The Medical, Agricultural, and Industrial Applications of Nuclear Technology

Alan E. Waltar
Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352
alan.waltar@pnl.gov

Abstract - The majority of our citizens are aware of the contributions of nuclear technology to the production of electricity via commercial nuclear power plants. But most are unaware that the impact of this technology is even greater for non-power applications. The world of medicine, agriculture, and modern industry has been substantially improved by the harnessing of radioisotopes, and new applications continue to make major humanitarian contributions to our quality of life.

I. INTRODUCTION

In his 1953 United Nations Atoms for Peace address, President Eisenhower specifically challenged scientists and engineers to harness the atom for humanitarian applications in medicine, agriculture, and other non-power aspects of direct benefit. Hence, a key part of the Lawrence Livermore National Laboratory Center for Global Security "Atoms for Peace" workshop series held during 2003 was to consider how well his challenge has been addressed, and what the future may hold for such non-power applications.

Table I summarizes the economic and job impacts of nuclear technology in the United States for both 1991 and 1995 as compiled by the pioneering work of Management Information Services (1,2,3). Whereas the total impact, both in terms of dollars and jobs is most impressive, perhaps the biggest revelation for the United States is that the impact of the atom is substantially larger in the non-power sector than in the sector comprising nuclear power. For both 1991 and 1995, the ubiquitous use of radioisotopes to serve a myriad of beneficial purposes yielded revenues and jobs well over three times that contributed by the nuclear generation of electricity.

Table I. Overall Impact of Nuclear Technology in the United States (using multiplicative economic model)

	1991 (1,2)		1995 (3)	
	Sales ($B)	Jobs (M)	Sales ($B)	Jobs (M)
Radiation	257	3.7	331	4.0
Nuclear Power	73	0.4	90	0.4
Total	330	4.1	421	4.4

In order to appreciate how the economic impact can be so high, it may be of value to summarize how the atom has been harnessed globally for use in everyday non-power applications.

II. MEDICINE

Perhaps the most significant success story over the past half-century in harnessing radiation to serve modern humanity is in the field of medicine. Both the quality of life and longevity of citizens throughout the developed world have improved substantially within the twentieth century, largely due to dramatic medical advances.

II.A. Sterilizing Medical Equipment

Ever since the advent of germ theory, medical teams have demanded cleanliness as a crucial part of good practice. Knowing that radiation in high enough quantities can kill microorganisms, the medical community quickly recognized the potential for employing certain types of radiation (mainly gamma radiation) to sterilize dressings, surgical gloves, bandages, plastic and rubber sheets, syringes, catheters, sutures, heart valves, and a myriad of other devices routinely used during medical procedures. Because radiation is a 'cold' process, radiation can be used to sterilize a range of heat-sensitive items such as powders, ointments and solutions, and biological preparations such as bone, nerve, skin, etc., used in tissue grafts.

Today, well over half of all sterilized medical equipment used in modern hospitals is a direct result of radiation treatment. This process is safer and cheaper than most other methods (such as steam) because it can be done after the item is packaged. Hence, the sterile shelf life of the item is then practically indefinite—provided the package is not broken open.

II.B. New Drug Testing

It is nearly impossible for today's physicians to effectively deal with severe patient illness without modern drugs. The pharmaceutical industry has recently skyrocketed in most developed countries as new drugs are produced to treat previously incurable diseases and anomalies. But in order for such treatments to be approved by the designated federal agencies and reach the physician's hands, substantial testing must be done. Mammoth hurdles must be overcome by the drug companies, both to determine how a new product attacks the targeted disease and then to ascertain what the side effects might be. Radioisotopes, due to their unique imaging characteristics (particle emission), are ideally suited to deal with such questions—including material uptake, metabolism, distribution, and elimination of unwanted residues from the body.

It is estimated that over 80% of all the new drugs eventually approved for medical use employ radiation techniques as a crucial component to their success. It should not be surprising, therefore, that radiation techniques played a key role in 12 of the recent 15 Nobel Prizes awarded in medicine and physiology. The International Atomic Energy Agency (IAEA) has estimated that between 100 and 300 radiopharmaceuticals are in routine use throughout the world, and most are commercially available.

II.C. Diagnostic Techniques

A crucial part of successful medical practice is to diagnose ailments. There are countless examples in every corner of the globe where an early and exact diagnosis could have prevented tragic results.

It is this element of medicine where radiation techniques have made their most significant contribution to enhanced health care. The earliest use of radiation in the medical field was employing portable x-rays sources in World War I, where such devices helped field surgeons save many lives. Dental x-rays, chest x-rays, mammograms, and a plethora of other tests are in routine use today in the medical/dental professions.

But x-rays, useful as they are, provide only a snapshot of a particular piece of the anatomy. The imaging properties of radioisotopes allow modern nuclear medical specialists to measure the activity of some specific physiological or biochemical function in the body as a function of time. This has enormous implications, all the way from determining nutritional deficiencies to locating and identifying various types of cancer.

