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CONTRIBUTIONS AND FUTURE OF RADIOISOTOPES IN MEDICAL, INDUSTRIAL, AND SPACE APPLICATIONS

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INTRODUCTION

Of the over 2300 isotopes identified to date, more than 1700 are short-lived with half-lives less than one day, 291 are stable, and 333 have a half-life between 1 day and 100,000 years.[1] It is on this last group that we focus for the isotopes with useable radioactivity. In addition to the wide range of half-lives, this group of isotopes includes varying types of decay (i.e., alpha, beta, and gamma), various energies released per disintegration, and a wide variety of chemical and physical properties. Thus, there are almost unlimited potential applications for these materials.

Radioisotopes are used in a wide variety of applications including public health, medicine, industrial technology, food technology and packaging, agriculture, energy supply, and national security. In 1988, the Department of Energy reported transfers of 64 separate radioisotopes to 233 domestic and 69 foreign organizations.[2] These isotopes are reported to have a value of over $11,000,000. In addition several private organizations produce and market radioisotopes on a smaller scale.

Worldwide radioisotope use is increasing in many applications, particularly in medicine. Nordian International is continually increasing its production of cobalt-60 for irradiation services all over the world with an estimated capacity in excess of 100,000 Ci/year before the turn of the century. The purpose of this paper is to provide an overview of some of the most extensive applications of radioisotopes including some observations of future uses. In the future, those radioisotopes will contribute to a myriad

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of diverse applications to improve technological, scientific, and industrial endeavors, which include improving the length and quality of life through improved diagnosis and treatment of the human ills.

APPLICATIONS

Radioisotope Power for Space and Terrestrial Systems

In June, 1990 Ulysses was launched on its way to the poles of the Sun to observe the solar wind, magnetic field, solar corona, sun spots, solar flares, solar x-rays, and other physical phenomena.[3] It was the 17th NASA launch using isotopic power (Table 1). Radioisotope power systems have been the only alternative in outer planetary, lunar, and solar exploration with trajectories out of the ecliptic plane. About this time last year the Galileo spacecraft began its eight-year mission to explore Jupiter, with about twice the amount of isotopic power generation capacity as Ulysses. Galileo also was equipped with 120 radioisotope heaters on the orbiter and entry probe each of which produce one thermal Watt to heat instruments.[4]

Table 1. NASA Missions Utilizing Isotopic Power

Mission	Year	To	Radioisotope Systems
Ulysses	1990	Sun	power
Galileo	1989	Jupiter	power, heaters
Voyager 1	1977	Outer Planets	power, heaters
Voyager 2	1977	Outer Planets	power, heaters
Viking 1	1975	Mars Surface	power
Viking 2	1975	Mars Surface	power
Pioneer 11	1973	Outer Planets	power, heaters
Pioneer 10	1972	Outer Planets	power, heaters
Apollo 17	1972	Moon	power
Apollo 16	1972	Moon	power
Apollo 15	1971	Moon	power
Apollo 14	1971	Moon	power
Apollo 13	1970	Moon	power*
Apollo 12	1969	Moon	power
Apollo 11	1968	Moon	heaters
NIMBUS III	1969	Earth Orbit	power
NIMBUS-B-1	1968	Earth Orbit	power**

* Aborted Mission, intact heat source disposed of in Tonga[5] Trench.
** Aborted Mission, intact heat sources recovered from Santa[5] Barbara Channel.

Since 1968, when NASA lost NIMBUS-B-1, its first nuclear-powered spacecraft, and safely recovered its isotopic heat sources intact,[5] NASA has used isotopic power. Another isotope powered NIMBUS weather satellite was successfully launched in 1969. Between 1969 and 1972 NASA used one isotopic heater on the first lunar landing and six power sources on subsequent Apollo Lunar Surface Experiment Packages; one on the aborted Apollo 13 mission was safely deposited in the Tonga Trench.[5] In 1972 and 1973 isotopic power and heater sources were launched on

Pioneers 10 and 11; both spacecraft led to the first exploration of the outer planets, and one is the first manmade object to leave the Solar System.

In 1975, radioisotope systems were launched and went on to power the two Viking landers to help bring us the first pictures of the rocky and windswept surface of Mars. In 1977, the Voyager 1 and 2 spacecraft, powered by and heated with isotopes (plutonium-238), were launched and subsequently explored Jupiter, Saturn, Uranus, and Pluto on missions lasting a decade. The images of the planets are everlasting and have inspired scientists and students alike throughout the world.

