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Introduction

There are several factors in the present interest in radioactive fallout from nuclear weapons. Except for the remarks contained in this introductory section, this discussion will be largely confined to the technical and scientific considerations enumerated in the following paragraph.

From the scientific point of view, one is concerned with the amounts and types of radioactive material produced by detonations of nuclear weapons, the mechanisms involved in local and world-wide distribution of fallout, incorporation in the food chain and eventual uptake by human beings, estimated exposures of the whole body and of particular organs of the body to radiation from fallout both outside and inside the body, and with possible biological consequences to both the present generation and succeeding generations. Obviously, this cannot be viewed solely as an academic exercise. From the point of view of our interest in human welfare, concern for possible harmful effects on this and future generations immediately comes to the fore and constitutes a primary factor in our interest in the subject.

At this point it becomes necessary to distinguish between one's interest in fallout from tests of nuclear weapons, per se, and one's interest in the development and testing of nuclear weapons in relationship to such questions as international relations and nuclear warfare.

While many people were willing, prior to 1954, to let the memory of the effects of the atomic bomb on the peoples of Hiroshima and Nagasaki grow dim with the passage of time, and thoughts of a possible future war involving atomic weapons took on a more and more hypothetical cast, the fact that Japanese fishermen and the Marshall Island natives some 100 miles from the detonation of a large test device on March 1, 1954 received sufficient fallout to cause skin burns and clear cut effects on the blood-forming organs once again suggested the possible horrors of a nuclear war.

What captured the imagination was the realization that in addition to radiation, blast and thermal effects at the site of a megaton burst, whole cities downwind might be involved with purely radiation effects with no fires, no falling buildings, no traumatic injuries at all. This concern is enhanced as it has become apparent that there could be a long-term hazard as well. In addition to delayed effects from increased radiation exposure at the time of the bombing some of the fallout material remains radioactive for years and could thus constitute a continuing hazard.

Also inherent in current discussions of fallout is the matter of whether or not the United States should attempt to build optimal capability in the use of nuclear weapons in the event of war and even as a deterrent to war.

One of the difficulties in discussing fallout is that of achieving objectivity. The subject has become intimately involved in many people's emotions. During the 1956 Presidential election campaign it even became a political issue. Some persons who believe that a strong military position increases the probability of a major war have urged the biological effects of fallout as a reason for cessation of weapons tests and have played up uncertainties in our estimates of the upper limits of possible biological hazards of radiation from fallout. Others, believing that a strong military position is vital to our national welfare, have discounted these uncertainties. Both may be assumed to be motivated by a strong desire for national security and world peace and to be sincere, although not always wholly objective, in the relative importance which they ascribe to fallout from weapons tests or to weapons tests themselves. Undoubtedly, many citizens who conscientiously abhor war have found an outlet for their emotions in campaigning against the testing of nuclear weapons. Unfortunately, cessation of testing, particularly on a unilateral basis, does not of itself even begin to resolve the intricate problems in human relationships which have in the past repeatedly led to war.

Another difficulty is one of achieving a proper perspective in dealing with the manner in which the effects which might be produced by fallout would appear. The unknown is always difficult to grasp and engenders fear until it becomes known or can be related to something familiar. The fact that many of the effects from fallout from nuclear testing are ones which do not become apparent at once is baffling to the majority of people and the fact that they could be produced by something as intangible as radioactive atoms lends the subject a weirdness that is hard to dispel.

We have a situation quite the reverse of what has pertained in the past with respect to the great epidemic diseases. Smallpox, cholera, and typhoid fever epidemics were very real and terrible events that in devastating fashion decimated whole populations. The problem was to seek the cause and eliminate it by sanitation or by immunizing the population to the specific causative organism. With radiation hazards whether from fallout, from weapons tests or from the medical uses of x-rays it is otherwise. There are no formidable pressing measurable effects for which to seek a cause. One can with varying degrees of confidence predict effects from the present rate of nuclear weapons testing that can never be measured or clearly identified with the specific cause. Yet each predicted effect is described in the form of some well-known tragic event — a deformed or weakened child, leukemia, bone cancer or the vague but seemingly familiar "premature death."

The problem here is to find some means of comparing the radiation hazards inherent in fallout and in the medical and industrial uses of atomic energy with some more familiar natural or man-made hazard which is presently accepted for one reason or another. There is a natural tendency to reject comparisons with the hazards from such a familiar thing as fire. Fire exacts 10,000 lives a year in this country and at the present rate 300,000 per generation. It scars and maims many thousands more. The automobile, a very real symbol of modern civilization, is the cause in the United States alone of some 40,000 deaths and a like number of maimed each year — at the present rate more than a million deaths per generation. Similarly, people reject comparison with the deaths and injuries which are very substantial and sine qua non for the non-atomic aspects of our national defense effort including, of course, aviation. I suspect one of the reasons for this is the commonplace nature of the incidents which lead to death and injury. They are recorded in our newspapers daily. A hazard more comparable to that of radiation — smog or air pollution — cannot be used for comparison simply because we have no comparable body of knowledge upon which to base an estimate of the possible deleterious effects on our citizens. For radiation, and especially radiation from fallout, is the only contemporary man-made general environmental hazard about which we have sufficient information to define it at all, and because we can define it there is a greater obligation to keep it minimal.

The present level of exposure from medical and dental x-rays (4 r in 30 years) is of about the same magnitude as the exposure from natural sources of radiation. The present level of radiation exposure from fallout from weapons testing to date and future levels at any realistic rate of weapons testing, whether by one nation or by many, are even lower (0.02 to 0.5 r in 30 years). They are a fraction of the natural radiation exposure to which man and other living things have always been subjected. In fact they are far below those which have been employed in experimental work in order to demonstrate detectable pathologic or genetic changes.

By the spring of 1957 the pros and cons of the hazards from radioactive fallout from nuclear weapons tests were being hotly debated in the lay journals and even to some extent in scientific publications. Thus, it was not surprising that on April 18, 1957 the Joint Committee on Atomic Energy, which had for nearly a year been accumulating background information on fallout, formed a special subcommittee on radiation for the purpose of conducting open hearings on the entire subject of the "Nature of Radioactive Fallout and Its Effects on Man." Congressman Chet Holifield is Chairman of this Committee. These hearings took place between the dates of May 27 and June 7, 1957 and the hearings themselves together with the abundant appendices in the printed text of the hearings, constitute the most complete body of information and authoritative statements on the subject available now. With very few exceptions the material which will be covered in this paper is either contained or referenced in the printed text of the hearings.