Two of the most common approaches used in modern diagnostic nuclear medicine are single photon emission computed tomography (SPECT) and positron emission tomography (PET).

SPECT is widely used for routine clinical work because it is relatively inexpensive and utilizes radioisotopes available from nuclear reactors. Technetium-99^{m}, a very popular 140 keV gamma emitter with a 6-hour half-life, is the most popular radioisotope used in this device. It is derived from a common nuclear reactor fission product (Molybdenum-99). Mo-99 has a 66 hour half-life and it decays to Tc-99m. The "generator" consists of a lead pot enclosing a glass tube that contains Mo-99. When an order for Tc-99m is placed, it is washed out of the lead pot by a saline solution and prepared for injection into the patient. After about two weeks of use, the generator is returned for a new batch of Mo-99.

The SPECT system works by placing a solution containing a short-lived radioisotope such as Tc-99m into the patient. The patient stays in a fixed position and cameras (detector systems) rotate around the patient, picking up the gamma rays emitted by the Tc-99m circulating in the patient's body. By the clever use of microprocessors, the data collected by the cameras can be sorted out and the location of the Tc-99m radioisotope can be followed as a function of time. If bone cancer exists, the chemical carrier to which the Tc-99m is attached will tend to collect at the sites of the tumors, and the "tell-tale" sharp images at those sites clearly reveal the problem. If the physician is looking for other types of abnormalities, a different chemical carrier is used (one that has a propensity of accumulating at the suspicious sites). This procedure is now employed so frequently that one of every three patients that enter a U.S. medical center today directly benefits from nuclear medicine.

Whereas Tc-99m is by far the most popular radioisotope used for such purposes, some SPECT systems have been equipped with Flourine-18 embedded in 18F-deoxyglucose (18FDG). F-18 has a substantially more energetic gamma ray (511keV), thus requiring a different detector system. Other radioisotopes, generally produced by nuclear reactors for such use, are I-131, Ga-67, and Tl-210.

PET devices are based on the detection of a pair of photons emitted from positron annihilation. Very shortly after a positron is emitted from a radioactive substance such as flourine-18, it collides with an electron and the two particles are literally annihilated. The mass of the two particles is translated into pure energy and two gamma rays of at least 511 keV each move apart at light speed in precisely opposite directions. By surrounding the patient into which the radioisotope was injected with special detectors, the location of the radioisotope can be pinpointed by determining counts recorded at exactly the same time (coincidence counting) at opposite sides of the patient. PET systems tend to be more expensive than SPECT systems, partly because of the sophistication of the counting system and partly because the radioisotopes that emit positrons typically have a very short half-life (minutes). Hence, they must be produced on-site by accelerators (usually cyclotrons) and administered to the patient with the proper chemical carrier very quickly. But PET machines are becoming increasingly popular because they are capable of more precision than most SPECT devices. Three dimensional PET systems are particularly impressive and can provide the diagnostician excellent images. Radioisotopes often used in such devices, in addition to F-18, include carbon-11, nitrogen-13, and oxygen-15.

Nuclear diagnostics are now routinely employed throughout the developed world to determine anomalies in the heart, brain, kidneys, lungs, liver, breasts, and thyroid glands. Bone and joint disorders, along with spinal disorders, also benefit directly from this routine use of radioisotopes.

In addition to the accuracy in determining medical abnormalities that nuclear diagnostics provides to the physician, a great advantage to the patient is that there is no discomfort during the test and after a short time there is no trace that the test was ever done. The radioisotopes simply decay and disappear completely. The non-invasive nature of this technology, together with the ability to observe an organ functioning from outside the body, makes nuclear diagnostics a very powerful tool.

II.D. Therapeutic Approaches

Until recently, the use of radiation to actually cure diseases has been rather limited. One of the first therapeutic uses of radioisotopes was employing Iodine-131 to cure thyroid cancer. Since the thyroid gland has a special affinity for iodine, it is a relatively simple and straightforward matter to have a patient drink a carefully determined amount of I-131 in a chemically palatable form of solution. The I-131 then preferentially lodges in the thyroid gland and the beta emitting properties of this radioisotope subsequently target and destroy the thyroid malignancy. Since I-131 has a half-life of 8 days, it does its job and then effectively disappears within a few weeks.

Another widespread use of radiation is in the treatment of other cancers. Surgery, chemotherapy, and radiation (often used in combination) constitute the principal venues of cancer treatment today.