The history of isotopic power in space was treated extensively previously.[6] What is the future of isotopic power in space? The Comet Rendezvous Asteroid Flyby (CRAF) mission in 1995 is to carry radioisotope power systems. This mission is to fly by asteroids, rendezvous with a comet, and deliver a penetrator into the comet's center. The Cassini mission, scheduled to be launched in 1996 and terminate in 2006, will orbit Saturn and its moon Titan and deliver a scientific probe into Titan's atmosphere.[7]

Later, isotopic power will have a major role in NASA's Space Exploration Initiative aimed at lunar bases, Mars Rover Sample Return (MRSR), and future missions to the outer planets. Can exploration of lunar surfaces, planetary surfaces, the other planets, and ultimately other galaxies be done without nuclear power? Very probably not; certainly not efficiently and reliably. Aside from two launch aborts where the isotopic power units were either recovered or safely disposed, all isotopic power sources have performed without failure for periods up to and exceeding 15 years.

Isotopic power has been used all over the world in terrestrial applications, including those in the Arctic, Antarctic, under the oceans, and in remote areas. These generators have varied in power level from a few tenths of Watts to 500 Watts and most have been fueled with strontium-90, a nuclear waste byproduct. The units are maintenance free and have provided continuous power for 25 years or more. Some of the first units made in the early 1960s have recently been retired. Paradoxically, it has historically been a problem for the manufacturers of terrestrial isotopic power systems to sell additional units because the service lives of the power conversion systems and half-lives of the heat sources are so long.

Nuclear Medicine

On October 1 of this year, Professor Henry N. Wagner, Jr., M. D., Director of the Divisions of Nuclear Medicine and Radiation Sciences at The Johns Hopkins University School of Medicine and an international authority on nuclear medicine, was interviewed by a coauthor of this paper. The purpose was to obtain his views on the most recent and promising advances in nuclear medicine. He cited a recent paper where, at the opening session of the Society of Nuclear Medicine's (SNM) 37th Annual Meeting, the Secretary of Health and Human Services reminded the attendees that President Bush has designated the 1990s as the "Decade of the Brain."[8]

The far reaching ramifications of the applications of nuclear medicine to the workings and treatment of the human brain are covered in a book entitled "Living with Radiation"[9] by Professor Wagner and Linda E. Ketchum. In the foreword written by Glenn T. Seaborg, the Nobel laureate, they are requoted, as follows:

"One of the paradoxes of all time is that nuclear radiation is likely to be our salvation. Radioactive tracers may be what it takes to increase our understanding of the emotions of fear, violence, and destructiveness to the point that we can diminish the dangers of nuclear war. PET (positron emission tomography) studies of the human brain can help us understand better the chemistry of fear, aggression, and violence, so that we can direct our energies in a safe and constructive direction toward further human progress rather than a nuclear holocaust. The solution to the dangers of the atomic nucleus may lie in the exploration of the chemistry of human emotions, the chemistry of fear, paranoia, and aggression."

Nuclear medicine now offers the opportunity to enhance preventive measures, diagnosis, and/or treatment of mental disorders, epilepsy, brain tumors, stroke, Parkinson's disease, Alzheimer's disease, and other neurological diseases and disorders.

PET scans use the positron emitting radionuclides carbon-11, fluorine-18, and oxygen-15 *in vivo* to build up sections of the organ into a three-dimensional image. PET and SPECT (single photon emission computed tomography) reveal images of regional chemistry and disease. Half of the papers of the SNM's meeting, where about 1000 oral presentations were made, involved PET or SPECT, with the brain being the dominant subject. The current focus is upon the mechanisms of intercellular communication. A number of papers were on receptors, a chemical binding that occurs between drugs and specific chemical groups on cell surfaces. Chemical neurotransmitters such as dopamine and norepinephrine can be varied in concentration by certain drugs. For example, drugs are effective in treating schizophrenia by blocking the binding of dopamine in the brain's receptors or in treating Parkinson's disease by administering L-dopa to increase the concentration of a neurotransmitter in the brain.

Today nuclear medicine is advancing beyond that point and a number of papers were given at the SNM Meeting on iodine-123 receptor ligands. The longer half-life of iodine-123 allows for longer studies than are possible with carbon-11 or fluorine-18. Thus, other receptors can be examined as well. Another mystery of the brain is the role of receptors in the process of neurotransmission because of the lack of knowledge on their synthesis and metabolism. However, measurement of the neuronal energy supply and the synthesis of neurotransmitters are now possible in human beings. A number of papers concerned the use of technetium-99m in connection with isonitriles and antibodies that serve to advance nuclear medicine with greater SPECT scanning and resolution.