It should be made clear at the outset that the author has done none of the scientific work discussed in this paper although for a number of years he has been intimately associated with the biomedical research program of the AEC which sponsored a very large share of it. Enough cannot be said in recognition of the many scientists who have worked so hard to develop such information as we now have available on the subject. This they have done tirelessly and even enthusiastically in spite of the fact that many of them would have preferred other outlets for their scientific talents more basic and perhaps more glamorous. They recognised the importance of the problem and have pitched in when and wherever they could make a contribution to our knowledge of the subject, regardless of where their research support came from and regardless of the implications of their observations insofar as tending to increase or decrease current estimates of the hazards of fallout.

The Nature and Production of Radioactive Fallout

The detonation of nuclear devices produces fission products in greater or lesser amounts depending on the characteristics of the particular device used. The smaller devices, those in the thousands to several hundred thousand tons TNT equivalent range, produce their explosive force by nuclear fission giving rise to proportionate amounts of fission products while so-called H-bombs, bombs in the million-ton range, may derive less than 10% of their explosive force from fission. Thermonuclear reactions per se may give rise to tritium (radioactive hydrogen) while the neutrons produced in the reactions produce radioactive carbon from the nitrogen in the atmosphere. The amount of carbon-14 produced is small relative to that normally present in the atmosphere, so that with a half-life of the order of 5000 years its activity is not significant when compared with the amount of fission product activity resulting from the fission reactions. In addition, the neutrons produced by nuclear devices detonated on the surface of the earth or on towers and the like induce radioactivity in a variety of materials. This results for the most part in radionucleides of relatively short half-life such as Fe-59 half-life 47 days, manganese 54 half-life 310 days, Si-131 half-life 2.6 hours, and Cl-38 half-life 37 minutes, sodium-24 half-life 14.8 hours. Measurable amounts of Zn-65 half-life 250 days, and CO-60 half-life 5.3 years have also been detected in fallout material.

In early fallout from a surface explosion radioisotopes of short half-lives are quite abundant and may represent a very important part of the total activity. In fact the external radiation dose from the short-lived gamma ray emitting isotopes in near-in fallout may constitute the principal hazard to unshielded persons as was the case with the Marshall Islanders on the ATOLL of Rongelap at the time of the March 1, 1954 detonation (31). From the standpoint of possible damage from radio-isotopes which may be ingested or inhaled soon after fallout the dose to the thyroid gland, to the gastro-intertinal tract and to other regions of the body from I-131 with a half-life of eight days, and Ba-140, Strontium-89 and Strontium-91 with half-lives of 12.8 days fifty-five days and ten hours respectively may overshadow in significance the effects of the longer-lived fission products. These fission products have been identified in fallout and in biological material, plants, animals, and animal and human urine collected a few days to a few weeks, and in the case of Sr-89 several months, after the passage of a cloud of nuclear debris over an area (16, 33, 11, 32). These isotopes are important in tropospheric latitudinal fallout up to distances of several thousand miles from surface bursts of high fission yield megaton range weapons. They are of lesser importance with fallout (off-site) from kiloton range tests. Hartgering's studies suggest that under these circumstances the amounts are small in absolute terms and that the radioactivity may gain access to the human body by inhalation rather than by going through the food chain. From the standpoint of the long-term world-wide fallout hazard, however, these isotopes are of little concern.

The important fission products from the standpoint of world-wide, or delayed fallout, are Sr-90 and Cs-137 with half-lives of 28 and 27 years, respectively. Their importance in delayed fallout lies in their relatively long half-lives, and their ready assimilation by the human body and the fact that they are produced in relatively large quantities in the fission process. Ce-144 of half-life 275 days is also readily taken up by the body. It belongs to the rare earths and is not readily taken up by plants. Having an intermediate half-life it might be of some concern were it present in greater quantities than it is and more readily absorbed from the soil by vegetation into the food chain.

Finally, a word concerning Pu-239 (22). Although the mass of plutonium disseminated by a nuclear detonation may be greater than the mass of strontium-90 or of cesium-137 it is taken up very poorly from the soil by plants — only about one part in 10,000. Further, the human intestinal tract takes up only about one part in 10,000 to one part in 100,000 of Pu which may be present in the food. Adding to these facts knowledge of the amounts actually dispersed in nuclear tests one can readily dismiss Pu as unimportant in the long-term fallout problem.

Types of Fallout and Their Transport and Distribution

Before discussing the three general types of fallout, it is well to call attention to the fact that a deep underground burst such as was accomplished in Nevada in September 1957 is completely contained and produces no surface or atmospheric contamination.

There are three different classes of fallout from tests, the relative abundance of which is determined by the nature of the weapon, its yield, and the conditions of detonation, particularly the altitude of firing.

Local or near-in fallout occurs when the fireball of the bomb touches or comes sufficiently close to the ground to draw up into the vaporized cloud matter from the surface of the earth. The radionucleides produced by the explosion may be deposited on or incorporated into this material depending upon whether or not it is more or less completely fused or totally vaporized. After the fireball cools, the larger particles deposit on the earth in a matter of minutes and up to several hours after the detonation. This constitutes the local or near-in or early fallout which for small weapons may extend out from the point of burst a few miles and cover tens to a few hundreds of square miles while for megaton weapons it may extend out to a several hundred or more miles and cover thousands of square miles.

Tropospheric or latitudinal fallout is a more delayed fallout of the debris which either has not penetrated the tropopause to the stratosphere or if it has penetrated into the lower stratosphere the particle size is such that it comes down fairly rapidly. It occurs over a period of two or three weeks or a month or so after a detonation and consists of relatively fine material (a few micra to small fractions of a micron) suspended in the lower part of the atmosphere, the troposphere, where rain and other weather phenomena occur. It is carried around the world in the same general band of latitude as that of its origin and does not in any significant amount cross the equator. It is deposited on the earth's surface by weather events, principally rain and snow and probably to some extent by dew. Thus, the distribution of tropospheric fallout is determined generally by the site of formation, factors such as local weather conditions and distance traveled (in thousands of miles) determining regions of greater or lesser concentration. (26, 27)

Tropospheric fallout has contributed significantly to the radioactive debris now encountered over the northern hemisphere as a result of weapons testing in the Pacific, in Nevada and by the USSR.

Stratospheric fallout has somewhat different characteristics and distributions. It consists of particles which rise into the atmosphere but which do not fall out either as near-in or early fallout or as tropospheric or latitudinal fallout during the first month or two following their formation but because of their small size are removed from the upper atmosphere so slowly that their average period of suspension is a matter of years. Machta stated that it is not known whether they are carried down into the tropopause only by air currents or are also carried down by their own weight. He conjectured, however, that the principal factor in removal is downward atmospheric motions, though the particles may in addition settle downwards at a rate of a mile or so a year. Unfortunately, knowledge of atmospheric movement in the stratosphere is still very primitive and it will take several more years of intense effort, much of it associated with studies of nuclear weapons tests debris, before one can make more definitive statements on this point.

