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# PEACEFUL APPLICATIONS OF NUCLEAR TECHNOLOGY AND ITS CHALLENGES

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**Abstract**— Nuclear Technology is perceived as destructive because its first widely publicized use was in Hiroshima and Nagasaki, Japan, where nuclear bombs destroyed the two cities and many lives, subsequently ending the Second World War. However, there are numerous peaceful uses of nuclear technology, including electricity generation, medicine, food and agriculture, the process and petroleum industry, commerce and space. The article describes nuclear energy's origin, explains some introductory nuclear physics concepts, and represents many nuclear technology applications. Finally, the pros

| | |
|---|---|
| Nuclear Medicine, Process Industry | and cons of using nuclear technology for each application and its future uses are discussed. |

## I. Introduction

The first widely publicized nuclear energy used was in 1945 when atomic bombs destroyed Hiroshima and Nagasaki, resulting in the loss of lives in Japan. The event subsequently led to the end of World War II [1]. Nuclear technology used as weapons also fuelled the cold war between the Soviet Union and the United States of America and is still a big issue in many parts of the world, including but not limited to North Korea, Iran and India. These events and incidents gave the impression that nuclear energy is only suited for destructive purposes. However, on December 8, 1953, Dwight D. Eisenhower, the then-U.S. President, indicated peaceful use of the "atoms" was possible instead of using them for mass destruction. Eisenhower's speech awakened the world that nuclear technology could benefit humanity and peaceful purposes [2].

Furthermore, Eisenhower's "Atoms for Peace" program opened up many scientific and technological knowledge incentives, allowing the subsequent commercial exploitation of nuclear energy. The creation of the UN's International Atomic Energy Agency (IAEA), based in Vienna, in 1957 further enhanced this initiative [3]. The 2016 World Nuclear Association report provides a comprehensive history of nuclear energy [4].

A primary goal of nuclear research in the mid-1950s was to show that atomic energy could produce electricity for commercial use. The first electricity generation was from an Experimental Breeder Reactor in Idaho, USA, on December 20, 1951 [5]. The Nuclear Power Plant at Obninsk, Russia was the first commercial electricity-generating nuclear reactor [6]. In 1954, The USSR built a reactor in the "Science

City" of Obninsk, Kaluga Oblast, about 110 km southwest of Moscow. Since the first one, many more operational nuclear reactors have been constructed. As of March 2022, nuclear power plants are working in 32 countries worldwide, operating 437 nuclear reactors for electricity generation, and many new nuclear plants are under construction in 15 countries [7].

After years of rigorous research, scientists have successfully applied nuclear technology to a wide range of scientific, medical, and industrial applications. In addition to its role in electricity generation, nuclear energy and technology have found peaceful applications in the food and agricultural industry, medicine, other industrial sectors, commerce, space technology, and the petroleum industry, among others. This paper provides a comprehensive discussion of these applications, thoroughly evaluating their merits and demerits to ensure the audience is well-informed and knowledgeable.

## II. Nuclear Electricity Generation

Electricity is generated from various sources, including coal, gas, oil, hydro, nuclear, solar, wind, and biofuels, as well as wave and tidal. Most countries obtain electrical power from multiple sources. Figure 1 illustrates the breakdown of the 2020 electricity mix by source for different regions and a few countries. Nuclear and renewable energies accounted for over one-third (38.21%) of global electricity in 2020 [8]. Furthermore, most of the world's electricity comes from nuclear energy. Nigeria's electricity production from 2000 to 2020 is primarily from gas and hydro, accounting for about 96-98% of production; coal, solar, and other renewables comprise the remaining 2-4%. Nuclear and wind are not part of Nigeria's electricity mix as of 2020.

Nuclear technology and renewable energy are alternatives to conventional power generation using fossil fuels [9]. Conventional power systems use coal, natural gas and fuel oil as feedstock sources. In addition, nuclear power systems use uranium and plutonium as fuels. In contrast, renewable power systems use solar, geothermal, wind, hydro (water), ocean (wave, tidal, ocean energy thermal system), and natural biomass sources [10].

