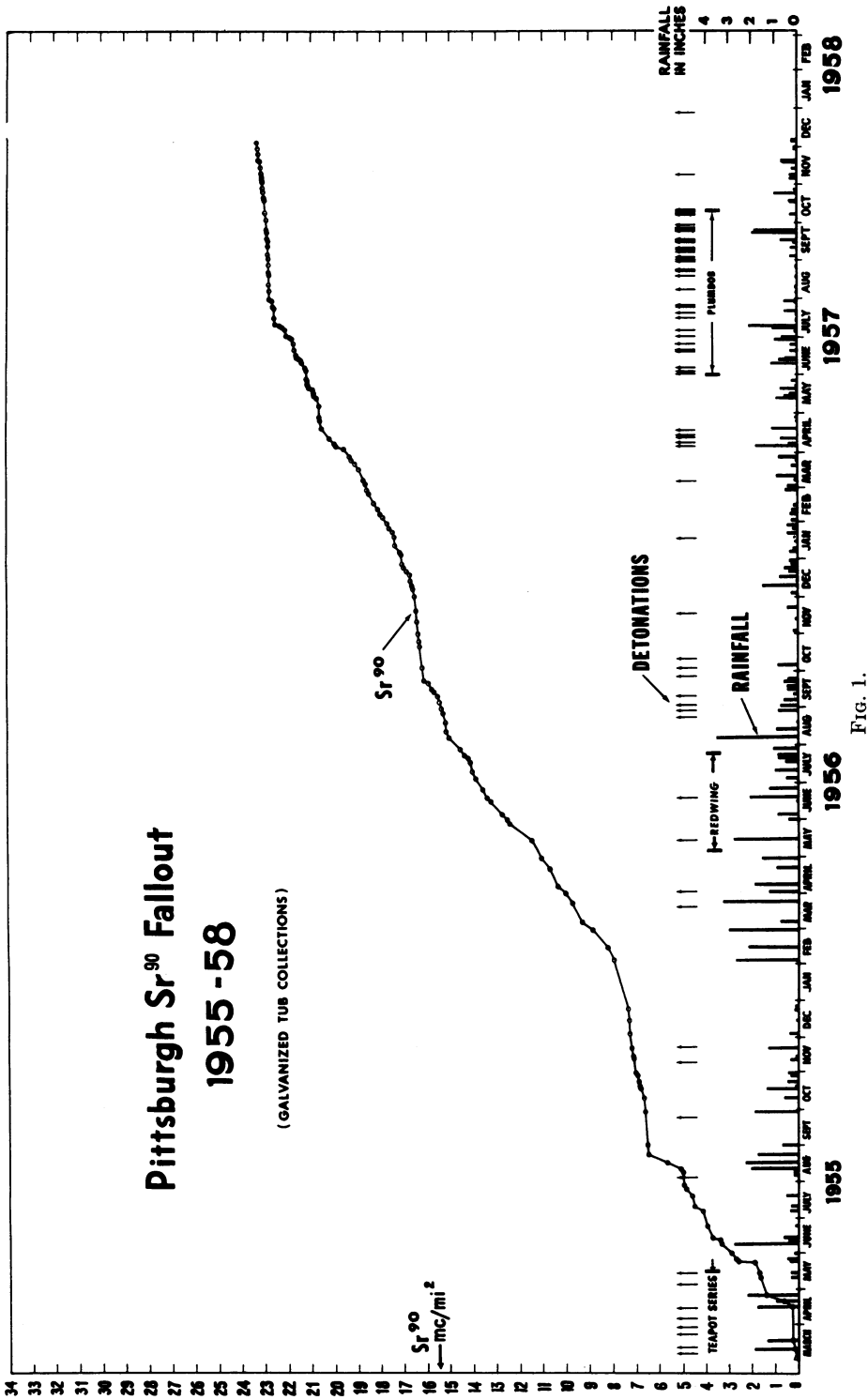
Pittsburgh Sr90 Fallout
1955-58
(GALVANIZED TUB COLLECTIONS)
Sr90
Sr90 ←mc/mi2
DETONATIONS
RAINFALL
TEAPOT SERIES
REDWING
PLUMBBOB
RAINFALL IN INCHES
1955
1956
1957
1958

FIG. 1.

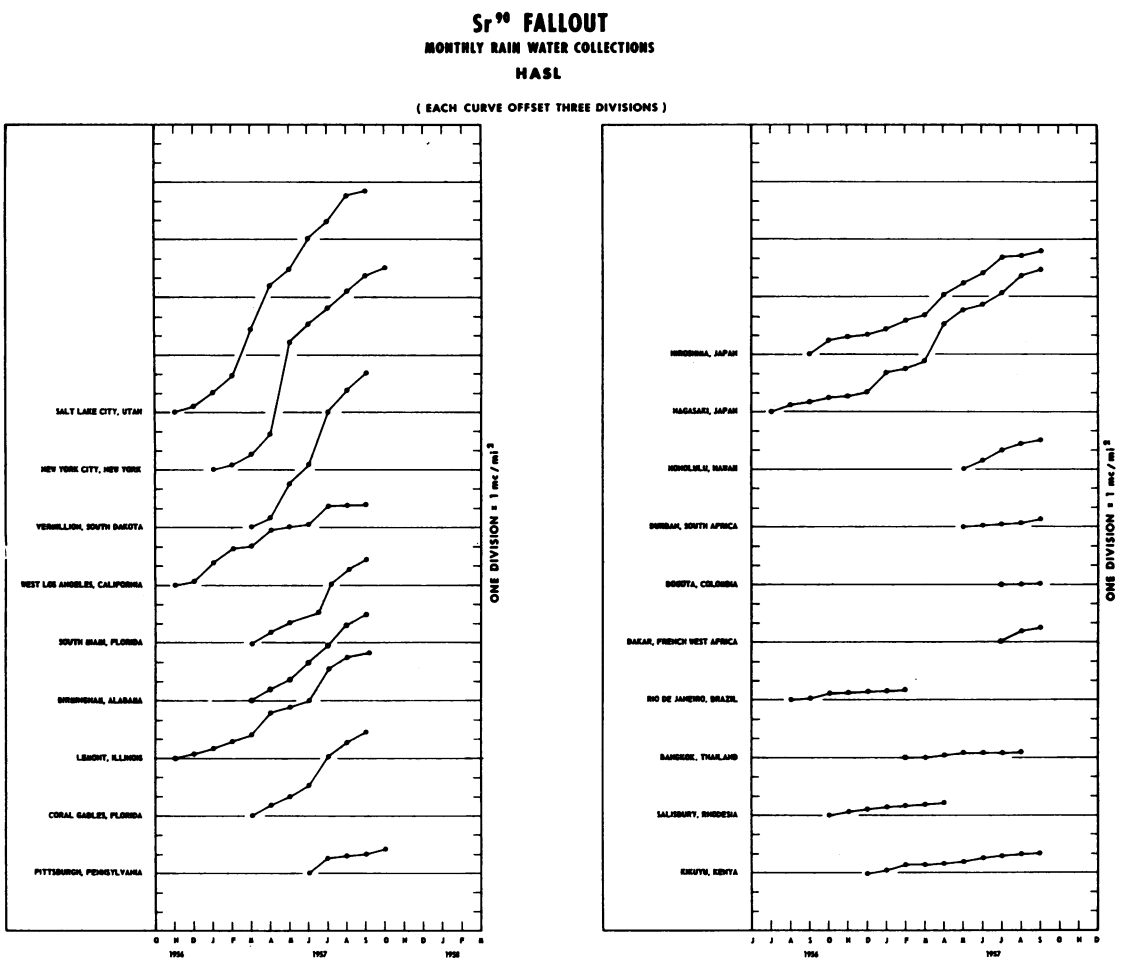


FIG. 2.

value about the circulation of the atmosphere of the world, and we have much more to learn as the study continues, particularly in the stratosphere by balloon and aircraft sampling techniques being carried out principally in the United States at the present time. As we undertake the problem of locating the fallout in the oceans, we undoubtedly will learn much of interest to oceanographers about the circulation of the water in the seas.

