INDUSTRIAL USES OF ISOTOPES[1]

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Uses as Isotopes

By isotopes is meant the radioactive and stable nuclides that are of the same element and are distinguishable one from another either by their radioactive radiations or by their mass as measured in the mass spectrometer. In this first section the uses in industry which exist because the isotopes are chemically identical, or nearly identical, with the ordinary nuclides constituting the main part of the element will be discussed.

Nutrition of farm animals.—By the use of radioisotopes, the metabolism of many elements in farm animals can be followed conveniently from their uptake in food in the form of elements and compounds, through their incorporation into various regions of the body, and finally to their degradation and excretion. Tracer techniques are of extreme value in such nutritional studies. For example, an element which occurs in amounts of only a few parts per 100,000,000 parts of feed can be traced from the feed, through the digestive tract, and finally to its location in the tissues of a 1000-pound animal. All this can be done without interference with the normal physiology of the animal.

Many elements are required in small amounts by farm animals. For example, a lack of cobalt in the diet decreases the formation of vitamin B_{12}. Tracer techniques also showed that high levels of molybdenum in cattle feed inhibit synthesis of vitamin B_{12}. Vitamin B_{12} labeled with cobalt 60 has been used for many types of investigation with farm animals. For example, it is transferred from the body of the cow to its milk during lactation, and the vitamin B_{12} content of milk may be used as an indication of the status of the cobalt nutrition. Vitamin B_{12} also is transferred from the hen to the egg; the amount deposited in the egg actually is the principal source for the chick up to several weeks after hatching. Even 12 weeks after hatching, the original vitamin in the egg represents an appreciable part of the total vitamin in the bird.

Sulfur is rapidly metabolized by animals. For example, the milk proteins of goats contained radioactivity within three hours after the goats were fed sodium sulfate labeled with radioactive sulfur 35. Until recently it was thought that chickens could not use sulfur in the form of inorganic sulfate for synthesizing sulfur-containing organic compounds such as the amino acid cystine. Again, with the use of radioactive sulfur, it has been possible to show

[1] The survey of literature pertaining to this review was concluded September 30, 1960.

that both hens and growing chicks can utilize inorganic sulfur. In fact, under certain conditions, the addition of sulfate to certain poultry feed increases the rate of chicken growth. The growth of cattle and sheep on a low-protein diet can be increased by feeding them inorganic sulfur.

Isotope techniques have permitted important practical studies on the absorption and utilization of calcium from feed by farm animals. These studies are complicated by the loss of endogenous calcium from the blood through the intestinal wall into the feces. The availability of radioactive calcium 45 has made such studies much simpler. It has been shown, for example, that the level of endogenous calcium in feces changes appreciably with age, becoming progressively greater in older animals, and that both calves and adult cattle can obtain large amounts of calcium from powdered limestone in the feed. It was found further that calves could absorb and retain significantly more calcium from milk than from hay or grain. Other tracer studies permit livestock feeders to get more efficiency from feed by more careful control of the calcium-phosphorus ratio of the diet and by eliminating high concentrations of materials which adversely affect absorption of these elements.

As indicated in the selected examples, radioactive tracer techniques have been of great importance in studying the mineral nutrition of farm animals. Tracer methods have been perhaps even more important in studying the uptake and metabolism of organic foodstuffs. In the past, most detailed nutritional studies on animals were carried out with small laboratory mammals; large farm animals have not been widely used because of the expense of purified diets. The use of tracer techniques, however, has permitted nutritional studies in livestock as well as in the smaller animals. Studies with tagged compounds have been carried out with vitamin A, the lack of which sometimes produces impaired vision in cattle. Other tracer studies have led to techniques for correcting deficiencies in the amino acid methionine in dry plant livestock feeds by the addition of compounds such as choline and betaine.

Milk production.—A study of the biochemical functions of microorganisms that inhabit the stomachs of grazing animals may result in methods of controlling the chemical composition of milk. Grazing animals that chew their own cud (ruminants) depend for their existence on billions of bacteria and other microbes contained in the rumen (first compartment of the ruminant stomach). These microbes produce materials necessary to the life of ruminant animals. In this way, the tiny organisms are in effect a "fluid tissue" and are just as vital to the animal as the tissues of solid organs, i.e., the heart, liver, and kidneys.

The ruminant is dependent upon a supply of fatty acids for its existence; these acids are the fermentation end-products of carbohydrates taken into the animal system in feed such as hay. Some complex carbohydrates are manufactured and stored by the microbes in the rumen. The complex carbohydrates made by rumen microbes are called polysaccharides and constitute a reserve source of energy for the microbes. This storage polysaccharide is chemically identical regardless of which species of microbes is involved in its production; and the same end-products, fatty acids, are formed from the storage polysaccharide and from rapidly used external energy materials. This means the ruminant is assured of a continuous supply of the fatty acids upon which it depends.

Once the role of this "fluid tissue" in manufacture of milk components is understood, as well as what the animal system does with products formed by the rumen bacteria, controlling the type of milk produced by the ruminant may be possible. For example, milk low in fat might be obtainable directly from the cow, making unnecessary the mechanical processing to reduce fat content.

Control of end-products formed by the rumen microflora also may result in regulation of the chemical composition of milk. Scientists must first understand what substances go into manufacture of the milk component they want to control, and they must know what substances are produced from the materials that the animal is fed. Then the principle of physiological control might be extended to include regulation of other animal products, such as proteins.