Most of the current procedures utilizing radiation to kill cancer in humans are based on delivering the radiation to the patient externally. This is called teletherapy. Accelerators are used to deliver either protons to the target (such as the system used for external beam prostate treatment at the Loma Linda facility in California) or beta particles, which are normally directed onto a target that secondarily produces x-rays. Whereas substantial benefits can be obtained by such treatment, it is essentially impossible to keep the radiation from killing or impairing healthy tissue in the immediate vicinity—especially if the beam must pass through healthy tissue to reach the malignancy.

The two principal approaches underway to prevent radiation therapy from injuring healthy cells are 1) creating radioisotopes at the site of the malignancy, and 2) developing a method to deliver appropriate radioisotopes directly to the cancerous tissue.

An example of the first approach is called boron-neutron capture therapy (BNCT). Boron is placed into the patient as part of a special chemical carrier such that it preferentially concentrates at the tumor site. A neutron beam is then focused on the boron, producing alpha particles that destroy the malignant cells only in the immediate vicinity of the concentrated boron. Since alpha particles are stopped at a very short distance from their point of origin (typically about one human cell), the intense radiation damage is very localized. Some damage may be done to healthy cells through which the neutrons must pass to reach the malignancy, but special "beam tailoring" can be done to minimize this concern.

An example of the second approach is cell-directed radiation therapy. In order to attain the localized damage desired, either beta or alpha emitters are needed. For solid tumors, one method of getting the radioisotope to the target is direct injection, assuming the tumor is accessible. An example of this approach is Brachytherapy. One well-founded application of this technique is treating prostate cancer. This is accomplished by encapsulating a small amount of a radionuclide such as I-125 or Pd-103 within a titanium capsule about the size of a grain of rice. These "seeds" are then placed directly into the prostate gland where they remain for life.

Another approach to cell-directed radiation therapy is to find a chemical that has a special affinity for the malignancy, and then attach the radioisotope to this special carrier. This is called the monoclonal antibody (or "smart bullet") approach. It is also sometimes called targeted alpha therapy (TAT), since much of this research is focused on the use of alpha particles. Such an approach is particularly suited for treating malignancies that are not confined to a particular spot. Leukemia and Non-Hodgkin's diseases are examples. Recent work employing the "smart bullet" approach has revealed some very impressive results. End stage Hodgkin's disease has been treated with Yttrium-90 (a beta emitter), with a positive response rate of over 80% (for patients who have failed all other known treatments). Patients with advanced stages of B cell lymphomas treated with Iodine-131 have a demonstrated survival rate of over 90%. Recent trials using an alpha emitter (Bismuth-213) have shown remarkable results in treating leukemia.

Several specialized areas of treating specific abnormalities are developing on almost a constant basis. Most people are aware of the procedure called angioplasty (that of inserting a "balloon" into a clogged artery and passing it through in a "roto-rooter" manner to unclog it). Whereas this procedure has a high success rate, and has prevented a plethora of heart attacks, there are several cases where the arteries slowly become re-blocked. Several years ago, it was discovered that lining the "balloon" with rehenium-86 made a huge impact in preventing re-closure of the arteries.

Another example of a specialty area is the treatment of arterio-venous malformation (AVM). This condition is a malformation of blood vessels characterized by a mass of unwanted arteries in the brain. A special mixture containing a radioactive powder is injected into the artery, causing an arterial occlusion, thereby stopping the blood flow into the unwanted vessels. This is but one example of numerous applications of radioactivity to somewhat unique conditions.

Although many of the above results are still in relatively early trial stages, the potential for success is enormous. Given that cancer remains a major concern in most areas of the world, and that it is the most prevalent childhood disease in the Western World, the incentive for further harnessing radiation in the field of medicine remains huge.

III. AGRICULTURE

It is sobering to realize that here at the beginning of the 21st century, some one billion of our fellow citizens on planet Earth (approximately one out of every five) go to bed hungry every night. Tens of thousands die every day from hunger and hunger-related diseases. Hence, there is an enormous need to find new ways to increase food production and deliver it to an increasing population of hungry mouths with only minimum spoilage. The following paragraphs provide a glimpse of the enormous contributions radiation makes in our constant quest for enhanced supplies of quality food.

III.A. Higher Crop Production

It is well known that the yield from any crop is directly dependent upon the proper amounts of nutrients and water. The demand for fertilizer, which is essential in modern agriculture practices to maximize crop yields, will continue to mount in order to provide food for the rapidly increasing world population. Radioisotopes can be used to "label" different fertilizers. By attaching radioactive tracers to known quantities and varieties of fertilizers, it is possible to directly determine the associated nutrient efficiencies as the labeled products are absorbed at critical locations in the plant. This technique can be used to substantially reduce the amount of fertilizer required to produce robust yields, thereby reducing costs to the farmer and minimizing environmental damage.

Water is a critically important factor for crop production and it is becoming quite scarce in many areas of the world. Neutron moisture gauges, which measure the spectrum shift resulting from the impingent of energetic neutrons upon protons, can measure the hydrogen component of water in both the plant and the surrounding soil. As such, they are ideal instruments to help farmers make the best use of limited water supplies.