7. From our understanding of radioactive fallout from tests, we are the better able to devise methods of civilian defense against fallout in the case of nuclear war, and widespread popular interest in the potential possible hazards from radioactive fallout from nuclear tests has led to a considerable understanding on the part of the general public of these strange phenomena. From this debate and study may come the protection for millions if nuclear war should occur.

Understanding of the nature of the mechanism by which radioactive fallout is disseminated has led to the reduction of the offsite fallout from testing. We know now that bombs placed upon the ground produce relatively more local fall-

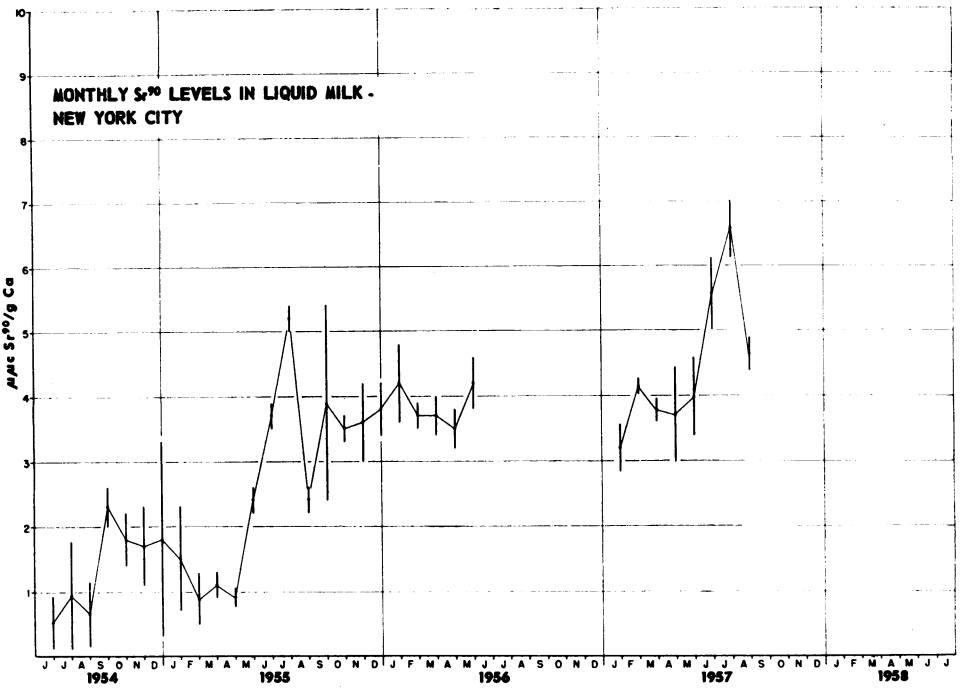


FIG. 3.

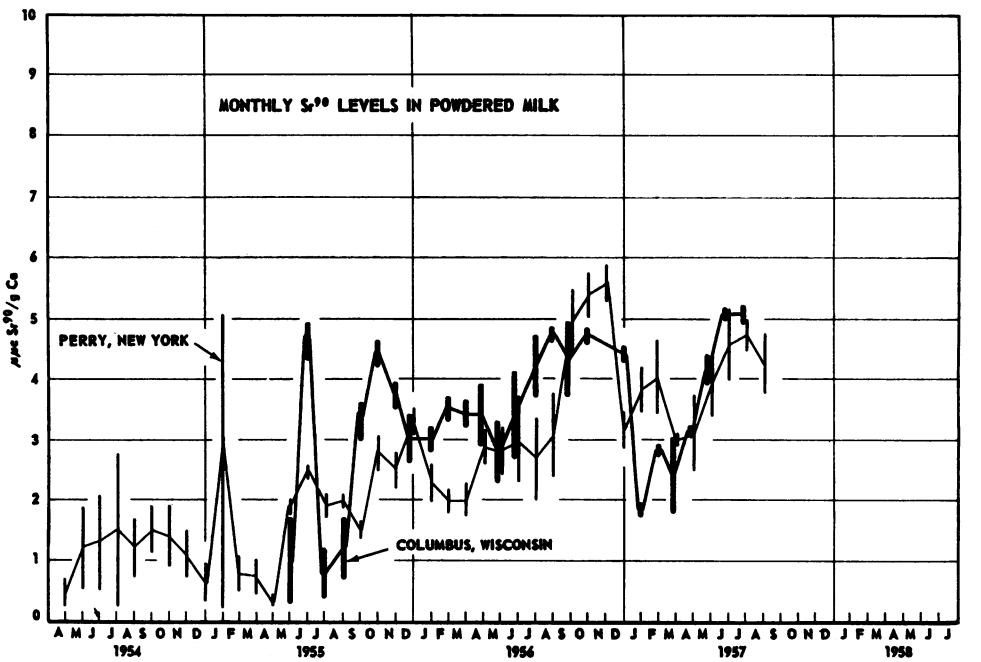


FIG. 4.

out and therefore less world-wide fallout. It seems likely that firing on the surface of the sea has a similar, though probably considerably less marked, effect.

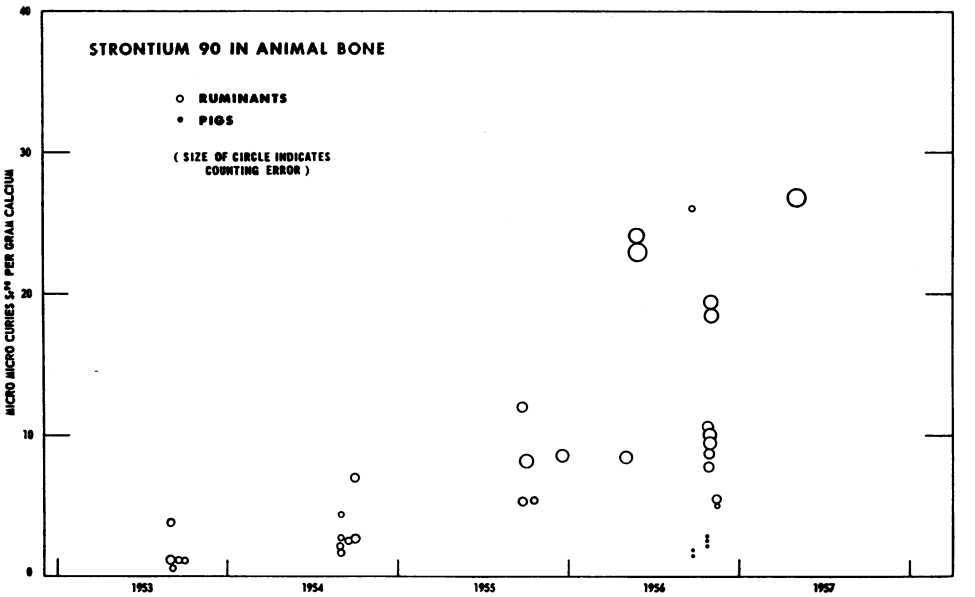


FIG. 5.