There are two major hypotheses as to the distribution pattern of stratospheric fallout which are being considered at the present time. One is the relatively simple one of relatively rapid horizontal mixing with more or less uniform passage of the debris through the tropopause, thence to be relatively uniformly distributed over the surface of the earth as a result of tropospheric weather phenomena. In this case, there would be essentially no fallout where there is no rain at all and variations by factors of no more than two to three at the most among those areas where rainfall is moderate and heavy.

The other major hypothesis discussed at the fallout hearings was that of Brewer of England (6). Machta described this theory of a slow poleward circulation of stratospheric air from the equatorial regions during which time the air may be carried to heights in the range of 100,000 feet. Accordingly, debris injected into the stratosphere at 11°N, the longitude of the Pacific test site, would be transported in lesser amounts to the Southern Hemisphere with the lion's share moving towards the Temperate and Arctic latitudes. Machta states (26, 27) that it is possible that the formation of new higher tropopauses by the passage of storms in the Temperate latitude may entrap stratospheric air into the troposphere, and that the break in the tropopause found frequently in the vicinity of the jet stream is a place of preferential exchange of air between the troposphere and the stratosphere. A corollary to this would be less stratospheric fallout near the equator where the tropopause is very persistent and clearly defined as opposed to the polar regions where it is generally lower and less distinct. With present patterns of testing this would mean a greater removal of stratospheric debris in the Temperate and polar regions of the Northern Hemisphere with little or no debris coming out near the equator and again some but lesser amounts of fallout appearing in the South Temperate and South polar regions.

Actually the observed distribution of strontium-90 is similar to that discussed by Machta. The only trouble here is that such a pattern in the Northern Hemisphere could be in large part a reflection of the fact that the nations who have done the most weapons testing to date have done so quite extensively in the North Temperate Zone and farther north. The observed fallout pattern might thus represent distribution of tropospheric fallout. Undoubtedly, an appreciable part of the fall-out observed in the Northern Hemisphere is the result of this mechanism of transport, but whether this mechanism accounts for five or ten or more mc $Sr\text{-}90/mi^2$ of the present average of 30 mc $Sr\text{-}90/mi^2$ in the USA is at present uncertain. The pot collections of the AEC Health and Safety Laboratory in New York City (15) show jumps in the amount of Sr-90 collected during the winters of 1954-55 and 1955-56. There was a definite increase in the slope of this cumulative tabulation at the time of Operation TEAPOT at the Nevada test site in the spring of 1955, but the following year the increase occurred prior to the beginning of Operation REDWING at the Eniwetok proving ground May through July 1956. In 1957 it preceded Operation PLUMBBOB in Nevada (May 28 to October 7). It would appear then that major increments in Sr-90 fallout have occurred seasonally in New York City, whether or not test activities were going on at the time. This would suggest that these late winter fallouts contained a considerable amount of stratospheric debris. It is hoped that pot sampling at various sites around the world will determine whether the increases observed at New York and also at Pittsburgh are truly seasonal effects characteristic of these latitudes, and if so, whether it is characteristic for the South Temperate Zone and even the Tropic Zone as well. Pot samples were being taken at the following stations as of October, 1957.

UNITED STATES

Birmingham, Alabama

West Los Angeles, California

Coral Gables, Florida

Lemont, Illinois

New York, New York

Vermillion, South Dakota

Salt Lake City, Utah

OUTSIDE THE UNITED STATES

Vienna, Austria

Rio de Janeiro, Brazil

Santiago, Chile

OUTSIDE THE UNITED STATES (contd.)

Bogota, Colombia

Guayaquil, Ecuador

Quito, Ecuador

Dakar, French West Africa

Honolulu, Hawaii

Hiroshima, Japan

Nagasaki, Japan

Kikuyu, Kenya

Karachi, Pakistan

Durban, South Africa

Pretoria, South Africa

Causeway, South Rhodesia

Taipei, Taiwan

Bangkok, Thailand

Good data from these stations will go a long way toward clarifying the picture. At the same time the AEC is sampling the stratosphere by means of balloons up to 95,000 feet. This will provide some factual information on the concentrations of Sr-90 and other fission products at different altitudes and locations in the stratosphere. A recently inaugurated Department of Defense high altitude sampling program will be an important supplement to this.

I believe one can state with confidence that two or three years from now we will have to depend much less on hypotheses and may even have settled on a firm basis the broad principles of stratospheric movement, mixing and the mechanism of the escape of nuclear debris to the tropopause.

The Present Distribution and Amounts of Fallout Radioactivity

Sampling Methods

During the past several years several thousands of samples of fallout material on gummed paper, in pots, in soil, in water, in milk and other foodstuffs and in human and animal bones and other animal tissues have been collected in the United States and from all over the world. They have been analyzed for gross gamma activity, mixed beta gamma activity, for strontium-90, for cesium-137, cerium-144, barium-140, and a number of other fission products as well as for induced activities. In general, we have as much or more fallout on the United States as anywhere in the world outside of nuclear weapons test sites. Furthermore, average values of Sr-90 in soils and food supplies in Northern United States are as high as are found in other similarly large geographic areas. There may, however, be in remote localities areas with greater average soil content of Sr-90 of which we are as yet unaware. Likewise, we know that in 1956 in one area in Cardigan Wales, where the soil is extremely low in calcium (0.3 gms/Kg), bones from a sheep grazing the area have shown as high as 170 μμc Sr-90/gm Ca.

Probably the most reliable index of total fallout to date in a given area is to be found in analyses of carefully selected soil samples. Dr. Lyle Alexander, U.S. Department of Agriculture, has been in charge of the United States soil sampling program and has collected many of the samples himself. In the United States samples have been collected periodically from 17 sites in addition to sampling for special studies. On a world-wide basis 51 sites were sampled in 1956 and most of these sites are being resampled in March, 1958. Samples are collected from level open areas uncultivated and with low ground cover such as grass. Samples are taken usually down to a depth of two inches and again from two to six inches in depth. The amount of Sr-90 found per unit area sampled is readily converted to equivalent Sr-90 per square mile. For the first several years of sampling the top two inches contained practically all of the Sr-90. Recent samples indicate penetration by some of the Sr-90 to below this layer to a depth of several more inches. It has been clearly shown from these studies that in areas like Antofagasta, Chile, where there is essentially no rainfall, there is practically no Sr-90, i.e., 0.02 in 1956 as compared with 2.0 Sr-90 mc/mi^2 in areas within a few hundred miles with adequate rainfall (24). Sr-90 values in soils collected along the equator the same year ranged only from 1.8 to 2.9 mc/mi^2 in areas with average annual rainfall of from 50 to more than 100 inches.