Another effective way to improve crop production is the development of new species--varieties that can better withstand heat or storm damage, exhibit enhanced maturing times (to escape frost damage and allow crop rotation), attain increased disease and draught resistance, provide better growth and yield patterns, deliver improved nutritional value, allow improved processing quality, and provide enhanced customer acceptance. For centuries, selective breeding and natural evolution resulting from spontaneous mutation has winnowed out weak plant species, allowing only the hardiest to survive. But specialized radiation techniques (either directly bombarding seeds to alter DNA structures or irradiating crops to induce variations in the resulting seeds) can greatly accelerate this process to produce superior species (4). Subjecting plants and seeds to carefully tailored ionizing radiation to create new combinations in their genetic makeup has resulted in improved strains of numerous crops. Many of these superior species now constitute a key part of modern agricultural commerce around the world. In fact, over 30 nations have developed more than 2250 new crop varieties in the past 70 years—with radiation being the key element in the development of 89% of this enormous new stock (5).

Indeed, the application of radiation techniques to the development of new crop varieties has likely provided the highest global economic value of any form of harnessing radiation. Mutant varieties (called cultivars) that have made major contributions to the global economy include grains such as rice, barley, wheat, beans, lentils, and peas. Other crops include new varieties of cotton, soybeans, sunflowers, and peppermint. New fruit varieties include apples, cherries, oranges, peaches, bananas, apricots, pomegranates, pears, and grapefruit. There is even one cultivar for raspberries and grapes. Of the 2250 new crop varieties noted above, 75% are crops of the type just mentioned. The other 25% are ornamental flowers, such as chrysanthemums, roses, dahlias, bougainvillea, begonias, carnations, alstroemerias, achimenes, streptocarpus, and azaleas.

All of this technology started as far back as 1928 with the discovery of mutagenesis—an important tool for locating genes on chromosomes. Plant breeders and geneticists soon became interested in radiation as a fast and effective way to alter plant traits. Gamma rays are used in the majority of cases to change plant characteristics (64% usage) and x-rays are employed in another 22% of the cases. The bulk of the remaining 14% is done via fast and thermal neutrons. To date, China has benefited the most from the utilization of radiation to improve crop species. As of 2002, nearly 27% of the crops grown in China were developed using radiation techniques. China is followed by India (11.5%), USSR/Russia (9.3%), The Netherlands (7.8%), USA (5.7%), and Japan (5.3%).

Rice is the major source of food for over 50% of the global population, and is especially important in the Asian diet. Some 434 mutant varieties of rice have been developed, of which half were developed from gamma radiation. Because of radiation, Thailand has become the largest exporter of aromatic rice in the world. During the decade from 1989 to 1998, Thailand produced $19.9 billion of milled rice!

Barley is a prime ingredient in making malt. Mutant varieties such as 'Diamant' and 'Golden Promise' are two radiation products that have made a major impact to the European brewing and malting industry. This industry provided Scotland with a revenue of approximately $417 million over the last quarter century. Both the United Kingdom and Ireland likewise make wide use of 'Golden Promise' for their beers and whiskey.

Wheat is the staple grain for many countries, including the United States. In Italy, the Durham wheat 'Creso' mutant was developed via radiation. By 1984, this mutant reached 53.3% of the Italian market—such that over 50% of the pizza consumed today in Italy is the direct result of harnessed radiation!

Cotton has been the bread and butter crop to underpin the clothing industry in many nations for decades. A special high-yielding cotton mutant NIAB-78 was produced by gamma rays and released for commercial production in 1983. This variety has shorter stature (so that the nutrients go into the product rather than the stock), better growth, enhanced heat tolerance, and it is resistant to bollworm attack due to early maturity. This variety has had a pronounced impact in Pakistan, where their entire clothing industry was threatened by an insect infestation. Within 5 years of the release of this new, radiation-induced variety, the cotton production in Pakistan doubled! Within 10 years of release, this variety yielded over $3.0 billion in cotton production.

The above examples only begin to describe the impact that the world of radiation has had in the development of crops and flowers. It is nothing short of amazing!

III.B. Improving Animal Health

Farm animals, essential for providing commodities such as milk, meat, wool, and leather, have likewise benefited from the application of radiation techniques. One key venue concerns the best way of feeding animals, i.e. the optimal use of natural pastures or commercially prepared feeds. This is accomplished by labeling the feed with specialty radioisotopes, such as Carbon-14, and then tracing the paths of the food within the animal's digestive system to determine where and how quickly the food is broken down into body tissues or milk. The nutritional value of the food is thereby determined.

In many parts of Asia, the primary feedstock for buffaloes and cattle consists of rice straw and native grass. This combination often lacks sufficient protein, energy, and minerals needed for a balanced diet. Employing tracer radioisotopes to determine the key nutritional deficiencies has been used quite effectively in places like India and Indonesia.