II. *Recent Data and Their Implications.*—Figures 1, 2, 3, 4, and 5 and Tables 1 and 2, which are up-to-date versions of earlier publications, give the most recent results for the fallout observed for rainfall collections, for the strontium-90 content of milk (fresh and dry), for human bone, and for animal bone. It is particularly

TABLE 1*

$Sr^{90}$ IN FALLOUT AT MONITORING SITES OUTSIDE CONTINENTAL UNITED STATES
(High-walled Stainless-Steel-Pot Collections)

| | Precipitation (Inches) | Observed mc $Sr^{90}/mi^2$ | mc $Sr^{90}/mi^2$ Calculated from Theory |
|---|---|---|---|
| *Bangkok, Thailand (14° N.)*: | | | |
| March, 1957 | 1.95 | 0.05 | 0.085 |
| April, 1957 | 5.85 | 0.13 | 0.25 |
| May, 1957 | 1.56 | 0.037 | 0.068 |
| June, 1957 | 9.36 | 0.016 | 0.41 |
| July, 1957 | 6.63 | 0.022 | 0.29 |
| August, 1957 | 11.70 | 0.039 | 0.051 |
| *Nagasaki, Japan (35° N.)*: | | | |
| August, 1956 | 17.43 | 0.34 | 0.76 |
| September, 1956 | 16.1 | 0.17 | 0.71 |
| October, 1956 | 3.59 | 0.20 | 0.16 |
| November, 1956 | 1.44 | 0.08 | 0.063 |
| December, 1956 | 1.37 | 0.22 | 0.069 |
| January, 1957 | 3.94 | 1.01 | 0.172 |
| February, 1957 | 3.28 | 0.17 | 0.143 |
| March, 1957 | 1.40 | 0.38 | 0.061 |
| April, 1957 | 11.27 | 1.98 | 2.4 |
| May, 1957 | 6.44 | 0.72 | 1.3 |
| June, 1957 | 10.18 | 0.27 | 2.1 |
| July, 1957 | 28.67 | 1.07 | 6.0 |
| August, 1957 | 11.35 | 0.457 | 2.4 |
| September, 1957 | 14.74 | 0.260 | 3.1 |

* Program administered and monitored by Health and Safety Laboratory of New York Operations Office, USAEC.

TABLE 1—*Continued*

| | Precipitation (Inches) | Observed mc $Sr^{90}/mi^2$ | mc $Sr^{90}/mi^2$ Calculated from Theory |
|---|---|---|---|
| *Hiroshima, Japan (35° N.):* | | | |
| August, 1956 | 11.93 | 0.50 | 0.52 |
| September, 1956 | 9.83 | ... | ... |
| October, 1956 | 3.51 | 0.27 | 0.15 |
| November, 1956 | 1.64 | 0.11 | 0.072 |
| December, 1956 | 0.23 | 0.06 | 0.010 |
| January, 1957 | 2.15 | 0.29 | 0.097 |
| February, 1957 | 2.26 | 0.53 | 0.098 |
| March, 1957 | 1.29 | 0.23 | 0.056 |
| April, 1957 | 11.00 | 1.12 | 2.3 |
| May, 1957 | 6.44 | 0.567 | 1.35 |
| June, 1957 | 10.22 | 0.493 | 2.2 |
| July, 1957 | 21.10 | 0.817 | 4.4 |
| August, 1957 | 4.48 | 0.047 | 0.94 |
| September, 1957 | 10.92 | 0.277 | 2.3 |
| *Rio de Janeiro, Brazil (23° S.):* | | | |
| September, 1956 | 1.95 | 0.12 | 0.085 |
| October, 1956 | 3.12 | 0.21 | 0.135 |
| November, 1956 | 3.51 | 0.06 | 0.155 |
| December, 1956 | 3.51 | 0 02 | 0.155 |
| January, 1957 | 2.73 | 0.04 | 0.12 |
| February, 1957 | 5.07 | 0.05 | 0.22 |
| *Salisbury, South Rhodesia (20° S.):* | | | |
| November, 1956 | 7.41 | 0.18 | 0.32 |
| December, 1956 | 7.80 | 0.12 | 0.34 |
| January, 1957 | 5.85 | 0.11 | 0.26 |
| February, 1957 | 8.97 | 0.08 | 0.04 |
| March, 1957 | 5.46 | 0.05 | 0.24 |
| April, 1957 | 1.17 | 0.04 | 0.05 |
| *Kikuyu, Kenya (0°):* | | | |
| January, 1957 | 9.75 | 0.14 | 0.43 |
| February, 1957 | 2.34 | 0.26 | 0.10 |
| March, 1957 | 3.12 | 0.03 | 0.13 |
| April, 1957 | 7.02 | 0.03 | 0.31 |
| May, 1957 | 14.82 | 0.138 | 0.64 |
| June, 1957 | 1.56 | 0.187 | 0.068 |
| July, 1957 | 0.08 | 0.148 | 0.0035 |
| August, 1957 | 0 20 | 0.020 | 0.0087 |
| September, 1957 | 2.34 | 0.038 | 0.10 |
| *Dakar, French West Africa (14° N.):* | | | |
| August, 1957 | 5.2 | 0.532 | 0.23 |
| September, 1957 | 10.44 | 0.244 | 0.45 |
| *Durban, Union of South Africa (30° S.):* | | | |
| June, 1957 | 0.39 | 0.080 | 0.017 |
| July, 1957 | 0.39 | 0.012 | 0.017 |
| August, 1957 | 0.78 | 0.096 | 0.034 |
| September, 1957 | 4.64 | 0.230 | 0.21 |
| *Pretoria, Union of South Africa (30° S.):* | | | |
| July, 1957 | 4.29 | 0.061 | 0.187 |
| August, 1957 | 1.56 | 0.074 | 0.068 |
| *Vienna, Austria (47° N.):* | | | |
| June, 1957 | 0.78 | 0.45 | 0.29 |
| July, 1957 | 5.07 | 1.95 | 1.85 |
| August, 1957 | 2.73 | 0.79 | 1.0 |
| *Klagenfurt, Austria (47° N.):* | | | |
| August, 1957 | 3.51 | 1.17 | 1.3 |

| | Precipitation (Inches) | Observed Mc $Sr^{90}/Mi^2$ AEC Lab. | Observed Mc $Sr^{90}/Mi^2$ Weather Station | Precipitation (Inches) | Observed Mc $Sr^{90}/Mi^2$ University of Hawaii | Mc $Sr^{90}/Mi^2$ Calculated from Theory |
|---|---|---|---|---|---|---|
| *Oahu, Hawaii (20° N.):* | | | | | | |
| June, 1957 | 0.32 | 0.72 | ... | 0.83 | 0.58 | 0.036 |
| July, 1957 | 2.10 | 1.36 | 0.477 | 1.62 | 0.42 | 0.071 |
| August, 1957 | 1.57 | 0.303 | 0.156 | 3.09 | 0.306 | 0.134 |
| September, 1957 | 1.54 | 0.274 | 0.188 | 0.62 | 0.159 | 0.027 |

TABLE 1—*Continued*

$Sr^{90}$ IN FALLOUT AT OTHER UNITED STATES MONITORING SITES
(High-walled Stainless-Steel-Pot Collections)

| | Precipitation (Inches) | Observed Mc $Sr^{90}/Mi^2$ | Mc $Sr^{90}/Mi^2$ Calculated from Theory: With Russian Component | Mc $Sr^{90}/Mi^2$ Calculated from Theory: Without Russian Component |
|---|---|---|---|---|
| *Lemont, Illinois (44° N.)*: | | | | |
| December, 1956 | 1.26 | 0.14 | 0.51 | 0.053 |
| January, 1957 | 2.06 | 0.30 | 0.38 | 0.088 |
| February, 1957 | 1.77 | 0.27 | 0.72 | 0.076 |
| March, 1957 | 1.98 | 0.47 | 0.80 | 0.085 |
| April, 1957 | 6.09 | 1.15 | 2.5 | 1.3 |
| May, 1957 | 3.21 | 0.27 | 1.5 | 0.68 |
| June, 1957 | 5.94 | 0.48 | 1.95 | 1.0 |
| July, 1957 | 8.98 | 1.57 | 3.6 | 1.9 |
| August, 1957 | 5.36 | 0.69 | 2.1 | 1.1 |
| September, 1957 | 1.08 | 0.12 | 0.41 | 0.21 |

| | Precipitation (Inches) | Observed Mc $Sr^{90}/Mi^2$ | Mc $Sr^{90}/Mi$ Calculated from Theory: With U.S. Component | Mc $Sr^{90}/Mi$ Calculated from Theory: Without U.S. Component |
|---|---|---|---|---|
| *Birmingham, Alabama (33° N.)*: | | | | |
| April, 1957 | 5.41 | 0.83 | 1.1 | 0.23 |
| May, 1957 | 2.96 | 0.39 | 0.62 | 0.13 |
| June, 1957 | 7.70 | 0.95 | 1.6 | 0.33 |
| July, 1957 | 2.62 | 0.80 | 0.55 | 0.11 |
| August, 1957 | 4.19 | 1.10 | 0.87 | 0.37 |
| September, 1957 | 9.59 | 0.42 | 2.0 | 0.41 |