Cattle breeds of temperate areas (such as the Shorthorn) do very poorly in tropical areas. As environmental temperatures approach 80°F, food consumption, milk production, and growth rate begin to fall off, and at 100°F these processes drop to perhaps one-quarter the ordinary values. The thyroid secretory activity of cattle, as studied with radioactive iodine, showed a temperature dependence that paralleled the processes listed above. On the other hand, the thyroid activity of Zebu cattle (a tropical breed) remained the same over a very wide environmental temperature range; also the food consumption and growth of these cattle are essentially independent of temperature. Basic studies of this type may some day permit the raising of high-productivity temperate zone cattle in tropical regions, perhaps as the result of appropriate hormone treatments (1).

Detergent residues on food products.—Detergents are frequently difficult to remove completely, and it is important that the degree of removal be measurable because of possible deleterious effects upon foodstuffs. Alkylbenzene sulfonate labeled with sulfur 35 is used in a typical case. In general, over 98 per cent of the total detergent can be followed in the washing process by using the radioactive sulfur radiation as detected by a Geiger counter, whereas ordinary methods keep track of only 85 per cent, some 15 per cent being lost. All relevant experiences today demonstrate the superiority of the radioisotope tracer method in sensitivity and reliability.

Use of potassium-40 gammas to estimate lean meat content.—A rapid, objective, and nondestructive method using natural potassium-40 radiation for determining the amount of lean meat present in live animals, carcasses, and cuts of meat is of considerable value in improving the pricing efficiency involved in the marketing of livestock and meat. Objective evaluation of the amount of lean meat present makes it possible to set a price that better reflects the desirability of the product (2, 3).

Potassium 40 occurs naturally, so it may be thought to be different from those isotopes which are synthetic and short lived. Potassium 40, with its half life of 1.3 billion years, is left over from the original genesis of the elements. It is naturally present in ordinary potassium at .0119 per cent. Table I, taken from (3), shows the results for various kinds of meat and fat. This application seems to be particularly promising.

TABLE I

K^{40} MEASUREMENTS OF LEAN AND FAT HAM

Sample	Weight (lb.)	K^{40} (cpm/lb) counting rate	Chemical analysis		
			Water (%)*	Fat (%)*	Lean (%)*,†
100% lean	59.50	44.1±0.6	73.3	5.9	91.8
55% lean	51.00	24.2±0.7	43.5	45.6	52.3
50% lean	58.13	22.5±0.5	39.7	49.5	50.0
45% lean	61.13	21.1±0.5	36.8	53.8	46.9
100% fat	57.56	0.4±0.5	6.1	92.3	7.3
Fat jacket‡	47.31	22.7±0.6	41.3	47.7	53.7
Fat and lean§	58.81	22.5±0.5	42.0	47.1	52.2

* These percentages are by weight. Fat and lean should add up to 100%. They fail to do so only because of experimental error.

† Estimate from nitrogen measurement.

‡ Roll of lean surrounded by roll of fat.

§ Roll of lean end-on to roll of fat.

Isotope dilution.—Isotope dilution can be used with either stable or radioactive isotopes. The procedure involves introduction of a known weight of material with a known amount of radioactivity into a sample of a compound to be assayed. By thorough mixing, the known concentration that was added is diluted by an amount proportional to the unknown amount of material present in the original sample. A small amount of the pure compound is separated and its final concentration of radioactivity determined. It then is possible to calculate the amount of material present in the original sample that produced the change in the specific activity, the concentration of the radioactivity, in the sample.

This method is used quite extensively in a wide variety of problems, for example, in chemical research to determine the amount of six different sulfur-containing compounds in the same mixture. The same technique can be used to determine the volume of liquid in a complex industrial system (4).

Particularly important in the isotope dilution method are the compounds of radioactive carbon (carbon 14) and tritium (radioactive hydrogen), for from them can be made the radioactive molecules for application of the isotope dilution technique in organic analyses. The synthetic problems may be of considerable difficulty. They have been attacked by the classical method of synthetic organic chemistry, supported by two new techniques—the Wilzbach method of synthesis of tritium compounds by direct exposure to tritium gas (5)—and biosynthesis, the growing of the compounds in radioactive environment. The largest single biosynthesis installation is that at the Argonne National Laboratory (6). The combination of the three techniques mentioned makes it possible to synthesize most organic compounds, at least in a randomly labeled way.

Of course, after biosynthesis, or with any of the three methods, it is necessary to purify and separate out the particular compounds desired. This is usually done by chromatographic methods, either paper or gaseous. These techniques are particularly valuable, since counters can be used to detect the radiation, either on the paper or in the gas stream itself.

Water movement.—The ideal tracer for water is tritium (radioactive hydrogen). It occurs in nature and can be used to detect rain water, since rain water has a tritium concentration derived from the cosmic ray bombardment of the atmosphere and from nuclear weapons tests. After the rain water has stood for twelve years, it loses half its tritium content because of radioactive decay. It thus is possible to tell the age of water in the sense of the time lapse since it fell as rain. In this way the age of underground waters can be measured and their origin and flow patterns studied. The technique will be particularly valuable when it is supplemented with the injection of known amounts of tritium in known localities. This has not been done to any great extent. However, there is considerable information about cosmic ray and bomb tritium in ground, river, and ocean waters (7 to 24), so these can be used for tracer purposes.

Uses as Radioactive Nonisotopic Tracers

There are many uses of radioactive isotopes that do not take advantage of the fact that the isotopes have the same chemical characteristics as the nonradioactive partner nuclides in the element, but merely use them as radiation sources in tracer applications.