In one example, scientists in Indonesia were able to develop a multi-nutrient block for buffaloes to lick. This increased buffalo weight gain at the rate of 3 kg per week and at the same time reduced their need for grass consumption by 80%.

Radioisotopes have also been used to develop vaccinations that are effective for certain animal diseases. A rather dramatic example was the approach used to fight rinderpest ("cattle plague"), a dreaded cattle disease that has devastated untold African farms for the past four decades. Millions of cattle have died from this disease. Punctuated by a series of rinderpest outbreaks in the 1980s, a combined effort from the IAEA, FAO and a British laboratory was initiated to employ radioisotopes in developing an effective vaccination. They accomplished their mission in 1987. By the year 2000, use of this special-developed vaccine had eradicated this disease in 16 of the 18 African countries previously infested (6).

III.C. Eradication of Pests

Unwanted insects on the farm can lead all the way from substantial irritations to livestock to complete devastation of crops. Estimates of harvest loss due to unwanted insects range from about 10% annually to as high as 30% in some of the developing countries (7). Conventional chemical treatments used to control such insects often create environmental pollution and even toxic residues in our food chain. Further, many insects have developed enough resistance to insecticides to force the use of even higher quantities of insecticide to be effective.

One proven way to use nuclear technology in controlling or even eradicating unwanted insects is the sterile insect technique (SIT). This approach involves rearing a large male population of the unwanted insects, subjecting the un-hatched eggs to sufficient levels of gamma irradiation to achieve sexual sterilization (but leaving other capabilities unchanged), and then releasing the hatched sterilized males into their native environment. When the sterile insects subsequently mate with the wild insects, no offspring are produced. In addition to being environmentally sound, this technique is often the only practical means to ensure pest eradication.

Since initial successful testing of this technique in the mid 1950s, the screwworm has been eradicated in both Mexico and the United States. The Tsetse fly, which transmits disease in cattle and sleeping sickness in humans, once prevented the settlement and development of large areas of Africa. Fortunately, the SIT technique has successfully eradicated one species of tsetse flies in parts of Nigeria.

Perhaps the largest success to date in utilizing this technique is that achieved in Mexico against the Medfly (Mediterranean fruit fly) and the screwworm (7). By 1981, essentially complete success was declared for the Medfly operation. By 1991, the screwworm eradication program had yielded some $3 billion in benefits to the Mexican economy.

III.D. Food Processing

Once food has been grown, it is crucial that this precious commodity be preserved and protected against contamination until consumed by an increasingly hungry world. Tragically, infestation and spoilage prevents at least one-fourth of the annual food production in the world from reaching the mouths of its citizens. The percentage of harvested seafood that never reaches a human mouth is even higher—sometimes well over 50%. This is particularly the case in countries with warm and humid climates, characteristic of many of the developing nations.

In addition to the spoilage of massive quantities of needed nourishment, food can become unsafe for consumption due to contaminants such as insects, molds, and bacteria. The U.S. Centers for Disease Control and Prevention estimated in 1999 that approximately 5000 Americans die each year from food-borne diseases, beginning with symptoms including nausea, cramps and diarrhea (8). In addition to these deaths from eating contaminated food, some 30 million U.S. citizens become sick from food-related illnesses each year, and approximately 300,000 of these persons are hospitalized.

Historically, food preservation methods have evolved from the earliest days of sun-drying to salting, smoking, canning, heating, freezing, and the addition of chemicals such as methyl bromide. Fortunately, food irradiation is now positioned to provide a substantially superior method.

Food irradiation involves subjecting the food to carefully controlled amounts of ionizing radiation, such as beta particles or gamma rays, to break the DNA bonds of targeted pathogens. This is especially effective in destroying the reproductive cycle of bacteria and pathogens. Such radiation can eradicate unwanted organisms and specific, non-spore forming pathogenic microorganisms such as salmonella. It can also interfere with physiological process such as sprouting in potatoes or onions. Thus, shelf life of many foods can be extended appreciably, and food-born disease organisms such as E-coli (0157:H7) can be dramatically reduced.

The beta rays are produced by accelerators whereas the gamma rays are normally produced by the radioactive decay of cobalt-60. X-rays can also be effectively used. They are normally produced by accelerators in which the beta rays are directed onto a target material such as tungsten that converts the energy into x-rays.

During the irradiation process, prepackaged food is moved by a transport system into a thick-walled room that houses the irradiator. The food is exposed to the beta rays, x-rays, or gamma rays for a pre-specified amount of time in order to receive the precise dose determined optimal for the particular type of food being processed. The food is then removed from the irradiation beam and placed onto a truck for delivery to the consumer. It is important to note that the processed food does NOT become radioactive. At the doses prescribed, it is impossible for the beta, gamma, or x-rays to transform (transmute) the food into becoming radioactive.