| | | | With Russian Component | Without Russian Component |
|---|---|---|---|---|
| *Salt Lake City, Utah (38° N.)*: | | | | |
| December, 1956 | 1.67 | 0.31 | 0.66 | 0.071 |
| January, 1957 | 1.37 | 0.8 | 0.54 | 0.058 |
| February, 1957 | 0.72 | 0.83 | 0.29 | 0.031 |
| March, 1957 | 2.18 | 2.39 | 0.87 | 0.093 |
| April, 1957 | 3.24 | 2.30 | 1.4 | 0.65 |
| May, 1957 | 3.37 | 0.81 | 1.5 | 0.70 |
| June, 1957 | 1.47 | 1.61 | 0.66 | 0.31 |
| July, 1957 | 0.31 | 0.94 | 0.13 | 0.06 |

| | Precipitation (Inches) | Observed† mc $Sr^{90}/mi^2$ | mc $Sr^{90}/mi^2$ Calculated from Theory | |
|---|---|---|---|---|
| *West Los Angeles, California (34° N.)*: | | | | |
| December, 1956 | 0.49 | 0.15 | 0.02 | |
| January, 1957 | 3.88 | 0.99 | 0.16 | |
| February, 1957 | 1.94 | 0.76 | 0.08 | |
| March, 1957 | 0.95 | 0.09 | 0.041 | |
| April, 1957 | 1.33 | 0.84 | 0.28 | |
| May, 1957 | 0.27 | 0.24 | 0.056 | |
| June, 1957 | 0.06 | 0.12 | 0.012 | |
| July, 1957 | 0.03 | 0.92 | 0.006 | |

| | | | With U.S. Component | Without U.S. Component |
|---|---|---|---|---|
| *South Miami, Florida (26° N.)*: | | | | |
| April, 1957 | 5.04 | 0.53 | 1.07 | 0.22 |
| May, 1957 | 10.11 | 0.50 | 2.10 | 0.44 |
| June, 1957 | 5.82 | 0.56 | 1.28 | 0.27 |
| July, 1957 | 8.5 | 1.51 | 1.7 | 0.35 |
| August, 1957 | 13.6 | 0.75 | 2.8 | 0.58 |
| September, 1957 | 6.27 | 0.52 | 1.3 | 0.27 |

† Some local fallout from Nevada.

interesting to note that the data continue to show the principal features noted previously and that little new in principle has appeared.

TABLE 2*

AVERAGE STRONTIUM-90 CONTENT IN MAN, JULY 1, 1956–JUNE 30, 1957

| Location | AGE AT DEATH (YR.) 0–4 | 5–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–80 | 20–80 (Average) |
|---|---|---|---|---|---|---|---|---|---|
| North America | 0.67(30) | 0.69(17) | 0.38(15) | 0.07(14) | 0.06(9) | 0.08(16) | 0.05(5) | 0.07(18) | 0.070(62) |
| South America | 0.16(3) | 0.20(1) | 0.19(5) | 0.03(5) | 0.02(2) | 0.03(2) | 0.06(3) | 0.01(1) | 0.034(13) |
| Europe | 0.65(2) | 0.34(4) | 0.34(9) | 0.06(20) | 0.07(4) | 0.04(6) | 0.06(1) | 0.08(2) | 0.059(33) |
| Africa | ... | ... | 0.06(2) | 0.03(2) | 0.03(3) | 0.04(4) | ... | ... | 0.035(9) |
| Asia | 0.93(1) | 0.12(2) | 0.32(2) | 0.06(8) | 0.04(6) | 0.12(8) | 0.06(5) | 0.05(5) | 0.070(32) |
| Australia | 0.75(3) | 0.60(2) | ... | ... | 0.03(3) | 0.03(4) | 0.03(3) | ... | 0.03(10) |
| Entire world | 0.64(39) | 0.57(26) | 0.30(33) | 0.059(49) | 0.047(27) | 0.070(40) | 0.052(17) | 0.065(26) | 0.060(159) |

* Values are in uuc Sr/g of Ca, normalized to the whole skeleton. Figures in parentheses give the number of samples in the category. Data of Kulp, *et al.*, *Science*, **127** 266–74, 1958.

Figure 6 shows preliminary data from the AEC program on the stratospheric content of strontium-90. The data are preliminary for the reason that the air-filter efficiencies are unknown at the present, although estimated to be something like 25 per cent. The samples are taken by pumping stratospheric air through filters, which are then analyzed. Even though an enormous scatter is present for reasons of time and experiment, it is clear that there is no large variation in the stratospheric content of strontium-90 between the latitude of 30° S. and the Northern Hemisphere. Since most of the megaton-yield explosions have occurred in the northern latitudes, though the Pacific Testing Grounds are only 11° north of the equator, it appears that this evidence argues for rapid north and south mixing in the stratosphere. As we shall see later, other evidence in the dissemination of non-radioactive carbon dioxide derived from the combustion of fossil fuels[33–37] and in the dissemination of bomb-derived radioactive carbon-14 seems to confirm this.[38–40] It is interesting to note also that the actual content of the stratosphere is not in disagreement with the estimates given earlier,[5, 6, 15] although the value of the filter efficiencies remains to be settled, and it is estimated at the efficiency of about 25 per cent on evidence assuming homogeneity of the particle size. Experiments are now under way to settle the point.

In the model previously advanced,[5, 6, 15] it is proposed that material introduced into the stratosphere is mixed immediately horizontally to a uniform concentration and has a residence time of 10 years. Further, it is assumed that the latitudinal spread of tropospheric bomb clouds is only 10°, with a sharp step function rather than a normal error-curve distribution. The bomb debris is arbitrarily assigned to the stratosphere except for 1 per cent tropospheric in the case of megaton yields. Local fallout is assumed to be 80 per cent for land surface shots, 20 per cent for surface-water shots, and zero per cent for air shots. All kilo-yield shots are assigned to the troposphere. On these very simple bases we are then, from classified data about the magnitudes and nature of the explosions, able to estimate the total fallout for any place on earth if the deposition from the troposphere is assumed to be proportional to the rain content at a given location. Figure 7 gives such a theoretical latitudinal fallout profile

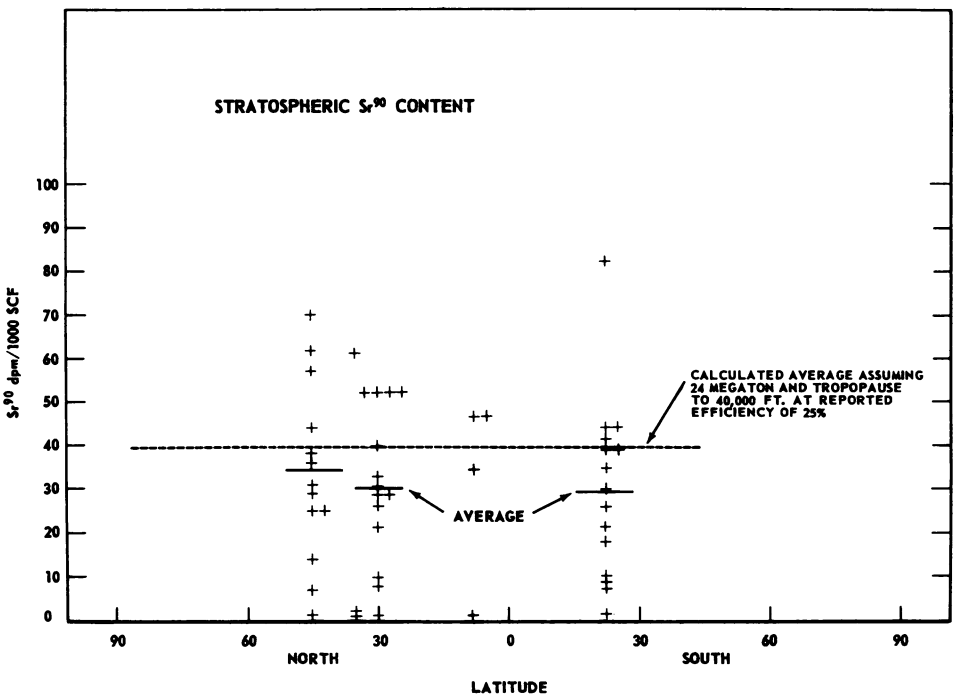


FIG. 6.