Many applications have been made of isotopes carried in foreign bodies as radiation sources into slurries so that the mechanics of slurry mixing processes can be studied. In particular, this technique has proven useful in controlling and monitoring the operation of catalytic cracking units in oil refineries; radioactive pellets are introduced into the catalyst powder in order to trace its movement (25). The volume of liquid in a closed system may be measured with a radioactive tracer by the dilution method: a known volume of radioactive solution is introduced and allowed to mix (either by circulation or by internal stirring); the tracer concentration is measured after mixing in comparison with the initial concentration of the tracer; the dilution ratio multiplied by the original volume gives the desired unknown volume (26). Another application of the technique is the Hull total-count method (26), which is based on the principle that the total number of gamma rays registered by a Geiger counter strapped to a pipe through which fluid containing a fixed amount of radioactive isotope is flowing varies inversely with the velocity of the flow. At the same time, the integrated count is independent of the way in which the radioactive intensity varies along the stream as long as it passes at constant speed. This principle, which can be demonstrated mathematically, is valuable in actual practice.

There are many applications of radioactive isotopes as nonisotopic tracers in attrition studies. One of the most celebrated is the use of radioactive engine parts to study wear as first proposed by Ferris (27) in 1943. In 1948 Hull and co-workers (28) showed the way to inexpensive and practical radioactive engine tests by neutron activation of standard piston rings inside a nuclear reactor. This technique has been used to study the influence of fuels, lubricants, and operating variables on engine wear rates. It has also been applied to field tests and ordinary passenger car service using a radioactive ring in the top front cylinder in each car; these tests demonstrate the efficacy of a high detergent-type oil for reducing ring wear in cars. The radioactive ring technique is about fifty times as fast as the weight loss method used before, and the reproducibility of wear rates obtained is much better.

A similar technique has been used in measuring gear wear, using neutron-irradiated gears. Other examples of engine parts that have been irradiated for wear lubricant testing are combustion cylinder liners, ball bearings, and piston-ring rest pins for Diesel locomotives.

The diversion of any fluid stream from one channel to another can be readily detected with radioactive tracers. Sometimes the extent of such a leak can be measured quantitatively. This technique of leak detection has wide applicability.

A significant application of the isotopic tracer technique is to the measurement of the movement of oil in pipelines. When two different stocks are adjacent in a pipeline, the introduction of a gamma-emitting tracer in one of these or at the interface between them allows the position of the interface to be fixed by means of its radioactivity. It is thus possible to distinguish between the two stocks, or rather to locate the interface, and Geiger counters attached to the pipeline can tell when the interface passes. Antimony 124 in the form of triphenylstibine is most widely used for this purpose, but cobalt-60 naphthenate is also used. A millicurie of a radioisotope provides a satisfactory signal in most cases.

Other examples are the determination of the uniformity of mixing of cement, the following of littoral drift using radioactive glass sand, and the full-scale measurements of siltation in estuaries. In the manufacture of paper pulp, wood chips are treated with cooking liquor for a suitable period in digesters, with a forced liquor circulation to ensure uniform treatment. The circulation carries the process heat, and the circulation characteristics thus are important for the quality of the pulp produced. One tracer used is sodium 24; about 5 mc have been found by experience to be suitable. It is injected into the system as an aqueous solution by means of a simple apparatus, and the activity of the circulating liquor after the injection is recorded continuously at a point in the external part of the circulation system. A series of evenly spaced activity maxima corresponding to each cycle of circulation is found. These peaks broaden increasingly for each cycle, and finally successive peaks start to overlap as the process continues.

Material flow in sponge iron furnaces.—Sponge iron is produced in a continuous process, involving reduction of sintered iron ore concentrate with gas. Because of its high reactivity the sponge iron must be cooled before meeting the open air, and it is therefore collected in closed containers, which are kept closed for several days before opening. The sponge pellets can only be inspected through a small window as they leave the furnace; it is thus difficult to study the transport of single pellets through the furnace and to find the transport rate by, for instance, the addition of colored pellets at different points in the furnace and visual determination of the time of their appearance at the outlet. Radioactive tracer methods have, however, been used successfully for this purpose. Chamotte balls were made of the same size as the iron ore pellets, and small pieces of irradiated platinum-iridium wire were enclosed in the balls. These were added to the charge at different points in the furnace, and the time when they left the furnace was determined with a scintillation detector connected to a recorder. The furnace outlet was connected to the container by a tube. The detector was mounted outside this tube. Experiments had shown that an activity of 100 μc of Ir^{192} gave significant signals to the recorder if the labeled ball was dropped in front of the detector. The pellets were supposed to pass the detector at a constant distance as the tube was not vertical. These balls labeled with different amounts of active material should give different signals. Three balls labelled with 50, 150, and 500 μc Ir^{192} were placed at three different points at one level in the furnace. One ball was placed in the center, one close to the wall, and the third at a point between these two. The balls are unambiguously identified by the different heights of the peaks in the diagram. A certain difference in transport time was found, as expected from the construction of the furnace. The results from several series of investigations indicated, however, that the operation of the furnace showed excellent stability as far as the flow rate of the pellets was concerned and that the rates along different verticals were quite uniform.

Among these various applications, perhaps one of the most underdeveloped at this time is the total-count method for measuring flow. It depends on the principle, as stated above, that a finite amount of radioactivity introduced into a flowing stream and passing a counter gives a number of counts inversely proportional to its flow rate. After measurement of the geometrical factors involved, it is possible to make an absolute measurement of the flow rate (29).

Uses as Radiation Sources for Gauging

Some of the more important uses of isotopes in industry apply the penetrating power and absorbability of the isotopic radiations to measurements of thickness and locations in manufacturing processes. Of all these, probably the most important is the beta thickness gauge.