It should be noted that the goal of food irradiation is not to totally eliminate biological contamination, but rather to reduce it to about 0.001 percent of its original value (i.e. reduce the contaminants by about 5 orders of magnitude). It is important that a small residue of pathogenic microorganisms remains in a healthy body in order to keep our immune system functioning. Without an active immune system, we would be forced to live in a completely sterile environment. This would leave our bodies susceptible to attacks from even minute amounts of foreign substances—and we would have no defense systems left to ward off severe illness or even death.

The ability of food irradiation to rid contaminated food of unwanted pathogens and bacteria is of paramount importance. Whereas some Americans continue to labor under the impression that modern medicine can cure any malady, the fact is that our bodies are gradually becoming immune to some of the standard antibiotics, and many epidemiologists are becoming concerned that we need to be giving more attention to improving the safety of our food, rather than attempting to deal with the sickness that follows in eating contaminated food. The 5000 annual deaths from food poisoning in the United States further attest to the gravity of the situation.

One of the prime advantages of food irradiation is that it sterilizes food without altering its form or taste. The older methods of food processing, which rely on temperature extremes (heating or freezing), extreme drying or salting, or chemical treating, often do change the nature and taste of the food that is treated.

As of the year 2000, over 40 nations have approved the use of food irradiation for at least some products. In addition to the United States, they include China, France, Germany, Great Britain, Israel, Japan, the Netherlands, India, and South Africa. Irradiated food is now widely accepted for situations where food sickness could have particularly catastrophic implications. Examples include U.S. astronauts during space mission assignments and open-heart surgical patients. Groups that could particularly benefit from the large-scale employment of food irradiation include other hospital patients, school pupils, and airline passengers (particularly for long, international flights).

Whereas widespread acceptance of food irradiation by the general public has been slow, there are several signs—particularly in the U.S.—that indicate consumer acceptance is not far away. Major supermarkets such as Safeway, Albertsons, Giant Eagle, and Winn-Dixie have signed on to offer irradiated meat at some of their stores. Dr. Elsa Murano, Undersecretary for the Food Safety and Inspection Service of the U.S. Department of Agriculture (USDA), reported at the First World Congress on Food Irradiation (May 5-6, 2003 Chicago) that the 2002 Farm Bill approved by Congress mandates that commodities such as meat and poultry that are treated by any technology approved by the USDA and the FDA to improve food safety must be made available to the National School Lunch Program (8). She quickly pointed out that food irradiation is included in this mandate.

Given the unprecedented demands that an increasing world population will place on food supplies, there is little question that radiation will become far more visible to our everyday life through food irradiation. The only question is the timing.

IV. INDUSTRY

It is the modern factory from which we derive most of the products that we use on a daily basis, yet the use of harnessed radiation in industry is likely the most invisible to most citizens. But when we think about both the number of products now available, and the quality of products achievable, the correlation between the growth of the radiation industry and innovative product production becomes readily apparent.

IV.A. Process Control

Modern manufacturing succeeds when products can be turned out in high volume, high quality, and low cost. This places a high demand on instrumentation that can measure and rapidly adjust for any variations from product specifications during production. Typical measurements that are often made in production lines include liquid levels, the density of materials in vessels and pipelines, the thickness of sheets and coatings, and the amounts and properties of materials on conveyor belts.

Because radiation has the ability to penetrate matter, industrial measurements can be made using radioisotopes without the need for direct physical contact of either the source or sensor. This allows on-line measurements to be made, non-destructively, while the material being measured is in motion.

Level gauges generally operate on the principle of attenuation. A radiation source is placed on one side of a container being filled and a detector is located on the opposite wall. When the liquid rises to intersect the line between these two instruments, the signal seen by the detector drops dramatically. This is the technique used to guarantee proper filling of common soda cans. Gamma backscattering techniques are also used for some level gauge applications.

Radioisotope "thickness gauges" are unequalled in their performance and are used extensively in almost any industry involved in producing sheet material (e.g. sheet metal, paper, etc.). It is highly unlikely that automation in such industries would be possible without the use of radioisotopes. Modern steel mills utilize such gauges to accurately measure the thickness of rolled metals at every moment of the production process. This is likewise the case at paper mills, including the accurate measurement of wet pulp in the first stages of paper production. Such gauges are also frequently used in the food industry (including filling cereal boxes) and the oil industry, where determining the density of liquids, solids, or slurries is important.

IV.B. Plant Diagnostics

A plethora of radioactive tracer techniques have been employed to investigate reasons for reduced efficiency in modern plant operations. Tracers are now routinely used to measure flow rates, study mixing patterns, and locate leaks in heat exchanges and pipelines.