for world-wide fallout as of December, 1957, neglecting rainfall variation, and Figure 8 is the corresponding world map. Figure 9 gives the corresponding timewise variations in the nothern latitudes and compares them with the rainfall fallout curves for Milford Haven in England.[41] Figure 10 gives a similar comparison for Chicago and Pittsburgh. Curves for other latitudes are given in Figures 11 and 12. Figure 13 gives the estimated stratospheric reservoir and the expected composition in strontium-89 versus time. If a further assumption is made, namely, that the proportion of the fallout in a given location is given by the ratio of the rainfall to the world-wide average, 0.77 meters,[42] it is possible to compare the detailed fallout observed by the pot-collection programs in various localities with the theoretical predicted values, and these are given in Table 1.

On the basis of these comparisons and in the absence of conclusive evidence as to the age of radioactive fallout, it appears that the simple theory outlined explains the known information within the experimental error. It may develop when more reliable data are available on the age of fallout through the use of the short-lived, 12.8-day half-life barium-140 fission product that a mechanism by which a sort of concentrated leaking from the stratosphere occurs at a latitude of about 40° more may be proved or disproved. At the present time the observed extreme concentration may be explained as being due to coincidence of the tropospheric fallout from the United States and Russian tests. If this theory be correct, the barium-140 content in periods of high fallout will show that the fallout is young. It is to be hoped that these data will be forthcoming soon.

Machta,[13, 43] and Stewart, Osmond, Crooks, and Fisher[41] have stated that meteorological considerations and likely stratospheric wind patterns, together with

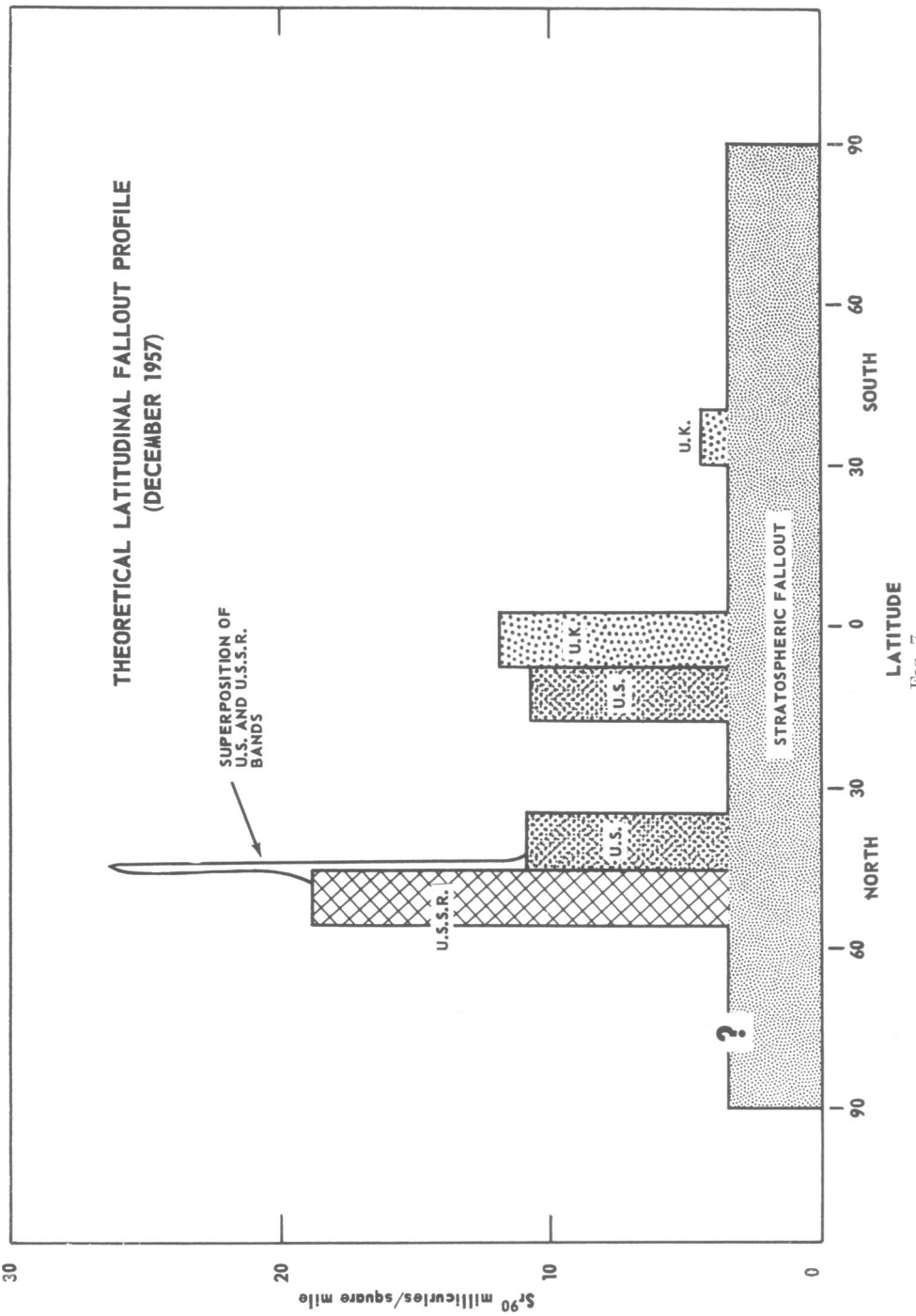


FIG. 7.

evidence that the $Sr^{89}/Sr^{90}$ ratio of the fallout shows the fallout to be old, have led them to the conclusion that the heavier fallout observed in the 40°–50° N. latitude band is stratospheric and not tropospheric in origin, as proposed here. The issue still seems to be unsettled, since the radiochemical difficulties of the deter-

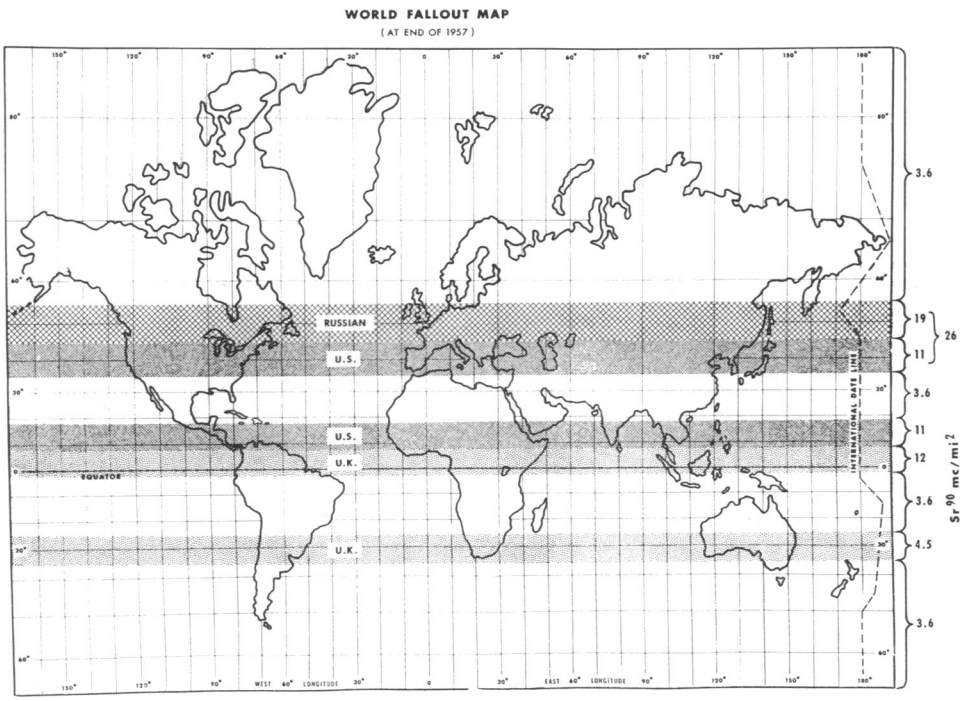


FIG. 8.