Beta-particle transmission gauges are used routinely for measurements from 1 to 1200 mg/cm^2. Several different sources are needed to cover this range adequately. For measuring a particular thickness of material with the best possible accuracy, it is desirable to choose a source of beta particles such that they are at least 50 per cent absorbed in the thickness to be measured. When this is done, since the emergent radiation falls off nearly exponentially with thickness, relatively small changes in thickness result in easily measurable changes in the number of emergent beta particles. The apparent advantages in sensitivity of using beta particles that are heavily absorbed are offset by statistical fluctuations when only a few particles emerge to the detector. Generally, beta particles from a given source can be used successfully for measurements from 0.2 to 4 times the "half thickness" for absorption of the particles, and best results (thickness to about 1%) are obtained at the equivalent of 0.5 to 2 half thicknesses. For low-energy beta particles, the range is further limited by absorption in air between the source and detector, and in the detector window.

Pure beta emitters are preferred as sources, especially for the smaller thicknesses, since the more penetrating gamma rays are only slightly absorbed and reduce the sensitivity of the system to changes in thickness. Long half life is desirable to avoid the need for frequent recalibration. High specific activity is required, especially when the beta-particle energy is low; otherwise self-absorption limits the effective strength of the source. For example, early attempts to employ Ca^{45} (maximum beta-particle energy 0.25 Mev) have been superseded by the use of Pm^{147}, which is more easily produced in high specific activity (as a fission product) and has a longer half life. Table II shows a series of beta emitters in popular use for thickness gauges.

Most of these sources are now available as foils containing the radioactive material sealed between thin sheets of silver. Thallium 204 is supplied as an electroplated deposit, covered with a thin protective plating of cadmium. Activities from 5 to 20 mc are commonly used in conjunction with ionization chambers as detectors.

Much greater thicknesses up to several inches of steel can be measured by use of gamma-ray sources. A typical application is to the gauging of hot-rolled metal strips. A useful series of gamma emitters is given in Table III (30).

One of the important applications of isotopes in industry is radiography. The isotopes most commonly used for radiographic testing of such products as castings and welds are cobalt 60, cesium 137, and iridium 192.

The level gauge is similar in operation to thickness and density gauges in that it measures changes in radiation intensity produced by an intervening

TABLE II

SOURCES OF BETA PARTICLES USED IN THICKNESS GAUGES

Isotope	Half life	Maximum energy (Mev)	Approximate half thickness mg/cm^2 (Al)	Approximate useful range of operation mg/cm^2
S^{35}	87 days	0.167	2.0	0.5–5
Pm^{147}	2.6 yr	0.23	4.5	1–12
Tl^{204}	4 yr	0.77	35	10–150
Sr^{90}	20 yr	0.53	17	
$+Y^{90}$	(in equilibrium)	2.2	160	50–650
Ce^{144}	280 days	0.30	7.5	
$+Pr^{144}$	(in equilibrium)	3.0 ($+\gamma$ rays)	220	100–1000
Ru^{106}	1.0 yr	0.03		
$+Rh^{106}$	(in equilibrium)	3.5 ($+\gamma$ rays)	270	130–1200

material. Commonly, the radioisotope source is attached to one side of a tank or vessel, and the detecting instrument is attached to the other side. When the content rises, it cuts off or reduces the beam of radiation to the radiation-measuring instrument. When it is desirable to read variations in level from a gauge, the source and detection instruments are placed so that the beam passes directly or diagonally from top to bottom of the vessel. Changes in level can then be read from a calibrated instrument activated by variations in beam intensity reaching the detector.

Level gauges are most useful where heat, pressure, corrosive substances, or the difficulties of maintenance make it impossible or undesirable to use level measuring devices of the contact type. Liquid-level gauges are widely used in the petroleum industry to measure the level of hydrocarbons in cracking units and tank farms, and in the chemical industry for determining the height of various materials in closed vessels or reactors. The levels of molten glass, molten metals, and paper pulp slurries in closed vessels are also

TABLE III

GAMMA EMITTERS USED IN THICKNESS GAUGES

Isotope	Half life	Gamma-ray energy (Mev)
Tm^{170}	127 days	0.085
Se^{75}	127 days	0.40–0.067 many γ rays
Ir^{192}	74 days	0.61–0.14 many γ rays (mean about 0.5 Mev)
$Cs^{137}+Ba^{137m}$	33 yr	0.66
Co^{60}	5.23 yr	1.33, 1.17

being measured in this manner. In addition, the heights of solids, such as catalysts in hoppers or scrap metal in cupolas, are being controlled with radioisotope-level gauges (31).

INDUSTRIAL USES OF RADIATION

The industrial uses of radiation from radioactive isotopes are important and promise to become more important as the present uses are further applied and new uses developed. The radiation from isotopes falls into two general classes: the soft and readily absorbed beta radiation and the hard and more penetrating gamma radiation. The isotopes differ in the particular proportions of beta and gamma radiation, and each must be considered for its own properties, but it is generally true that convenient and inexpensive sources of both kinds of radiation are supplied from the atomic energy plants either as waste products—that is, fission products—or as a result of neutron irradiation in reactors, such as cobalt 60. A third source of radiation, of course, is the reactor itself. And in some of the future uses of radiation it is to be expected that reactors will be the source, for they are the cheapest source per unit of radiation delivered. One can envisage the possible utilization of a reactor for four products—power, heat, isotopes, and reactor radiation; i.e., reactors might be constructed in the future to deliver these four products and furnish these four kinds of income.