The data presented by Mr. Merril Risenbud at the JCAE Hearings (13) clearly indicate that in terms of Sr-90/mi^2 fallout has been heaviest across the Northern United States. Present average values for that region are about 30 mc/mi^2. (We have no data from the great land mass encompassed by the USSR and Satellite States and Communist China).

Another method of sampling referred to earlier is by collection in stainless steel pots. These samples give good estimates of the present increments being added. Finally, there is the gummed paper network which though inherently less reliable, was started in 1951 and has given us data for estimating both cumulative Sr-90 deposition and gamma dose exposures. Food sampling activities have concentrated on milk from the Chicago and New York milk shed areas as well as sampling of other food stuffs both here and abroad with special reference to foods which constitute principle sources of calcium in the diets of various peoples. Peak Sr-90 content of milk in these two regions has risen each year with a peak for Perry, New York milk of 5.6 μμc Sr-90/gm Ca in November, 1956. More recent AEC Health and Safety Laboratory (HASL) data for Perry, New York dried milk in terms of μμc Sr-90/gm Ca follow:

December 1956 - 3.16	April 1957 - 3.12
January 1957 - 3.83	May 1957 - 3.91
February 1957 - 4.02	June 1957 - 4.59
March 1957 - 3.00	July 1957 - 4.74
	August 1957 - 4.25

The highest values recorded in the United States have been from Mandan, North Dakota, where in 1956 the average of the monthly samples was about 10 μμc Sr-90/gm Ca with a high value in May of that year of 17. More recent HASL data for Mandan powdered milk follow:

January 1957 - 4.4	April 1957 - 6.75
February 1957- 8.17	May 1957 - 9.79
March 1957 - 7.38	June 1957 - 10.91
	July 1957 - 17.33

Interestingly enough, British data on milk Sr-90 from six locations for October, 1956, range from 4.6 to 10.3 (5). The same month Mandan, North Dakota milk contained 8.9 μμc Sr-90/gm Ca and Perry, New York milk 5.68. This was in spite of the fact that there was more strontium-90 in the corresponding United States soils than in the United Kingdom soils. Undoubtedly milk Sr-90 reflects to a significant degree not only uptake of Sr-90 into the animal food from soil but also Sr-90 that has adhered to the plants in the field and hence has by-passed the soil. Thus, the milk data to some extent reflect rate of fallout.

Analyses for Cs-137 have been done on milk and other material including living human beings and human urine. Anderson and Langham (2) have put forth strong arguments for the concept that soil and plant data on Cs-137 which is generally very poorly taken up by plants but is readily taken up by animals might be used as an index of accumulated fallout in soil and of rate of fallout onto plants. Radioactivity from Cs-137 in all anlyses are very small in terms of natural radioactive potassium-40, in humans about 1/20th. Having a half-retention time in the human body of about 140 days it is not likely to build up significantly with a constant intake. In other words, the Cs-137 content of humans reflects rather well the intake rate, while as will be seen later, the Sr-90 content of humans reflects its build-up in the soil and the Sr-90 to calcium ratio of the diet.

Samples of human bone from all over the world and representing all ages have been collected by Dr. J. L. Kulp (12, 20) of Columbia University and analyzed for Sr-90. The most recent data, 1956-57, indicate an average in small children (a few months to a few years old) of about 0.8 μμc Sr-90/gm Ca. Samples containing more than three times this figure have not been reported for this age group. Older children and adults run appreciably lower. Interestingly enough and not inconsistent with the milk data from Western Europe the Sr-90 levels in human bone for the United States and for Western Europe are not very different.

The Effect of Agricultural Practices

As mentioned earlier, such farm practices as leaving sloping ground bare to erosion by water or by wind can move the fallout from where it fell to some place of accumulation. This, of course, makes for non-uniform distribution in an area.

The vertical distribution of fallout in a soil may be altered by agricultural practices such as deep plowing. This changes the position of the fallout with respect to the root zone of the crops. In the case of shallow-rooted crops such as some grasses and many vegetables, the deep plowing may materially reduce the uptake of Sr-90. At best, one can expect only a fewfold change in uptake by the plant from these mechanical soil treatments. Liming calcium-poor soil will somewhat reduce Sr-90 uptake by reducing the Sr-90/calcium ratio.

The Effect of Fallout on Water Supplies

Fresh fallout onto surface waters, streams, lakes and oceans is quickly diluted unlike fallout on soil which at first is concentrated in a few top inches and readily available to a variety of shallow rooted plants. In fresh waters the Sr-90 is taken up by the plant and animal life and eventually settles out in the lake bottom or the mud of the river. Open waters also contain more or less soil and powdered rock in suspension which may carry the Sr-90 with it removing it by sedimentation.

In the case of water that comes from wells and springs the Sr-90 has been largely removed by filtration through the soils. Mixed fission product tropospheric fallout in open lakes and rivers has posed a problem at the time of fallout to certain industries like the photographic film industry, which involve processes requiring large volumes of water which must be extremely low in radioactivity of any sort. From the standpoint of effect on man fallout into waters from weapons testing has not constituted a major concern, although drinking water made directly from melting snow has been found at times to contain levels of radioactivity higher than that in the more usual sources. In the event of nuclear war with high levels of fallout, much, indeed most, of it could be removed by water softeners and ion exchange resins (21).

Sources of Strontium-90 in Plants*

A few years ago, when the soil contained less fallout and the rate of fallout was increasing, a major share of the Sr-90 in forace consumed by livestock was from direct fallout on the vegetation. Since the level has increased in the soil, the indications are that most of the Sr-90 now gets into the plant by way of the soil and root uptake. Experiments with black-eyed peas, lima beans, and snap beans at Beltsville, Maryland, during 1956 indicated that only a small part of the Sr-90 in the vegetation came from direct deposition on the plant surfaces. In situations such as that reported by Alexander of alfalfa which was grown on two very sandy soils in Illinois and derived its calcium from high calcium subsurface horizons rather than from the plowed layer, the uptake of Sr-90 was very small in comparison to vegetation that obtains its calcium largely from the plow depth, where the Sr-90 occurs.