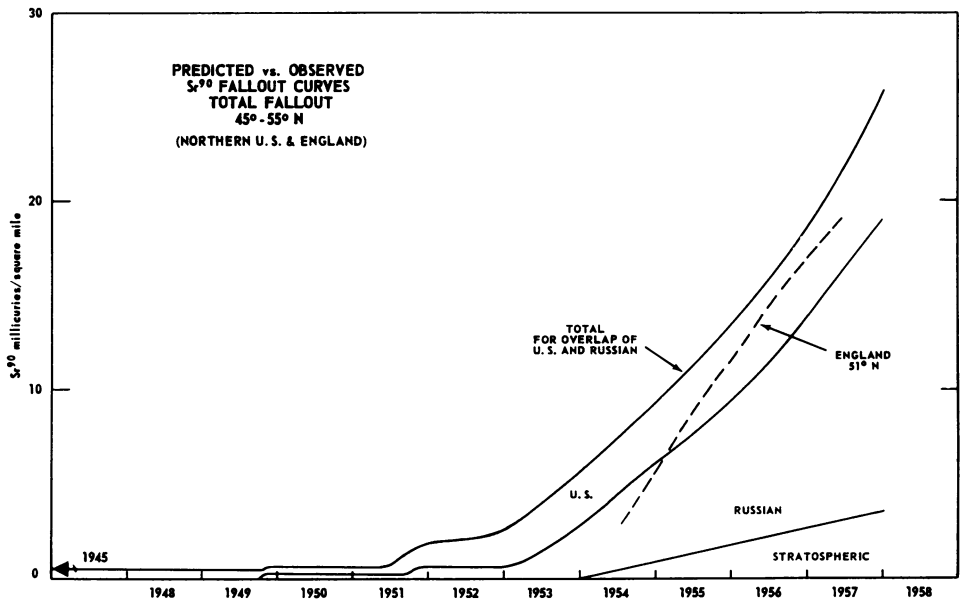


FIG. 9.

mination of the $Sr^{89}/Sr^{90}$ ratio are large and may well have introduced sizable errors into some of the reported values for this number and since it apparently is possible to account reasonably well for the observed fallout distribution on the present uniform stratospheric fallout theory as shown in the present paper. The critical difference between the two theories is in the matter of the age of the fallout. Better

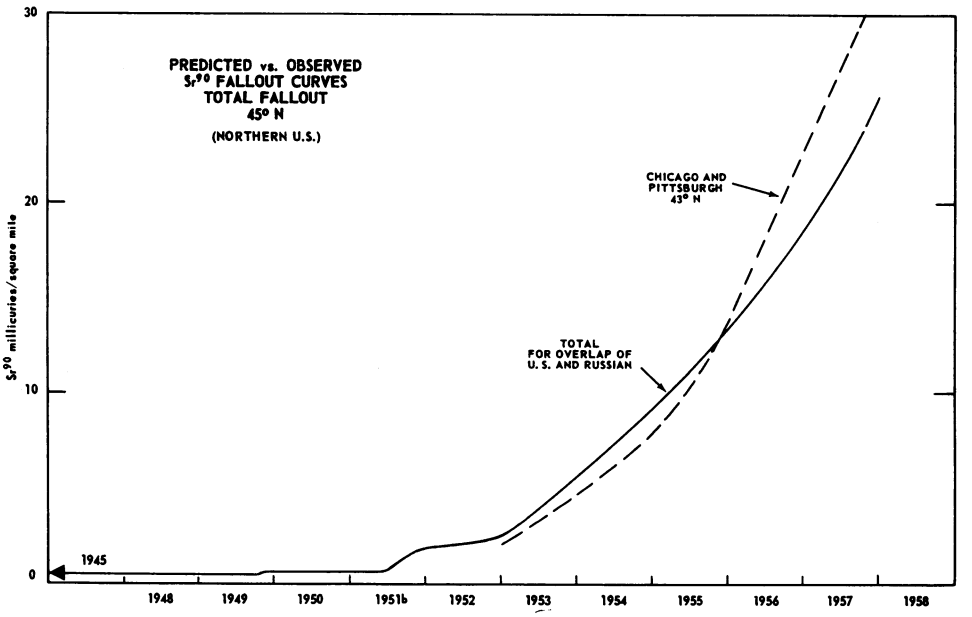


FIG. 10.

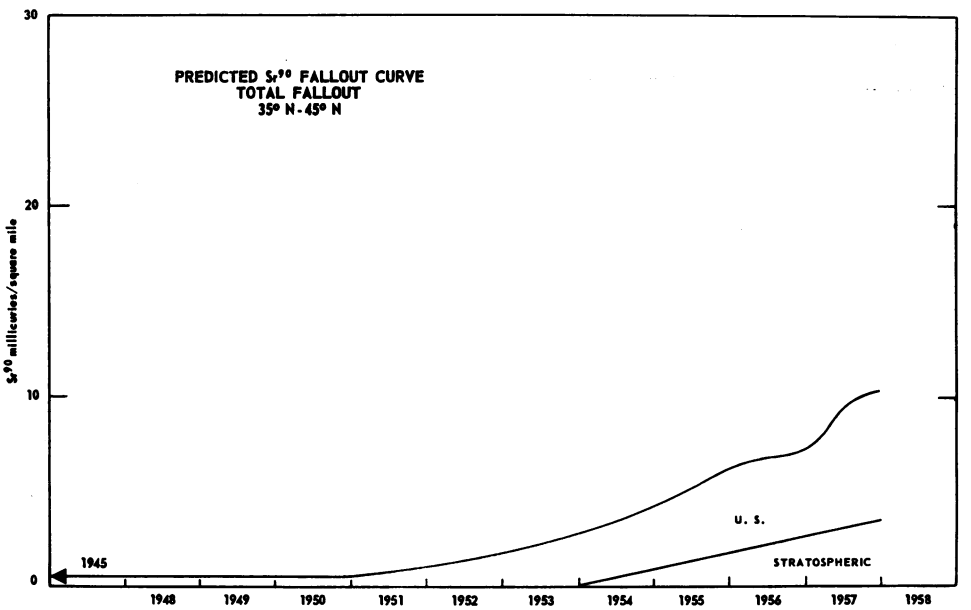


FIG. 11.

and more significant results probably will be available soon, using the $Ba^{140}/Sr^{90}$ ratio, which for both radiochemical and lifetime reasons is more suitable than $Sr^{89}/Sr^{90}$. Moreover, $Ba^{140}$ has a half-life of 12.8 days, which is more appropriate to distinguishing between an expected fallout age of perhaps 30 days, on the one hand, and of about 1–2 years, on the other, than is the $Sr^{89}$ half-life of 51 days. The radiochemical procedure for $Ba^{140}$ is very similar to that for $Sr^{90}$, and both are

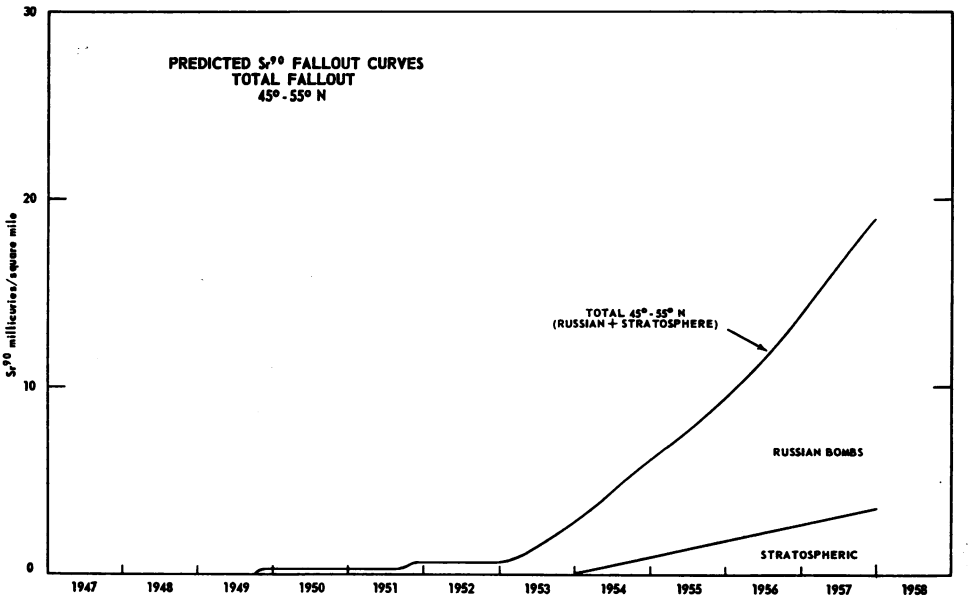


FIG. 12.