The principal present industrial uses of isotopic radiation are plant mutations for production of superior crop plants, pest control, and power sources.

Plant Mutations for Production of Superior Crop Plants

The production of improved agricultural and ornamental plant varieties requires many years of deliberate breeding and selection to obtain desired characteristics. The breeder needs a large pool of genetically variable source material for selective combination into a new variety. Ionizing radiation helps to provide this pool, since it produces rapidly a great variety of genetic changes in plant stocks.

With the use of radiation-altered stocks, abrupt improvements in resistance to disease have been produced. Small improvements in yield or in maturation time of crops have been achieved. The synthesis of small, independent, but scattered changes into one new variety can give surprisingly good results. Favorable genetic changes make up, of course, only a tiny fraction of all the changes produced by radiation, and the plant breeder still must eliminate and select with patience and care.

Irradiation of seeds used extensively in the United States has produced a number of promising mutations. Two new plant varieties obtained in this way have been formally released to plant breeders for practical agricultural use. One, the "Sanilac" bush navy bean, in several years of testing, outproduced the parent variety by approximately 30 per cent per acre and required fewer days from planting to harvesting. The other is an improved variety of peanut released to commercial sources two years ago; this peanut has higher yield and greater disease resistance.

Ionizing radiation also is used to produce somatic mutations in plants, such as fruit trees, that can be propagated with cuttings or grafts. Another technique involves using radiation to fragment chromosomes—genetic materials in reproductive cells—to permit recombining genes or sections of chromosomes in desired crosses. This technique has been successfully used in introducing genes for leaf rust resistance into wheat.

Disease-resistant strains have been reported in experiments with wheat, oats, and flax. High-yield dwarf forms of cereal grasses have been observed which suffer less wind damage than do customary strains. Encouraging results are reported from attempts to use mutation to eliminate a factor toxic to livestock from certain otherwise useful forage plants. Fruit trees grown in low levels of gamma radiation for several years and permitted to return to normal growth are being analyzed for possible useful mutations.

Two beneficial mutations have been reported in such experiments on peach trees: one branch on a Fairhaven peach tree bears fruit which ripens approximately ten days earlier than normal; a branch on a different tree ripens its fruit some three weeks later than normal. These two radiation-induced mutations may lead to increasing by more than a month the season over which the fresh fruit can be available (32).

Some of the useful and potentially useful plant mutations induced by irradiation are summarized in Table IV.

Pest Control

A fundamentally new method for controlling animal populations—one that enlists the reproductive process of the species in its own extinction—has entirely eradicated a major agricultural insect pest throughout a large continental region. The pest is the screw-worm fly which infests livestock; not a single screw-worm fly has been seen in the southeastern United States for almost two years. This unprecedented achievement was effected within a few months, the first time the self-eradication method was tried on such a large scale, and suggests that this method may be applied with the same results to other insect species and to rodents and other pests.

Entomologists and veterinarians of the Agricultural Research Service of the U. S. Department of Agriculture and the Florida Livestock Board reared millions of screw-worm flies in what was literally a screw-worm factory. The insects were made sexually sterile by exposure to high-energy radiation. They were then released in the infested area. The sterile males, mating with the females in the natural population, nullified their reproductive capacity. The result was the complete elimination of the natural population.

The new method offers obvious advantages over conventional techniques directed at killing the living generations of the pest. In the first place, it is highly selective, involving only the single target species and leaving the rest of the ecological system completely undisturbed. Secondly, no species can

TABLE IV

MUTATIONS INDUCED (33)

(Some Examples of Useful or Potentially Useful Mutations or Sports Obtained in Plants by Irradiation*)

Character improved or modified	Character or direction of change	Plant
IN CROP PLANTS		
Disease resistance	To stem rust	Barley, oats, wheat
	To stripe rust	Wheat
	To Victoria blight	Oats
	Leafspot	Peanut
Insect resistance	To gall fly	Sesame
Growth habit	Shorter	Barley, flax, oats, rice, wheat
	Taller	Flax, jute
	Dwarf	Sorghum, bean
	Giant	Pea, peanut, red clover
Maturity	Earliness	Barley, oats, soybean
	Lateness	Barley, oats, wheat
Self-incompatibility	To self-fertility	Red and white clovers
Quality	Improved	Tobacco, wheat
Yield	Increased	Oil mustard, peanut, peas, sesame, barley, oats, wheat
Hardiness	Increased	Oats, wheat
IN HORTICULTURAL PLANTS		
Disease resistance	To rust	Black currant
Flower color, shape, size	Various	African violet, carnation, cyclamen, petunia, phlox, snapdragon, tulip
Self-incompatibility	Self-fertility	Sweet cherry
Growth habit	Varied	Black currant
Leaf shape and color	Various	African violet, apple, phlox
Quality	Varied improvement	Black currant
Fruit size	Increased	Black currant
Fruit color	Improved	Apple, pear
Time of ripening	Earlier and later	Peach

* Some of these mutants have been induced at Brookhaven, but the majority are summarized from published articles. Space does not allow references to the original literature citations, but most of these may be found in articles (34 to 37).

Source: Sparrow, A. H., and Konzak, C. F. (1958) (38).

acquire immunity to sterile matings as it can to the insecticides used in the past. There is a third and not so apparent advantage. Killing agents tend to become progressively less efficient as the pest population declines, and so leave a few survivors to begin the cycle of geometric population increase all over again. The sterile-male method has the theoretical and, as shown with the screw-worm fly, practical capability of becoming increasingly efficient as the pest population reaches the vanishing point.