The petroleum industry routinely employs radioisotopes to locate leaks in oil or gas lines. For example, India recently completed a 140 km long crude oil pipeline and considered both a conventional approach (hydrostatic pressurization and visual inspection) and a radioisotope tracer technique to test for leaks. They chose the latter, which allowed testing to be completed in six weeks (relative to an estimated six months using hydrostatic pressure) and saved $300,000 in the process.

IV.C. Materials Development

Unique properties of radiation have been harnessed to produce a wide variety of specialty products. Changes in molecular structure, including the inducement of desired chemical reactions, can be created in certain materials by appropriate exposure to radiation. For example, some polymers, whose cross-linkage is induced by radiation, can be tailored to shrink when heated. Such "heat shrink" products are now widely used in the packaging industry. Wire and cable insulated with radiation cross-linked polyvinylchloride exhibits excellent resistance to heat and chemical attack. Such products are now commonplace in the automobile and aerospace industries, telecommunications, and in home electrical appliances.

The above process is being used at an increasing rate to cross-link foamed polyethylene for thermal insulation and wood/plastic composites cured by gamma irradiation. The latter products are gaining favor for flooring in department stores, airports, hotels and churches because of their excellent abrasion resistance, the beauty of natural grains, and low maintenance costs.

Many tire companies are now employing radiation to vulcanize rubber for tire production as an improvement over the conventional use of sulfur. Radiation is even used to "punch microscopic holes" in a special plastic to make filter material incorporated into dialysis units used for treating kidney patients. The list of applications is seemingly endless.

IV.D. Materials Testing and Inspection

One of the earliest applications of radiation to industry was to measure engine wear within the automotive industry. By irradiating the surface of the engine part under investigation (such as a ring or a gear), that portion of the metal can be made radioactive. Hence, during operation any wear on that part results in some radioactive material being deposited in the oil lubrication stream. The oil is then readily analyzed to accurately determine the degree of loss of the metal (engine wear). Further, such wear can be determined while the engine is operating, without the need for dismantling and reassembly. The savings in both time and dollars to rapidly test new materials are readily apparent.

Corrosion in pipes is a common problem in the industrial world. By moving a gamma source on one side of the pipe and a detector on the other, precise analyses can be made of the corrosion patterns.

The activation property of radiation is extensively used to determine precise layers of special coatings, such as metal coatings to produce galvanized or tin-plated steel. By exposing the product line to a beam of certain radioisotopes, X-rays characteristic of the coating material can be detected and used to confirm product quality.

The penetrating property of radiation is routinely used to check welds in crucial places such as airplane wings, housings for jet engines, and oil and gas pipelines. In most cases a gamma source is placed on one side of the material being inspected and a photographic film is placed on the other. Flaws can be readily detected on the exposed film. With the advent of high-speed computational systems, new techniques are now becoming available that are able to conduct such inspections without the need for film.

Other applications include testing of nuclear reactor fuel assemblies, detecting flaws in gas turbine blades, controlling the quality of ceramics, and confirming the presence of lubrication films inside gear boxes or bearings.

The field of radiography has become quite sophisticated, allowing three dimensional imaging of objects under investigation. This process, called computerized tomography, is also used extensively in the field of medicine.

IV.E. Materials Composition

Situations often arise where the composition of minerals and other mixtures must be determined. The property of X-ray fluorescence is often used to perform such diagnoses. A combination of radiation filters is sometimes used to systematically sort out the characteristic X-rays observed for a mixture of different minerals or materials, so that proper identification can be assured.

IV.F. Energy (non-nuclear power)

The coal industry, which currently accounts for well over half of the world's supply of electricity, benefits directly from using neutron gauges to measure and control the moisture content in coal and coke. Further, gamma sources are used to assay the ash content, as well as the combustion gases that go up the stack. It is important to determine the sulfur and nitrogen content of coal because these latter elements are of considerable interest due to environmental concerns of such contaminants in causing acid rain

It is within this context that one particular application is gaining increasing attention. Conventional devices, known as scrubbers, are widely used to remove large quantities of sulfur dioxide from the discharged flu gas. However, the byproducts of this process have no commercial value, thus causing additional waste disposal problems. Also, no reliable conventional process has been developed for simultaneous removal of both sulfur and nitrogen oxides in a single-stage operation. A new radiation technique, called electron beam (EB) processing, has been demonstrated to effectively remove both sulfur and nitrogen oxides in a single-stage process. By passing the gaseous sulfur and nitrogen pollutants under a strong beam of electrons, the pollutants become electrically charged and can then be collected. An additional attribute of this process is to convert these toxic substances into a commercially viable agricultural fertilizer.