Professor Wagner remarked that the road to nuclear medicine has two lanes: PET and SPECT. The revelation of regional chemistry images in the brain holds great promise for the future. Turning to other subjects, he estimated that one out of three hospital admissions in the United States involved nuclear medicine procedures and that such are growing rapidly in Japan and Europe. When asked how to create a better environment for nuclear medicine, he thought that expediting federal approvals of nuclear medicine procedures, dealing rationally and economically with low level wastes, and educating the public on the risks and benefits of radiation and radioisotopes would be most helpful.

In summary, Professor Wagner said that while the radioactive tracers carbon-14, tritium, and phosphorous-32 played a major role in the founding of modern biochemistry after World War II and remain the backbone of modern biological science; carbon-11, iodine-123, fluorine-18, and technetium-99m used with PET and SPECT are leading the way in *in vivo* chemistry.

The authors found other promising maturing applications including the uses of nuclear medicine to: predict a person's risk of having a heart attack, identify those who would benefit from bypass surgery, evaluate the effects of cancer therapy, locate occult abscesses, and relieve pain in cancer patients. It seems that nuclear medicine can touch all of us in some way.

Radiation Sterilization and Food Treatment

It has been estimated that about 45% of all single use medical products (syringes, surgeons gloves, and a large variety of other goods) are sterilized by irradiation in the United States. While most of these use cobalt-60 as the radiation source, one irradiator still uses a cesium-137 source and others use machine generated radiation. About 100 million curies of cobalt-60 are currently in use worldwide irradiating about 100 million cubic feet of product each year. A significant fraction of this is in use in the U. S. with about 50 large irradiators licensed by NRC or agreement states.

The use of irradiation for processing of food for insect disinfestation, control of food borne diseases, and shelf life extension is also increasing at a rather slow but steady rate when viewed on a global scale. Thirty six countries have approved some irradiation of food. In total, over 50 different commodities have been approved including many varieties of meats, grains, fruits, vegetables and spices. The most popular as measured by the number of countries approving them are potatoes, onions, and spices.[10] Eighteen of the 36 countries are irradiating food products commercially with the worldwide throughput approaching 450,000 metric tonnes each year; 90% of this total is from the irradiation of grain in the Odessa Port Elevator in the USSR using a machine generated source. The second largest commercial irradiation facility is the Shihoro Agricultural Irradiator in Hokkaido, Japan which irradiates about 20,000 metric tonnes of potatoes each year.[11] Although several commodities are now approved for irradiation in the U. S., commercial irradiation is limited, for the most part, to spices. There are two primary reasons for this limited use. The first is that current handling, distribution, and storage practices effectively minimize losses of fresh foods by spoilage. The second is that food irradiation has not yet been fully accepted by the general public as a safe process.

Other applications of radiation technology include sterilization of male insects, disinfestation of sewage sludge, curing of wood-polymer composites, polymerization, radiation grafting, and the vulcanization of rubber.

In 1984, the availability of cobalt-60 was less than the demand and the Atomic Energy of Canada, Limited (AECL) distributed the sale to its customers with some restrictions. At the same time they took steps to increase production with the goal of more than 100 MCi/year before the turn of the century. This seems to have alleviated the shortage and the supply now appears to be adequate. The U. S. production is minimal with the 1988 total of just over 1 MCi.[2] Cesium-137 was used in three large medical products irradiators and a smaller one for curing wood-polymer composites. However with the cesium contamination of the irradiator at Decatur, Georgia in 1988, that irradiator is shut down and a second one has converted back to cobalt-60; the third irradiator continues to operate with cesium-137. There is still about 60 MCi of encapsulated cesium-137 at Hanford. Because this is equivalent to only about 10 MCi of cobalt-60, its long term contribution to irradiation technology is small except for special applications requiring the lower gamma energy (0.66MeV) or longer half-life. The half-life of cesium-137 is 30.2 years; that for cobalt-60, 5.27 years). One such application is blood irradiators for hospital use.

Radioluminescent (RL) Photonics Advances

Very recently, the U.S., Canadian, and U.K. scientific, technical, and user community gathered in Annapolis, Maryland, in a unique technology transfer meeting sponsored by DOE's Office of Technology Policy.[12] The purpose of the meeting was to present recent advances in RL technology developed by the nuclear weapons laboratories that could be transferred to the private sector for peaceful applications as directed by the Congress. For several decades RL, low-intensity, tritium gas-tube light sources have been used routinely both here and abroad in aircraft exit signs, chronometers, and emergency egress signage in public buildings. In the past few years, the DOE has been conducting a program on aircraft runway lighting in cooperation with the State of Alaska, the City of St. Petersburg, Florida, and several U.S. Government and Canadian agencies. RL technology has been either studied or successfully demonstrated in runway lighting, airport signage, enclosed space, emergency, security, medivac, mine safety, ship safety, and other applications. Operating experience on airport signage in Florida, runways in rural Alaska, helicopter medivac pads in Ontario, and studies of naval safety applications were presented at the technology transfer meeting.