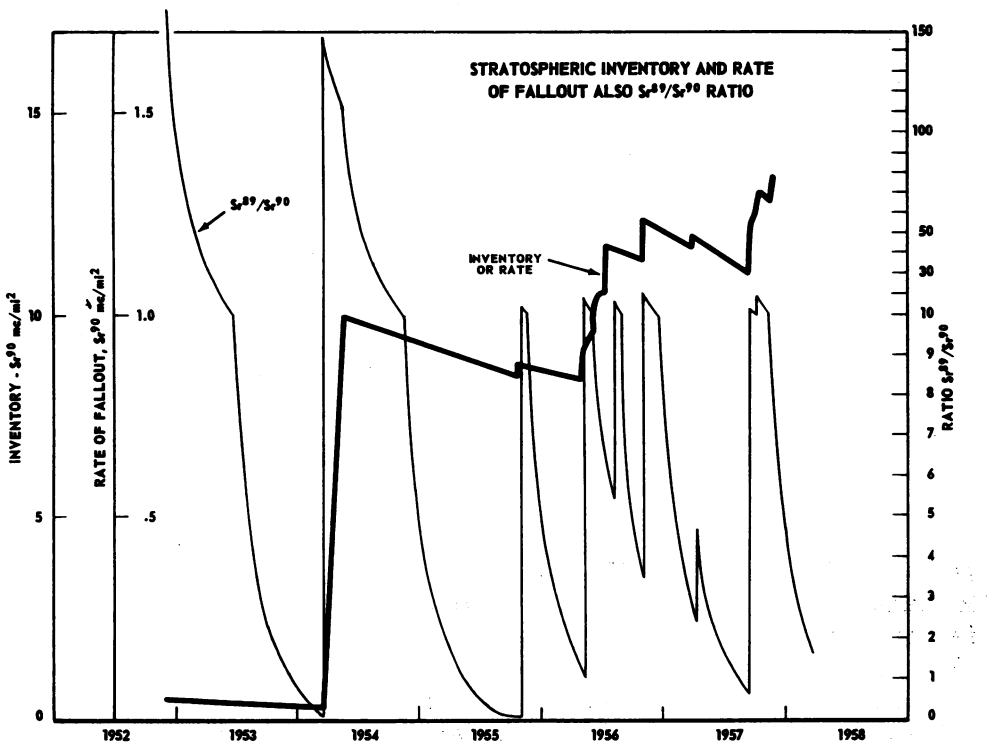


FIG. 13.

more sensitive and reliable than the $Sr^{89}$ procedure, which is particularly susceptible to errors from radioactive impurities such as other fission products which may have

been imperfectly separated. Both $Ba^{140}$ and $Sr^{90}$ are measured by short-lived radioactive daughters of characteristic half-life, which can be repeatedly removed and measured, since a new supply is grown into equilibrium each time a separation has been made.

The importance of settling this point is obviously considerable for both meteorology and geophysics and certainly for the understanding of the mechanism of radioactive fallout. Perhaps the $Ba^{140}$ data will show the truth to lie somewhere between the two mechanisms.

Rafter[39] and Rafter and Fergusson[38] have shown that carbon-14 increases in surface air at Makara in New Zealand and in New Zealand woods and ocean carbonate, as shown in Figure 14. This additional carbon-14 is due to bomb-generated neutrons which react with air nitrogen to produce it. They find about 2.1 per cent increase per year.

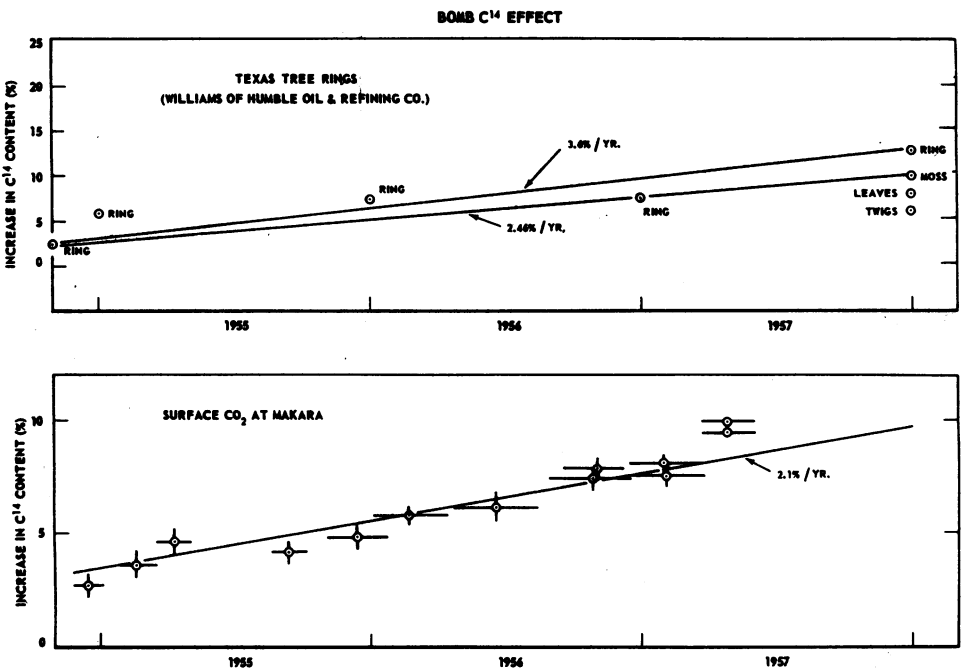


FIG. 14.

Williams,[40] of the Humble Oil and Refining Company, finds 3.0 ± 0.5 per cent per year in Texas tree rings (Fig. 14), and de Vries[44] in Holland and Münnich[45] in Heidelberg, Germany, both report increases. The carbon-14 increase in the flesh of the land snail, *Helix pomatia*, amounted to 4.3 per cent between November, 1953, and June, 1957, in Holland, while an increase of about 10 per cent during 1955 and 1956 occurred in Heidelberg in various biosphere samples.

At a rate of 2.5 neutrons per 200 Mev of energy release, 1 megaton would generate $3.2 \times 10^{26}$ carbon-14 atoms. The best estimate, keeping in mind that a substantial amount falls back as calcium carbonate, would be that about $10^{28}$ carbon-14 atoms have been introduced into the atmosphere, mostly into the stratosphere. The

estimate of 2.5 neutrons per 200 Mev energy released is higher than an earlier estimate based on an assumed 15 per cent escape efficiency,[46] the later value being based on firmer information. It also attempts to weigh fusion and fission as they have actually occurred.

About $9.4 \times 10^{27}$ carbon-14 atoms are normally present in the stratosphere because of cosmic-ray production.[47] This figure assumes 22 per cent of the atmosphere to be in the stratosphere. Therefore, with world-wide stratospheric circulation, the rise in the stratosphere should be about 100 per cent, as was found in a few measurements made on samples collected in October, 1956. Further measurements are in progress.