The oil industry also is heavily dependant upon the use of radiation to conduct business. Finding new oil fields is a constant effort, especially as traditional sites are becoming exhausted. Borehole logging is a term used in conjunction with analyzing test wells to determine the potential for economically viable oil deposits. Neutron probes, lowered into the test wells, constitute one technique. Fast bursts of neutrons from a neutron generator are injected into the surrounding earth and the amount of hydrocarbons (oil bearing media) present can be determined by measuring the resulting slow neutrons detected at a known distance from the source. Gamma ray backscattering techniques can also be employed in a similar manner.

Efficient refinery operation is a very important part of the oil industry. Whereas it is difficult to install and maintain diagnostic probes inside the distillation towers (due to the extreme environment), gamma probes can be rather easily installed on the exterior of the towers and then be moved up and down the tanks to easily record the composition of ingredients at various vertical levels. Any malfunctions within the tanks can be readily detected.

IV.G. Personal Care and Conveniences

Those who wear either contact lens or glasses benefit directly from radiation. The saline solution used to clean and store contact lens is sterilized by gamma radiation. High quality glass used in eye classes benefits from radiation due to the use of neutron probes in assuring the proper moisture content during the making of the glass.

There are many other items that we encounter that account for personal conveniences. Examples include Band-Aids®, wherein the gauzed part has likely been sterilized by gamma irradiation to assure proper sanitary standards, and the thickness of the glue on the remainder of the band has likely been established by radiation thickness gauges. Sandpaper actually employs radiation in three steps of the manufacturing process. Step 1 is the use of radiation thickness gauges to assure proper thickness of the paper (or cardboard); step 2 is a similar gauging process to assure proper thickness of the glue; and step 3 is to assure the proper grit size.

Women may be pleased to learn that most cosmetics have benefited from gamma radiation before the product is placed on shelves in the department stores. The oils and greases required to achieve the colors and textures desired have a considerable propensity for attracting impurities that would not be appreciated on the human face! Hence, the final product is subjected to either beta or gamma irradiation to be sure no live parasites remain by the time the product is actually used.

One particularly useful feature of radiation is to change the molecular structure of some materials to allow them to absorb huge amounts of liquid. Several industrial applications benefit directly from such transformed materials, such as air refresheners. Of a more personal nature, this process is being used to manufacture disposable diapers and tampons. Both products have enjoyed high customer acceptance.

As these examples illustrate, the modern industrial world benefits enormously from the harnessing of radiation.

V. OTHER

Radiation is used in an increasing role for public safety, including airport screening, smoke detectors, crime solving, deterrence of terrorism at points of entry, archeology dating, precious gem embellishments, etc. The use of Am-241 in smoke detectors has undoubtedly saved thousands of lives and associated property damage due to the avoidance of fire. The list of applications of radiation to enhance our modern life style literally goes on and on.

VI. PERSPECTIVE

In order to get a bit of a perspective on how the use of radiation in the U.S. compares to other countries, Table II has been included. This table contains a summary of studies recently released in Japan that compared the impact of radiation technology in Japan to that of the United States in the year 1997 (9). However, one key clarification must be made to properly interpret this data. The U.S. studies reported in Table I used a “multiplicative” economic model that recognizes the secondary economic impact of any primary market activity, i.e. the wealth and jobs created by the primary activity. It is the same model widely used in the economic analysis of the impact to a community should a military base be closed. For rough purposes, the multiplicative factor that a detailed analysis reveals is in the neighborhood of 2.5, and this is the factor used in Table II to translate the results of the Japanese studies (which were based on direct revenue only) to correspond to the results reported for the earlier years in the United States.

Table II. Comparison of U.S. & Japanese Nuclear Technology Impacts for 1997[9]

	U.S.	Japan
Pop. (M)	270	120
GDP ($B)	8318	4231

	SALES ($B) Direct financial contributions		SALES ($B) Multiplicative economic effect (assumed factor of 2.5)	
	U.S.	Japan	U.S.	Japan
Radiation	119	52	298	130
Nuclear Power	39*	47*	98*	118*
Total	158	99	396	248
%GDP =	(1.9)	(2.3)	(4.8)	(5.8)

* Delivered Average kW-hr price assumed: U.S. = 6.8 cents; Japan = 15.0 cents

It is interesting to note that the total impact of nuclear technology in both the United States and Japan is about the same, i.e. around 5% of the GDP of each nation. However, the relative impact of nuclear power in Japan is considerably higher that that of the United States. Part of this is due to the price of electricity in Japan (over twice that in the United States), and part is due to the substantially wider applications of radiation to the non-power sector in the U.S.

VII. CONCLUSION

In conclusion, we can confidently state that President Eisenhower's challenge to use the atom for a plethora of humanitarian applications has been ably met. The positive impacts that have been achieved in the past 50 years are nothing short of astonishing! But perhaps the biggest impacts are yet to come. Successful endorsement of food irradiation alone could easily double the impacts achieved to date. Such non-power applications remain a challenging and rewarding field for the best and brightest of our next generation of radiation scientists and engineers.

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