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* This and the following section are based almost entirely on the testimony of Dr. Lyle Alexander, Dr. Robert Reitemeier and Dr. Alan Seymour in The nature of radioactive fallout and its effects on man, Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, May 27, 28, 29, and June 3, 1957, Part 1, pp. 512-523.

Discrimination Factors in Plants

A number of studies of the uptake of Sr-90 have been undertaken with a variety of field crops. Considerable variation occurs from one species to another.

The cesium ion is so firmly held by the soil surfaces that it is not readily available to plants. Likewise, the rare earths and plutonium are little taken up by plants from soils, hence, these elements become of interest only to the extent that they are deposited directly on foodstuffs or in water supplies. All evidence available points to a rather large discrimination factor for the uptake of cesium from soil. Menzel and Heald found a factor of 50 in favor of the uptake of potassium relative to cesium. Evidence for discrimination against the uptake of strontium relative to calcium is conflicting. Under field conditions at 93 sites in 11 states no discrimination, on the average, was found between the ratio of calcium and strontium in alfalfa and wheat and the ratio in the exchangeable form in the soils on which they were grown. As Alexander has said, there may be no single answer to the question but it seems that one should not count on a large discrimination factor against strontium. " . . . At the present time in the United States, we can find forage that has Sr-90 to calcium ratios that are lower than, higher than, or equal to the ratio of these elements in an exchangeable form in the surface horizons of the soils from which the forage came." These variations are probably due to unequal distribution of the fission products and exchangeable calcium in the soil, and variations in what constitutes the root zone of these particular plants.

Strontium-90 and Cesium-137 in Meat and Milk

Cesium-137 in the diet of cattle is believed to come almost entirely from direct contamination on the plant. That entering the soil is bound up to about 99% and hence is not taken up by the plant. What Cs-137 is ingested goes to blood and soft tissues. The great bulk of it is found in the body muscle mass. Like potassium, it turns over fairly rapidly in the body with a half residence time in humans of about 140 days. In contrast to the case with Sr-90 the body content of Cs-137 reflects more nearly the rate of intake and is not cumulative. In other words, the equilibrium state is achieved in a few months. In the cow, Cs-137 is excreted in the milk as well as in the urine. Major sources of Cs-137 in our diets are thus meat and milk. As long as the rate of testing in terms of fission product yield remains what it is, Cs-137 as an internal radioactive contaminant in human beings will be relatively insignificant. (See earlier section on Cs-137/K-40 ratio.)

In mammals Sr-90, like calcium, is found for the most part, over 99% of it, in the bone. Therefore, meat is exceedingly low in Sr-90 and is a relatively Sr-90 free and equally calcium-free item of the diet. Meat contains only about 10% the calcium per unit of wet weight that milk does. Uptake studies of Sr-90 in milk-free diets in rats, goats, and humans indicate discrimination against Sr-90 in favor of calcium of about 25%. According to Comar, Sr-90 in milk is less discriminated against, about

55% uptake in relation to calcium. Equilibrium state studies in humans or animals have not yet been done so this may be a pessimistic figure. The cow does a very good job of discriminating against Sr-90 in the formation of milk. The milk has only about 1/7th to 1/10th the strontium-90/calcium ratio of the cow's diet. (1, 7, 8) Comar has described some factor present in milk which if taken in at the same time tends to increase the Sr-90/calcium uptake ratio from vegetables towards that of milk itself (9).

Present Levels of World-Wide Fallout Contamination and Predictions for the Future

The discussions which follow concern themselves with levels of fallout and their biological effects outside those areas nearby nuclear weapons test sites where "near-in" fallout may be heavy and where acute effects such as radiation burns and whole body radiation injury would be expected in unsheltered persons present in the area. The effects of the latter sort of fallout are fully discussed in "Some Effects of Ionizing Radiation in Human Beings" (30). It should be kept in mind also that where reference is made to the "present rate of testing" or "present pattern of testing" we are not dealing with something relatively precise like the present birth rate. The number of weapons tested, the fission product yield, and the relative amounts of fission product debris distributed as nearby fallout, latitudinal fallout and as world-wide stratospheric fallout have been different each year. In order to simplify the picture when extrapolating to future testing, we have quite arbitrarily had in mind effects that would result were the patterns of testing prior to 1957 or its equivalent repeated by 1965.

At the present writing the exposure of humans in the U.S.A. to penetrating external gamma radiation from fallout is at a rate of about 0.1 r (0.02 to 0.5 r) for 30 years according to the 1956 National Academy of Science report (34). Cesium-137, which is the source of an appreciable fraction of this figure, has been shown by Langham (21) not to concentrate in the gonads above other non-muscle containing body masses so does not add locally in a significant way to the gonadal dose from Cs-137 in the muscles (0.03 r), other radionucleides in the body and from Cs-137 and other radionucleides and cosmic radiations in the general environment.

Sr-90 levels in the bones of infants and young children average 0.8 μμc/gm of calcium with an observed range plus or minus of no more than a factor of 3. Adult bones contain much less Sr-90. There follows a table developed at a meeting of an ad hoc group called together by the

Concentrations in children, fall 1956	Predicted future concentrations from strontium-90 on ground before 1957	Predicted concentrations in 1975 from all Sr-90 produced before 1957	Predicted concentrations in 1975 if past tests or equivalent were repeated before 1965
0.8 μμc Sr-90/g Ca	1.5 to 2 μμc Sr-90/g Ca	1.5 to 3.5 2 to 5 4 to 10 μμc Sr-90/g Ca	3.5 to 9 5 to 12 10 to 25 μμc Sr-90/g Ca

AEC at the suggestion of the Joint Committee on Atomic Energy to attempt to estimate average future levels of Sr-90 in the population. (The full text of a summary report of this meeting is to be found in the JCAE Hearings.)* The figures and predictions summarise the conclusions of the group and deal with the northwestern part of the U.S.A. which is taken as representative of an area with above average Sr-90 contamination with respect to the world as a whole.

The considerations leading to each of the three estimates in the last two columns follow:

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* The nature of radioactive fallout and its effects on man, Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, Washington Government Printing Office, Parts 1 & 2, 1957.

1. If the residual stratospheric content were to be deposited with uniform distribution over the surface of the earth.
2. On the assumption that fallout of the residual (1956) stratospheric content would have the same geographic distribution as the previous stratospheric fallout.
3. On the assumption that Sr-90 injected near the equator may be moving northward and entering the troposphere preferentially above 30°N. in such a manner that the fraction of the stratospheric content falling out in these latitudes is increasing with time.