There are nonetheless disadvantages inherent in the method when it comes to planning campaigns against certain species and throughout large geographic regions. But eradication of the screw-worm fly surely urges the search for similar uses. The screw-worm fly itself remains a major objective. It continues to infest the livestock of the Southwest, where losses are estimated at $25 million each year (39).

The adult screw-worm fly lays a compact mass of two to three hundred eggs in the wounds of warm-blooded animals. The insect is especially damaging to newborn animals, infesting their navels; in fact, in areas heavily populated with screw-worm flies, few newborn calves, lambs, kids, pigs, or other young escape attack. Tiny maggots hatch from the eggs in 12 to 24 hr, becoming full-grown in about five days and reaching a length of about $\frac{2}{3}$ in. Then they drop out of the wound, burrow into the ground, and change to the pupal or resting stage in about one day. The adults emerge from the pupal case after about eight days during the summer months, live for two or three weeks, and range for many miles. They mate on about the third day after emergence, and the females are ready to lay eggs four days later. The generation period may thus be as short as three weeks; and in areas where the insect survives the year round, there may be ten to twelve generations during each year. The principle by which this eradication of the screw-worm fly is conducted is that sterile male flies made sterile by cobalt-60 irradiation are released in sufficient numbers to exceed the natural population. For example, even under conditions that are favorable to a fivefold increase in insect population per generation, it seems that the release of sterile male flies in an initial 9 to 1 ratio to the natural population could eliminate the fly in five generations. It was found that with this initial ratio, the eggs from the mated females were 83 per cent sterile; this was sufficiently close to the 90 per cent expected for the case of nondiscrimination between irradiated and nonirradiated males to justify the hope that the method would work. The first tests were conducted on Sanibel Island off the west coast of Florida, which has an area of 15 square miles and has a natural population of screw-worm flies. Irradiated sexually sterile screw-worm males were released at the rate of 100 per square mile per week for a period of three months. Within two months, 80 per cent of the screw-worm fly egg masses were sterile, and by the third month the natural population had virtually vanished.

The screw-worm fly precedent inspires people to think about application of the technique to other areas and to other varieties of pests, such as the oriental melon, Mediterranean and Mexican fruit flies, the pink bollworm, the boll weevil, the sugar cane borer, European corn borer, the gypsy moth, and the codling moth. Basic information and experience are still inadequate to determine just how far the technique can be applied and further developed. It does seem clear, however, that such dramatic success as that experienced in the southeastern United States with the screw-worm fly strongly indicates many other equally successful applications to be made in the future.

Isotopic Power Sources

While there are several methods known for producing electricity from radioactive atoms, the most promising technique is based on the thermopile principle, which was investigated years ago as a means of converting ordinary heat into electricity but was abandoned as uneconomical. With the advent of new semiconductor materials and the availability of large quantities of radioisotopes, a new type of battery has become practical, and means to extend its usefulness are being investigated. Conversion of the by-product material, strontium 90, into a safe and useful isotopic power source will provide a unique source of electrical energy.

During the past year it has been proved practical to use large quantities of strontium 90 in this way to produce electricity. The first requirement was to find a compound of strontium with proper thermal conductivity, strontium density, compressibility, and solubility characteristics. Strontium titanate meets the requirements. Strontium titanate melts at 3038°F and is soluble in sea water at 60°C to only 10 parts per billion. The solubility in fresh wash is not detectable by tracer techniques. As additional protection against environmental contamination, the material is triply encapsulated in 0.75 in. of Hastaloy C, which has a salt-water corrosion rate of 0.0001 in. per year. In addition 1.25 in. of tungsten surround the encapsulated strontium.

A 5-watt generator has been designed and is under construction to power an automatic data telemetering station. The construction of the battery is simple: strontium titanate ceramic pellets (containing about 20,000 curies of Sr^{90}) are encapsulated and sealed in a tungsten heat sink; 72 pairs of lead telluride thermocouples are placed around the heat sink and connected electrically.

The generator is capable of continuously delivering 5 watts at 4.0 volts dc for two years unattended. Even then its limit is the electronic equipment rather than the isotopic generator. The equipment will be capable of telemetering data at programmed times or on call from remote regions and will collect information such as meteorological observations from previously inaccessible regions (40).

The ultimate capability for producing power by isotope radiation is small. Since only a minute fraction of the total fission energy resides in the decay energy of the long-lived fission products and since production of radioactive isotopes, such as cobalt 60, by neutron irradiation is a highly inefficient process, large amounts of power can probably never be made from isotope radiation sources. There are, however, many instances in which the light weight and small need for maintenance are commanding features. An example is distant weather stations where the isotope power source will serve to charge batteries which, on occasion, send back weather information to the home station. The isotope power source is unique. Of course, the most important application and the most obvious one is to space-exploration problems requiring light-weight power sources capable of delivering up to several hundred watts of electric power. Above this power level, it is necessary to use nuclear reactors. Early in the program, it was recognized that the development of the radioisotope power source for space uses would take a relatively short time, and in January 1959 the first success was reported with a $4\frac{3}{4}$-in. diameter, 5-lb device generating 5 watts of electricity, fueled in this instance, however, with the natural isotope polonium 210. This device was a "proof of principle" effort. The next stage is, of course, to use fission products, such as strontium 90, and there seems to be no doubt that these sources will be completely successful in those applications where the small amounts of power they can deliver will suffice.