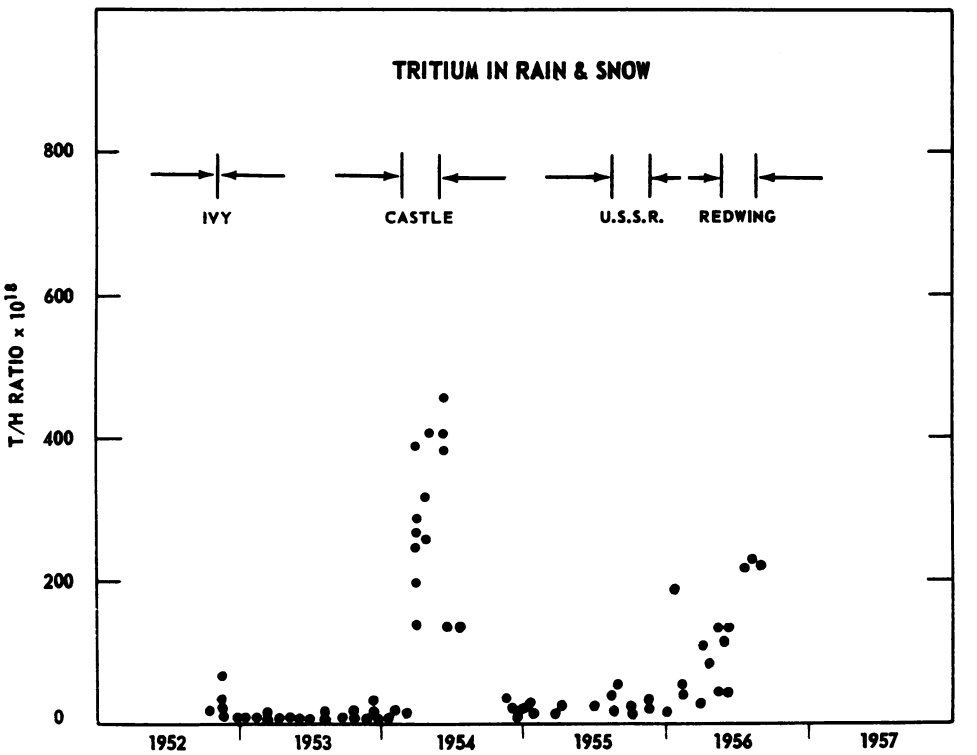


FIG. 15.

In the troposphere in the 3 years since the 1954 Castle test at the 10 per cent per year figure used for fallout, about $3 \times 10^{27}$ carbon-14 atoms should have descended, or about $1 \times 10^{27}$ carbon-14 atoms per year. The average carbon-14 inventory in the troposphere is $3.3 \times 10^{28}$ without including the ocean or biosphere; hence the observed carbon-14 rise might be as high as 3 per cent per year, as appears to have been observed.

If mixing with the biosphere and top ocean above the thermocline occurred immediately, according to Arnold and Anderson,[37] who gave 0.2 gm/cm$^2$ in the top 100 meters of the ocean, the total tropospheric reservoir would be $7.5 \times 10^{28}$, giving an expected rate of increase due to the bombs of 1.3 per cent per year, which

is in fair agreement with the observations if we assume that the mixing with the ocean and the biosphere, particularly the former, is not quite instantaneous.

The main points are that the ratio of the Northern to the Southern Hemisphere effect here is not enormous and fits fairly well with the notion that stratospheric gases have a residence time not too different from that of the ultrafine world-wide fallout particles.

In addition, Fergusson[33] has recently found in studying fossil $CO_2$ and its effect on reducing the carbon-14 content of the biosphere that the mean life of a $CO_2$ molecule before being absorbed from the tropospheric air into the oceans and biospheres is perhaps 2 years and that north-to-south mixing of the fossil $CO_2$ occurs in less than 2 years. Consequently, it seems clear that the 10-year residence time for stratospheric gases before descent into the troposphere seems to fit data for carbon-14 from bombs as well as the strontium-90 and cesium-137 fallout data.

The bomb tests to date have produced enough carbon-14 that, when it has come to mixing equilibrium, it will have increased the amount naturally present in all living matter by one-third of 1 per cent.

The normal radiation dose from carbon-14 may be compared with the increase in the dose from cosmic rays as the elevation increases. In these terms the normal carbon-14 dose (1.5 mr/year) is equal to about a 100-foot increase in elevation. Therefore, the extra radiation dose from this product of nuclear tests is equivalent to an increase in altitude of a few inches.

In the years before equilibrium with the deep ocean is reached—about 500 years—the level will rest temporarily at about a 3 per cent increase or the equivalent of a 3 foot altitude increase. This is after the first period of perhaps 10 or 20 years before dilution in the top layer of the ocean and with living and dead organic matter occurs, when the increase will be about 20 per cent, or about 20-foot equivalent altitude increase. Because the lifetime of radiocarbon is very long—8,000 years on the average—the equilibrium situation is the more significant.

Figure 15 gives up-to-date data on the occurrence of tritium in rainwater in the Chicago area.[22, 48, 49] It is clear that, whereas strontium-90 and probably carbon-14 remain in the stratosphere for years, the tritium from high-yield thermonuclear detonations does not, but descends in a matter of 1 or 2 months. This is most probably due to the enormous mass of water carried into the stratosphere by the fireballs of detonations in the moist tropospheric air. The characteristic white mushroom cloud is evidence of the formation of ice crystals in the cold stratospheric air, which, if large enough to be seen in this way, must certainly be large enough to fall into the troposphere, where they melt and join in the ordinary phenomena, i.e., fallout as rain or snow. Thus a large fractionation relative to fission products and radioactive carbon dioxide occurs. Of course, there probably is some entrainment of fission products on the surfaces of the falling ice crystals by the Greenfield Brownian-motion accretion mechanism. In fact, it is known that about 1 per cent of megaton yield offsite fallout occurs in the early banded tropospheric manner. This may be due to this entrainment, and thus one would expect that the latitudinal distributions of early tropospheric fallout of both fission products and tritium water from magaton-yield bombs fired in the troposphere[8] should be identical. No satisfactory data are now available to check this point. In the calculations in this paper the figure of 1 per cent for tropospheric contribution from megaton yields has been used.

III. *Conclusion.*—The more recent data, particularly on bomb carbon-14, when taken together with the earlier data on bomb fission products and tritium, give us some confidence in our present understanding of the fallout mechanism. All these observations and considerations afford unprecedented opportunities for the study of meteorology and geophysics, particularly in an international cooperative effort such as the International Geophysical Year.

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# *THE HUMAN ELECTROHYSTEROGRAM: WAVE FORMS AND IMPLICATIONS**

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*Communicated by H. W. Magoun, May 16, 1958*

Notwithstanding Bode's observation[1] of the deflection of a galvanometric needle during a uterine contraction, the development of bioelectric studies of the uterus *in situ* (electrohysterography) has proceeded slowly and sporadically. Studies both abroad[2, 3, 4, 5] and in this country[6, 7, 8] have made contributions. With our demonstration of a uterine electrical complex bearing a one-to-one relationship to the uterine contraction,[9, 10, 11] the studies have been placed on a firmer basis. In this communication certain recent findings which indicate pacemaker function and propagated waves will be presented and their implications discussed.

## MATERIALS AND METHODS

In the course of these investigations 293 subjects have been studied in labor, all under conditions of maximum comfort and quiet. Skin overlying the uterus is prepared by rubbing in ecg paste which is then washed off. Pairs of bipolar electrodes are placed on the uterus at 10-cm. spacing, or for unipolar recording the exploring electrode is over the uterus and the indifferent electrode on the thigh. Direct coupled recording systems are essential for the slow events of the uterine contraction. One-centimeter German silver electrodes and 5-mm. solder electrodes have been used. Details of the technique have been described.[9]

## RESULTS

For a better understanding of these studies, one of the first successful recordings of the human electrohysterogram is here reproduced (Fig. 1). Time and amplitude