Radiation exposure to the population as a whole can be categorized as follows:

Natural sources of exposure to gonads (sea level)	4.3r/30 yrs.
Medical X-rays	3.0r/30 yrs.
Gonadal dose in U.S. from fallout "at present rate of testing" (0.02 to 0.5 r)...............	0.13r/30 yrs.
Sr-90 dose to bone in 1975 to inhabitants of northeastern U.S.A. from present rate of testing continued through 1965	0.01 to 0.07 r per yr.
i.e., by 1975 the dose to bone	0.3 to 3.1 r

Biological Effects to be Anticipated from Fallout to Date

The radiation effects of world-wide fallout from weapons testing are delayed effects. Were the most pessimistic views eventually proved to be true, they would, if they could be measured at all, appear not as clear-cut events readily related to the cause, but as relatively small statistical increases in the number of cases of bone cancer, leukemia and congenital abnormalities, or as a shortening of the average life span.

Genetic Effects

In the field of genetics there are two principal hazards with which we are concerned when we study the effects of ionizing radiation as a mutagenic agent. First, there is the possible risk to the human race as a whole. There is undoubtedly some amount of radiation which, if the entire race were subject to it, would result in a mutation rate which would lead eventually to degradation of the species. On the other hand, the maximum tolerable mutation rate for humans, tolerable in the sense of survival of the race, is not known.

The other hazard is the danger to some individuals, the personal tragedies associated with the birth and life of a defective child. The N.A.S.-N.R.C. Committee estimated that in the normal course of events in the next 30 years 100,000,000 children will be born in this country and that there will be among them some 2,000,000 with "tangible" genetic defects. In the whole world 2,000,000,000 children will be born during the same period, of which some 40,000,000 will have tangible genetic defects. If 40 r is taken as the radiation dose per generation necessary to double the present "spontaneous" mutation rate, the 10 r dose per generation mentioned in the N.A.S.-N.R.C. report as being tolerable though not harmless would add in the United States alone 50,000 tangible defects in the first generation and eventually after 20 to 30 generations about 500,000 per generation, i.e., about 16,000 per year. A dose of 0.13 r to the gonads per U.S. generation is estimated to be incurred from the present rate of weapons testing. This would produce in the first generation an additional 650 persons with tangible genetic defects, and if this rate of exposure continued there would eventually be 6,500 per generation. There would be in addition about 5,000 embryonic and neonatal deaths, still-births and childhood deaths in the first generation and about 80,000 per generation eventually. There would also be a larger but unknown number of minor intangible defects. Were the dose received by the entire world population the same (actually it is lower) the figures would have to be multiplied by 20. In absolute numbers they are large. On the other hand, when one compares them with the 2,000,000 tangible genetic defects which are now occurring in each generation and the millions of embryonic, neonatal deaths, still-births and childhood deaths from genetic causes, they are a small fractional increase. The effects of medical x-rays could be said to be adding eventually about 1/13th to the present U.S. total, while fallout "at the present rate of testing" would add an increment of about 1/300th.

These figures are based on hundreds of experiments in fruit flies, a few very large experiments involving hundreds of thousands of mice in which only seven gene loci have been studied, and the large human genetics study in Japan by the Atomic Bomb Casualty Commission plus a few human genetics studies in non-irradiated populations. The estimates are crude and must be improved. There are needed additional careful human genetics studies involving a tremendous amount of work -- taking advantage of documented consanguineous marriages and using blood types as well as gross indices of genetic change. One of the big problems is the fact that many human abnormalities -- in fact, most -- are not clearly delineated as being genetically determined or developmental in origin. Indeed many of them, like mongolism, seem to be the result of both genetic and environmental factors.

It has been generally agreed that radiation mutations are cumulative and directly proportional to dose, down to zero. Yet below 25 r no studies have been done in other than single-celled organisms. Such studies may never be done in mammals, for in order to test accurately even a few loci at 25 r would require an experiment involving a million or more individuals. This means that much more basic work will have to be done at the macro-molecular level to establish once and for all that the single hit concept of radiation induction of gene mutation which seems to hold for bacteria, viruses and for the fruit fly hold for mammals as well at low dose rates and with low total doses. Meanwhile we must accept this hypothesis for there is little to no evidence to the contrary.

Life Span

To the best of our knowledge, except for high level radiation to vital organs, the life shortening effect of ionizing radiation is the result of total body exposure or it may manifest itself in succeeding generations as a result of genetic damage. There is considerable experimental data in small mammals on the effects of fairly large single event whole body exposure, i.e., one to two hundred r and more given either once or repeated. There is considerably less information at smaller dose increments. In general, it can be said that with large increments (100 r or more) there is a curtailment of life expectancy from the time of exposure of approximately 25% per LD/50. Thus, a single dose of 200 r would be expected to reduce an individual's life expectancy from that point on by roughly 12.5%. (28) With smaller increments, several r to upwards of 100 r, the effect in experimental animals is less marked. Probably this can be explained on the basis of a partially effective reparative process so that the curtailment of life expectancy is a little less than 1% per 100 r. (4) If this holds for humans a group of persons who had accumulated at the age of 45 years approximately 100 r in increments of several roentgens at a time and who would normally be expected to live another 25 years would lose an average of 2-3 months of their life span.

There is no definitive information at low dose rates, i.e., 0.1 r per day or 0.3 r per week, which is in the range of the permissible levels as recommended by the International Commission on Radiation Protection. A few experiments at these levels have been done in mice and rats. In each instance the average life span of the irradiated group was slightly higher than that of the control. It appears, however, that the sparing effect is during middle life and perhaps chronic low level exposure has some sort of non-specific effect by permitting survival of experimental animals in the presence of certain ectoparasites. In any event, the longer-lived animals in the irradiated group do not live any longer than the longer-lived animals in the control group. The causes of death in these low dose level experiments are not noteworthy though in one experiment there was an increase in the number of cases of leukemia. However, there was not a sufficient number of cases appearing early in life to swing the over-all statistics one way or another. A dose rate of 0.13 r per 30-year period would reduce the average life span by at the most a few days.