POTENTIAL NEW USES

Food Preservation by Irradiation

Research on the radiation processing of foods commenced over ten years ago. Within the past six years a full-scale development program has been concentrated in the United States on this new concept in food technology. Work on radiation-processed foods in other countries has also been initiated and is being pursued actively. Major effort in the United States has been supported by the government, primarily the Department of Defense, through contractual research projects at universities, research institutes, and private companies. Current selected information on radiation-processed foods technology can be found in the report on the Massachusetts Institute of Technology International Conference on the Preservation of Foods by Ionizing Radiation. A comprehensive survey of the field through 1957 is contained in the U. S. Army Quartermaster Corps publication entitled *Radiation Presrvation of Food* (41). However, the rate of accumulation of information in this subject area has increased sharply since the latter book was published. A good general reference is the material contained in the *Hearings on the National Food Irradiation Research Program—Jan. 14 and 15, 1960—held before the Joint Committee on Atomic Energy of the Congress, Parts I and II* (42).

The comprehensive research and development program on radiation processing of food has revealed some products having a potential for commercialization. However, the radiation sterilization of some meats, such as beef, still poses major problems. Other items, such as chicken, fish, and pork products, show promise as completely sterile products. Generally, however, substerilization offers more immediate promise since effects on quality (flavor, texture, and color) are minimized and the processing costs more nearly approach those of conventional processing methods. The sub-sterilization of marine products, chicken, and some selected fruit products, such as strawberries, to extend shelf-life appears promising (42).

In the development of radiation as a general processing agent, we are concerned with putting to work the millions of curies of fission products and other sources of radiation energy being produced in our atomic energy program. Already radiation energy is being used to yield several products of im-

TABLE V

ESTIMATED COSTS OF PROCESSING WITH RADIATION SOURCES

	Exposure	
	2.5×10^6 rep	10^5 rep
Spent fuel elements	2.050¢/lb	0.0820¢/lb
Gaseous fission products	0.360¢/lb	0.0144¢/lb
Separated cesium 137*	0.379¢/lb	0.0152¢/lb
Sodium 24	0.648¢/lb	0.0260¢/lb
Reactor-activated indium	1.402¢/lb	0.0560¢/lb
Electron accelerator (7.5-kw)	0.548¢/lb	0.0722¢/lb
Electron accelerator (50-kw)	0.235¢/lb	0.0854¢/lb

* Does not include the cost of the cesium source.

portance in our space and missile program. These specific advances were developed by private industry but are based largely upon technology which emerged in government programs in the early '50's. A concerted effort is being made to broaden the scientific base of this technology so that additional promising applications of radiation energy can be achieved.

The costs are potentially quite low. A reasonable set of estimates is given in Table V (43).

As the atomic power reactors become more common and the handling of reactor radiation and fission products is better understood, the cost will fall even further; e.g., in the sodium graphite reactor being built at Hallam, Nebraska, it was hoped at one time to incorporate a loop which took the radioactive sodium out of the reactor proper and passed it into an adjacent room, where the gamma radiation from the 15-hr half-life radiaoctivity could be used to sterilize food.

The question of the wholesomeness of irradiated food is a serious one, but, in general, the indications are favorable. However, the taste of various foods is altered somewhat, and it now seems likely that the program using less intense radiations than those required for complete sterilization will be followed, particularly with certain kinds of fish, as a beginning attack on the whole problem of getting the atom to work on the problem of food preservation.

Organic Chemicals

Radiation can be used to cause chemical reactions which, in the case of certain organic chemicals, are unique. The hardening of polyethylene plastic by irradiation is a case in point. Cross-links are induced that cause a structure to become rigid and glassy, so the plastic can be heated to higher temperatures before it softens. Similarly, rubber can be vulcanized with irradiation in a way that produces a superior product. None of these processes as yet is commercially economic or practical, but the whole idea of using radiation as a chemical reagent is catching on to a considerable degree. One of the barriers to the development of a radiation chemical industry is the lack of understanding of radiation effects on matter. This understanding is coming slowly; but as it does come, it seems likely that it will be possible to develop important chemical uses for radiation. The subject is still in the research and development stage, and it appears it will be some years before a fully practical process emerges. The properties of radiation which cause chemical reaction are fairly well understood, but the nature of the chemical entities that react is not clear. It is quite certain in many instances that the free radicals produced are responsible; but in other instances the ions produced seem to be responsible, at least in part, and it is probable that both are involved to a certain degree in almost every case. Radiation is cheap enough in the internal parts of an atomic reactor to indicate that if we had any process which appeared to be reasonably efficient, the chemical use of radiation might be important; in other words, a reactor might operate both as a chemical factory and as a power source.

LIMITATIONS (HEALTH AND REGULATORY)

Isotopic tracer uses are based on the fact that matter otherwise indistinguishable can be distinguished by virtue of the radioactivity contained in the isotopes, or by virtue of the difference in mass, as in the case of deuterium tracing or in a few instances by other characteristics of the atomic nuclei, such as fissionability; in most industrial applications of isotopes, the radiations of radioactive isotopes are used. There are two general subclasses of the uses—those in which the tracing is the main thing and those in which the radiation itself is the main thing, either for purposes of gauging or for purposes of radiation treatment or radiation chemical uses. The principles of isotopes, of course, contain the seeds for the limitations of the method, and these are simple. The radiations can be dangerous. So, in this section, the matter of the limitations on isotope uses which the public health demands will be discussed.