In 1988 the nuclear weapons laboratories, Sandia National Laboratory (SNL), and EG&G Mound Laboratory (ML) formed an R&D team to develop a solid state, photonic light source to enhance the brightness, safety, adaptability, and manufacturability of light sources. The laboratories set a goal to surpass RL gas tube technology which has plateaued at a brightness output of about 1 foot-lambert and to develop a more efficient solid state photon source that immobilizes the tritium in a molecular structure. They reported on their experiments where the tritium, phosphor, and various matrices produced brightness well in excess of their goal and indicated that a brightness of 10 foot-lamberts might be achieved. The future potential of a higher intensity recyclable tritium photon source, having a possible lifetime of a decade and capable of variable photon energies by varying the phosphor, offers a myriad of high technology opportunities in addition to the applications already proven with gas tube technology. SNL has studied the coupling of a light source and photovoltaic converter to produce a milliwatt-level, self-contained, and long-lived electrical power source.

Advanced electronics technology is applying photonics to replace electrical signals on wires with light signals on optical fibers. In this way RL light could someday be converted to electricity directly on a computer chip or could serve as the main light source for the optical computer. President Eisenhower's 1950s initiative to "turn weapons into plowshares" could be literally reborn in the 1990s as the principal ingredient of H-bombs is used to enhance the quality of life of mankind as disarmament proceeds.

Manufacturing and Testing

Radiation is used to measure and in some instances control the thickness of some manufactured materials such as plastics, paper, and photographic films. In these applications, the detector compares the attenuated radiation signal with the unattenuated signal to determine the thickness of the material.

One particular application now in use commercially is the detection of cracks and flaws in critical metal components such as jet aircraft turbine blades. In this case krypton-85 is sorbed on the surfaces of microdefects. Interaction of the krypton ß particles with a sprayed-on emulsion coating makes the defects visible. This technique has been shown to be particularly effective in detecting hot tears, microshrinkage, and microcracks in turbine blades.

Tracer Applications

Radioactive tracers have been widely used for decades in research. Because there are radioactive isotopes of all of the elements, suitable radioactive tracers with the same chemical properties as those of the nonradioactive element can be found for most reactions of interest. More recently, the use of tracers has expanded into manufacturing and industry. These radiotracers can be added to various solutions to indicate when mixing is complete; they can also be used to indicate wear, detect leaks in a pipeline, trace the movement and distribution of nutrients in plants, and in numerous other applications currently in use or yet to be conceived.

SUPPLY AND DEMAND OF RADIOISOTOPES

It should be evident from the examples given above that the applications of radioisotopes is almost unlimited and will continue to grow as imaginative scientists and engineers conceive solutions to the myriad of problems in research and industry. At the same time there is a need for a comparable effort to assure the continuing availability of the needed isotopes. There are a variety of sources which are more thoroughly discussed in other papers in this session. Some such as cesium-137, strontium-90, and krypton-85 are fission products produced in nuclear reactors. These become available when separated from the other materials in the processing of irradiated reactor fuels to produce fissionable materials for the weapons program. Much larger quantities are present in the higher-burnup fuels from commercial power reactors. However, these are not generally available at a reasonable cost because power reactor fuel is not currently being processed in the U. S. Other radioisotopes, most notably cobalt-60, is produced as a byproduct of power reactors by activating a suitable target during reactor operation. A large number of isotopes have been produced in isotope production reactors or in production facilities in test reactors. The potential for production in these facilities has only begun to be tapped. Another source of isotopes is by the use of particle accelerators. Many of the short lived isotopes, especially for medical use, must be produced in small accelerator facilities at the location of use.

SUMMARY

In summary, the applications of radioisotopes is extensive and increasing. There is a growing need for further applications development and production. Many current applications could better be met by other isotopes with more optimized properties. Efforts are ongoing to identify and develop new and more suitable isotopes for small remote power sources.

As we view the next decade, we will likely see continued advancement in the use of isotopes. It is the challenge to this community to find ways to meet the demand for the isotopes, to ensure their safe use, to inform the public of the benefits derived therefrom, and to provide the necessary information to alleviate the general fear surrounding their use.

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