Leukemia

The present leukemia rate in the United States is approximately 11,400 cases per year. It is an established fact in many experiments done on animals that large doses of radiation induce leukemia. In some experiments, although the total number of cases was not increased, the onset was greatly accelerated by the radiation exposure. Though the data from the Atomic Bomb Casualty Commission in Japan are still fragmentary and will not be complete for a number of years, they can be interpreted as consistent with the concept that large single doses of radiation to man do definitely increase or accelerate the appearance of leukemia (27). The data which have accumulated on the incidence of leukemia among radiologists is consistent with the hypothesis that large total doses in the vicinity of several hundred to 1000 r and more, even when received in small increments, are leukemogenic in some individuals. Finally, the study of Court-Brown and Doll in England on the incidence of leukemia in radiation-treated patients with spondylarthritis ankylopoietica suggests that large doses of radiation to the bone marrow may result in leukemia. (10) The control group for this study is so small that one really has no information on what the incidence of leukemia in these patients would have been without radiotherapy. However, if compared with the incidence of leukemia generally among the British population as a whole the effect is clear-cut. The available experimental data from fairly extensive studies indicate that depending on the type of leukemia the induction curve may be either sigmoidal or linear. For doses of less than 100 r in humans and in statistically significant numbers of experimental animals there are very little data. Whether or not there is a threshold for leukemia induction by radiation is not definitely known. While it has been generally accepted among students of leukemia that there is some dose of radiation perhaps in the vicinity of 50 r below which leukemia is not induced, Dr. E. B. Lewis of California Institute of Technology (22), and Dr. Hardin Jones of the University of California at Berkeley (17) have proposed the hypothesis that leukemia induction from ionizing radiation is a linear function of dose regardless of dose rate and have suggested that for each mr exposure per year to the entire population of the United States there would eventually be an additional 10 cases of leukemia per year, i.e., about 40 cases per year as a result of fallout. Using this same reasoning there would be roughly an additional 3,333 cases per year were the population to receive 10 r of man-made radiation every 30 years, the exposure consistent with the recommendations of the N.A.S. Committee on Genetics.

It has also been postulated that bone-seeking radioactive nucleids such as radiostrontium might be leukemogenic. The present average body burden of Sr-90 in children in the United States is slightly less than 1/100th the maximum permissible bone concentration for Sr-90 for the population as a whole. This has been given as 0.1 microcurie for an adult, i.e., 100 micromicrocurie per gram of calcium. 100 μμc/gram calcium would lead to an exposure to nearby bone marrow of about 0.14 rad per year, and that is, about 10 rad in a life time or less than 5 rad in 30 years. If Lewis' hypothesis is correct, that leukemia induction is linear with dose to the bone marrow, and were all the bone marrow to receive this dose, which it does not, such a body burden for all people in the United States could mean an additional 5-10% increase in leukemia (500 to 1000 cases) each year. There is a considerable body of experimental data indicating that with large single doses leukemia does not result if a fair fraction of the hematopoietic system is shielded from total body radiation. "ith a certain type of mouse lymphoma, even shielding one extremity of the animal will vitiate the leukemogenic effect of a large single exposure to radiation (18). One of the problems in attempting to estimate the leukemogenic effects of relatively low doses of radiation is that we do not know the proportion, if any, of the present incidence of leukemia which may be the result of natural radioactivity. Undoubtedly, hereditary factors play a role. Carcinogenic hydrocarbons are known leukemogens (29) while in experimental studies susceptibility to radiation induced leukemia can be appreciably altered by artificially induced endocrine imbalances (19). It is logical to assume that endocrine factors as well as chemical and hereditary ones all play major roles in determining the "natural incidence" of leukemia.

It appears then that if leukemia in general or even one type of leukemia can be the result simply of a radiation-induced somatic mutation untempered by homeostatic factors, fallout at the present rate of weapons testing could, on the basis of certain assumptions as to the number of cases of leukemia due to background radiation, result in this country in some 30-40 additional cases per year or about 1000 per generation. The same assumptions lead to a figure of 900 cases per year as the result of medical x-rays (27,000 per generation). If small amounts of Sr-90 relatively uniformly distributed in bone can indeed produce leukemia in the manner postulated by Lewis, fallout from continued weapons testing "at the present rate" could eventually lead to 35 to 250 additional cases per year (1000 to 7000 per generation). To complete the story, one must keep in mind that co-carcinogenic factors and additive factors may in certain susceptible individuals prepare the way for a small dose of radiation to trigger a case of leukemia.

Bone Cancer

The present incidence of bone sarcoma in this country is about 2000 cases annually. What, if any, part of this is the result of natural radioactivity is not known. It is quite apparent from the observations of radiotherapists that a dose of external radiation of something more than 1000 r given locally to the bone is required to induce cancer, and cancer induction by doses of less than 2000 r is a very rare occurrence. As to the induction of cancer by chronic irradiation from bone-seeking radionucleids we have a considerable body of data in humans (3, 24). Practically all of this information deals with exposure incurred during adult life. In the recent studies ten of the fifty persons who received radium therapeutically were discovered because of symptoms attributable to the radium such as bone marrow, while of the twenty-eight luminous dial workers studied sixteen came under observation because of symptoms. Thus, they represent a heavily biased sample. In order to achieve a more complete picture of radium and mesothorium toxicity in humans studies have begun on several hundred additional exposed persons not known to have symptoms at the present time. Briefly it can be stated that no case has come to our attention of bone cancer in an individual exposed to pure radium salt in adult life who had left in him at the time of observation (usually 20-30 years after the material was ingested) less than 1.3 microcuries of radium. The National Committee on Radiation Protection and the International Commission on Radiological Protection have taken a little less than 1/10th of this figure, 0.1 microcurie, as the permissible radium burden for adult workers and 1/10th of that or 0.01 μc for the population as a whole. With radium the exposure to the bone is not uniform. If it were, a person with 0.01 microcurie would be getting approximately 4 rads per year to the bone and one with one microcurie would get approximately 40 rads per year. Since radium distribution tends to be spotty one must think in terms of localized areas receiving 10 or more times this average exposure. On the other hand, Sr-90 tends to be much more evenly distributed in bone. This would be especially true in growing bone. The radiation from Sr-90 is a moderately energetic beta ray as opposed to the principally very short range alpha radiation from radium. The dose to the bone then will be much more uniform. There is experimental work in mice (14) indicating that at higher dose levels the more uniform the distribution of the radiation in bone the more tumors are produced. One hundred μμc of radiostrontium/gm calcium, the presently considered permissible body burden for the popululation as a whole, would give about 0.28 rad per year or 20 rad in 60 years, i.e., three times the exposure rate to bone from naturally occurring radioactivity or from 4 to 28 times that from the Sr-90 body burden estimates for 1975 referred to on page ______.

Experimental work in mice and dogs at low body burden levels is incomplete, but the evidence to date seems quite clear that the curve for bone tumor formation in mice is either steeply sigmoidal with much less relative effect at low doses or that there is actually a threshold at about 10 microcuries per kilogram at body weight. In other words, very few if any bone arcomas will result from 100 uuc Sr-90/gram of calcium (14).