The safe handling and use of isotopes has been given a great deal of attention by the federal government, particularly the Atomic Energy Commission, which dealt wisely with the problem by using education as well as regulatory techniques. The law vests the Atomic Energy Commission with the power to control the products of the atomic fission reaction and those isotopes which can be made by neutron irradiation, but it does not give it the power to regulate the use of X rays or natural isotopes, such as radium. This characteristic of the law has made the work of the Commission somewhat more specialized than it otherwise would have been, but the broad sweep of its responsibility, nevertheless, has meant that the Atomic Energy Commission has had to deal with the matter of the public health in connection with radioactive isotopes since its very inception. Recently, the Public Health Service and the Department of Health, Education, and Welfare have also had to pay increasing attention to this potential hazard.

The great benefits from isotopes are such that we will want to tolerate as general a use of isotopes as is reasonable and safe. So we must become educated about them and understand the hazards of radiation, in order to judge just how far it is possible to go in living with radiation and isotopes. There are various aspects of the problem; the most immediate one is the use of isotopes and the hazard that they constitute. Of course, there is a broad, general, and underlying hazard of radioactive fallout in time of war, but we are not dealing with it here. The question is: "Can you safely use isotopes for a particular application?" And this question is immediate and definite and important, and there must be an answer for it. Otherwise, progress in the direction of isotope use will stop.

The basic threat that radiation constitutes is that it does change tissue. It will cause somatic effects, i.e., damage to the health, and it will also cause genetic effects, i.e., changes in the characteristics inherited in the children and grandchildren and subsequent generations. Now, as stated, these facts have their beneficial aspects; e.g., in the treatment of cancer, the excision of tissue by irradiation is a standard and useful technique, and in the development of new kinds of plants, the horticulturist finds it useful to irradiate to get improved types. The hazard also lies in the same facts, and it must be dealt with against the background of the usefulness. A useful guide in this connection is the amount of radiation which is normally received from uranium, thorium, and potassium naturally present in the ground, and from the cosmic rays. The regulations have been set on the basis of the general feeling that the tolerable steady dose should not exceed a few times the natural dose rate and that even this should be restricted to a relatively small fraction of the total population, so that the genetic effects will be minimal. (It is a point in principle, of course, in genetics that the genetic effects require that large numbers of individuals be exposed in order that they may be manifested; i.e., the exposure of a few individuals will not cause widespread genetic effects.) On the matter of health, however, it is a matter of the individual. In general, effects on health are very hard to observe for radiation exposures below several roentgens in amount, whereas the natural dose rate is about .1 to .2 r per year. So one sees that at levels of radiation which are a few times the natural dose rate, the "permissible" dose can cause no immediately observable effects on health. However, there is a widespread feeling among certain life scientists who have studied the problem that some possibility exists that in a large number of individuals exposed to a very small dose, there is a certain probability of the development of serious maladies such as cancer. It has not been demonstrated that this is so, nor has it been demonstrated that it is not so; the known fact that cancer and other maladies can be caused by higher doses leads one to assume for reasons of safety that the effects are linear at low dose rates. So most of the regulations are set up on the linear basis. It is better to play safe in this way than to take an unwarranted chance. Further information and further research in this area are most important. Of course, we pay a price in having to live with regulations which are unnecessarily restrictive in the use of such valuable and generally applicable tools as radioactive isotopes; but until we know about the nature of the somatic and genetic effects of low dose rates it is difficult to do anything other than to take the linear assumption. On the linear assumption, the rules are made so that the tolerances are essentially of the order of the natural dose effects. And it can be said with certainty that, living with these regulations, the effects of radiation will certainly be minimal. It is, however, possible that the regulations are unnecessarily restrictive and that as we learn more about the nature of the effects of radiation on matter, particularly human tissue and the human genes, we will be able to relax somewhat. Conceivably, of course, the trend would go the other way, but the general consensus of opinion is that levels of exposure that are considered tolerable at present are really safe.

Practical problems, such as the granting of permission for a proposed use of radioactive isotopes or the disposal of radioactive waste, involve the people in the community and require the informing of public health officials about the effects of radiation on matter, especially on human tissue. And this general information is not as widely known as it should be, and so for some considerable time there will be a shortage of trained public officials. This need is recognized widely, and as the States get into the business of helping the Atomic Energy Commission and the Department of Health, Education, and Welfare police the atomic energy industry, we will require more and more trained people. So there is an educational program now under way to train public health officials for the type of inspection and regulatory activities required. The general literature on the subject of radiation hazard is voluminous. A few items, however, might be cited. They are:

Living with Radiation, Vol. I and II, and *General Handbook for Radiation Monitoring* (US Atomic Energy Commission); *Disposal of Radioactive Waste*, Vol. I and II; *Proceedings of International Atomic Energy Agency* (Vienna, 1960); *Selected Materials on Radiation Protection Criteria and Standards: Their Basis and Use* (Joint Committee on Atomic Energy Congress of the US, Govt. Printing Office Document 54561); and *Hearings before the Joint Committee on Atomic Energy—Jan. 28, 29, and 30; Feb. 2 and 3, 1959—on the Industrial Radioactive Waste Disposal* (*1959*), **1** and **2** (Govt. Printing Office—No 0-37457).

One problem of the atomic age is that radioactive material becomes widely disseminated in very small amounts, and though it constitutes essentially no health hazard, it may become a problem technically. Apparatus for the sensitive measurements of small amounts of radioactivity requires clean materials of construction, and it is necessary now in writing specifications for equipment of this sort to specify clean materials, materials free of radioactivity to specified levels. The problem is not yet serious, but could become so. For example, lead is normally radioactive because of the natural radioisotope, Radium D, but old lead which has lost its RaD (half life 19.4 years) by decay is not appreciably radioactive and can be used for the construction of low-level counting equipment whereas young lead cannot. The problem of assuring radioactive cleanliness in materials used in photography is another example.

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