World-Wide Fallout Effects in the Event of a Nuclear War in the Northern Hemisphere

Assuming that "the present rate of testing" lies somewhere between 5 and 10 megatons of fission per year, we can very crudely extrapolate to the world-wide effects of a nuclear war localized to the Northern Hemisphere. In areas not actually involved in near-in fallout for each 1000 megatons of fission one would multiply by from 100 to 200 the first generation effects, the possible increase in leukemia cases, and the effect on average life span as estimated above to result from the "present rate of testing". Any Sr-90 effects would be ten to twenty times those which might result from tests carried out prior to 1957. This of course assumes a megaton to kiloton detonation ratio and pattern (surface bursts to air burst ratio) comparable to that which has pertained in weapons tests to date.

Caution should be emphasized in such extrapolations because our figures have been based on the United States exposures which are two or more times higher than for Southern Hemisphere countries. Furthermore, a nuclear war would be as a single event, not a continued rate. For instance, the genetic effects from gene mutations induced would not build up to an equilibrium, but would gradually fall off after the first generation to that consistent with the then existing "residual background" exposure. Likewise any postulated rise in the number of leukemia cases resulting from external whole body exposure would be limited to a single generation except as the "background" exposure was to a lesser extent raised by the Cs-137 of half life about 28 years. On the other hand, any Sr-90 effects would involve several generations but in diminishing degree.

SUMMARY

The biological effects which may be incurred if past atomic tests or their equivalent are repeated by 1965 may be summarized as follows:

1. Genetic Effects

The estimate for the genetic effects in terms of gene mutations is based on a wealth of scientific data and while not absolutely proven, the burden of proof should lie with those who question it. The estimates indicate an increase in the present incidence of "tangible" genetic defects in the U.S.A. by a factor of 1/3000 and if the added exposure rate from weapons testing were to continue over many generations the increment after 20 to 30 generations would be 1/300th. For the world population as a whole the increase would be somewhat less.

2. Life Span Effects

There would be an average curtailment of life span of no more than a day or two.

3. Leukemia

The basis for the upper limit of increase in leukemia cases is still in the realm of hypothesis, therefore, the estimate would lie between essentially no increase to as much as 1/40th over the present incidence rate of 11,400 cases per year in this country.

4. Bone Cancer

Whether or not there would be any increase in bone cancer is questionable. In any event it would be very small.

All of these estimates which in absolute numbers add up to a figure well below present day experience with accidental deaths assume that there will be no further advances in the biological sciences with respect to the prevention and treatment of leukemia and bone cancer, and in our ability to counteract or protect against the mutagenic effects of ionizing radiation.

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References

1. Alexander, George V., Nusbaum, Ralph E., MacDonald, Norman S. (1956) J. Biol. Chem. 218, 911-919.

2. Anderson, Ernest C., Schuch, Robert L., Fisher, William R., Langham, Wright (1957) Science 125, 1273-1278; The nature of radioactive fallout and its effects on man, Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, Washington Government Printing Office, Part 1, 1957, 752-765 (hereafter referred to as JCAE Hearings).

3. Aub, J. C., Evans, R. D., Hempelmann, L. H., Maitland, H. S. (1952) Medicine 31, 226-239.

4. Blair, H. A. (1956) Univ. Rochester AEC Project Report UR-442.

5. Booker, D. V., Bryant, F. J., Chamberlain, A. C., Morgan, A., Spicer, G. S. (1956) A.E.R.E. HP/R 2182.

6. Brewer (1957) JCAE Hearings 1, 148.

7. Comar, Cyril Lewis. (1956) Radioisotopes in the study of mineral metabolism, Pergamon Press.

8. Comar, C. L. and Wasserman, R. H. (1956) Progress in Nuclear Energy, Series VI, Biol. Sci. 1, 153-196.

9. Comar, C. L., Wasserman, R. H., Nold, M. M. (1956) Proc. Soc. exp. Biol. 92, 859-863.

10. Court-Brown, W. M. and Doll, R. (1956) Brit. Med. Research Council, Appendix B, Cmd. 9780.

11. Dunning, Gordon M. (1956) Nucleonics 14, 38-41.

12. Eckelmann, Walter R., Kulp, J. Lawrence, Schulert, Arthur R. (1958) Science 127, 266-274.

13. Eisenbud, Merril (1957) JCAE Hearings 1, 557-575.

14. Finkel, M. P. Texas Rep. Biol. Med. (in press).

15. Harley, John H., Hardy, E. P., jr., Whitney, I. B., Eisenbud, Merril (1957) JCAE Hearings 1, Fig. 5, 602.

16. Hartgering, James B., Schrodt, A. G. (1957) JCAE Hearings 1, 725-741.

17. Jones, Hardin B. (1957) JCAE Hearings 2, 1116-1136.

18. Kaplan, Henry S. (1954) Cancer Res. 14, 535-548.

19. Kaplan, Henry S., Nogareda, C. Susan, Brown, Mary B. (1954) Recent Progr. Hormone Res. 10, 293-333.

20. Kulp, J. Lawrence, Eckelmann, Walter R., Schulert, Arthur R. (1957) Science 125, 219-225; (1957) JCAE Hearings 1, 694-704, 705.

21. Lacy, William J. (1957) JCAE Hearings 2, 2054-2056 (and references cited).

22. Langham, Wright (1957) JCAE Hearings 1, 741-751.

23. Lewis, E. B. (1957) Science 125, 965-972; (1957) JCAE Hearings 1, 962-977.

24. Libby, Willard F. (1956) Proc. Nat. Acad. Sci. 42, 945-962; (1957) JCAE Hearings 2, 1227-1229, 1373.

25. Looney, W. B., Hasterlik, R. J., Brues, A. M., Skirmont, E. (1955) Amer. J. Roentgenol. 73, 1006-1037.

26. Machta, Lester (1956) JCAE Hearings 1, 141-169.

27. Machta, Lester, List, R. J., Hubert, L. F. (1956) Science 124, 474-477; (1957) JCAE Hearings 1, 162-169.

28. Moloney, William C. and Kastenbaum, Marvin A. (1955) Science 121, 308-309.

29. Nat. Acad. Sci. Report (1957) JCAE Hearings 2, Appendix 4, 1827.

30. Shay, H., Gruenstein, M., Marx, H. E. and Glazer, L. (1951) Cancer Res. 11, 29-34.

31. Sondhaus, C. A., Sharp, Robert, Bond, V. P., Cronkite, E. P. (1956) USAEC T.I.D.-5358.

32. Van Middlesworth, L. (1956) Science 123, 982-983.

33. Western, Forrest (1957) JCAE Hearings 1, 499, 504.

34. Nat. Acad. Sci., Nat. Research Council. (1956) The Biological Effects of Atomic Radiation: A Report to the Public.