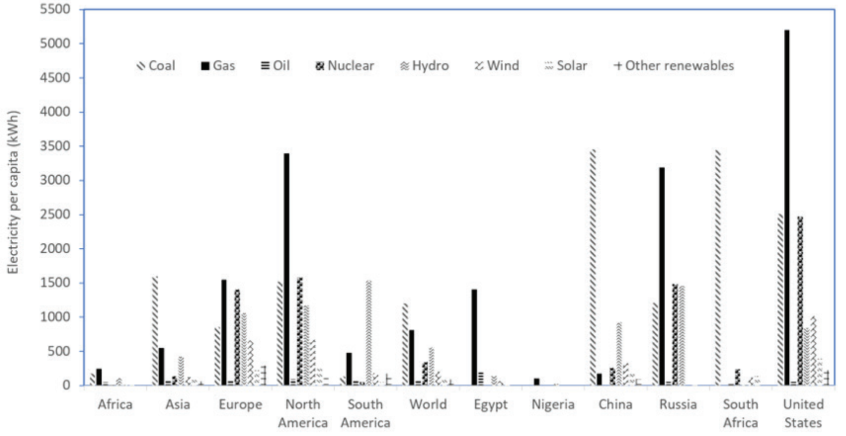


Figure 1: World Electricity Production Per Capita for 2020

A nuclear power plant (NPP) generates electricity through fission, which is the process of splitting 235U atoms after impact by a slow neutron (n) to produce energy, as can be seen in Equation (1).

$$^{235}_{92}U + \, ^{1}_{0}n \rightarrow A + B + x^{1}_{0}n + 200MeV \quad (1)$$

Equation (1) indicates that two smaller atoms, denoted as A and B, are formed when a 235U atom is split. The products A and B are highly radioactive and unstable, and the reaction forms fission products and minor actinides. This reaction, also known as a chain reaction, is self-sustaining because splitting releases more neutrons, which can then be used to split more nuclei of 235U.

NPP is similar to a conventional thermal power plant except that the heat released by fission is used to convert water to steam without the harmful byproducts emitted by fossil fuels. The generated steam then drives a turbine to produce electricity as can be seen in Figure 2. Nuclear power plant generates no emissions (clean power system) but there are concerns about the management of the nuclear waste generated during the process and the safety (accident and terrorist threats) of the nuclear power plant.

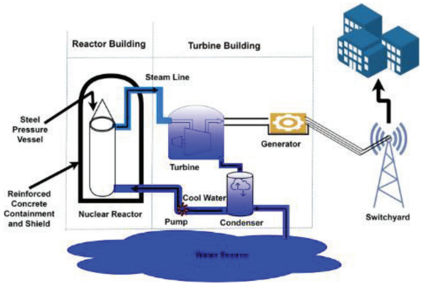


Figure 2: Schematic of a Nuclear Power Plant [11]

Renewable and nuclear energy sources are essential tools for $CO_2$ reduction. Several studies suggested that a nuclear energy source is a good tool for reducing $CO_2$ emissions [9, 12-17]. Nuclear power is the second largest source of low-carbon electricity globally after hydropower. It is a zero-emission, clean energy source. $CO_2$ emissions from nuclear power plants are the lowest, compared to the other low $CO_2$ emission resource such as wind and hydropower [18]. The lifecycle greenhouse gas (GHG) emission intensity of nuclear power generation is comparable with those from renewable energy sources, including biomass, hydroelectric and wind. However, natural gas and coal generation lifecycle emissions are 15 and 30 times greater than nuclear [19]. Nonetheless, the greenhouse gas emissions attributed to constructing a nuclear power plant are higher than emissions from other generation methods [19]. It is worth noting that the lifecycle approach accounts for emissions from all phases of the project (construction, operation, and decommissioning), with the lifecycle emissions normalized per gigawatt-hour.

NPPs produce energy with small amounts of fuel and occupy less land utilization compared with other methods. A nuclear source has a very high energy density. A single pellet of nuclear fuel, which weighs about 6g, is equivalent to one ton of coal, approximately 120gal of oil and about 17,000ft$^3$ of natural gas, making nuclear fuel more efficient than other types of fossil fuels [20]. Also, each power plant has its average capacity factor in producing electricity from its power capacity and the efficiency of converting fuel or resources to electricity. The system efficiency of solar power is only 10% to 18% compared to 30-50% for conventional and nuclear power systems. Solar power also has the lowest capacity factor. The capacity factor for solar power is 10% compared to 80% for conventional power systems (coal and natural gas power systems). Ghenai et. al [11] state that Geothermal power has the highest capacity factor of 75-95%; they used data from different regions in the world for the year 2010.

Table 1 presents more recent EIA [21] data for the United States of America. Table 1 indicates that nuclear power has the most elevated capacity factor, followed by geothermal for the 2020 data. The high-capacity factor in the USA for nuclear may be due to relatively more stringent regulations for nuclear plants when compared with other power plants.

Table 1: Electric Power Plant Capacity Factors Using Fossil and Non-fossil Fuels for 2020

| Fossil | Capacity Factor (%) | Non-Fossil | Capacity Factor (%) |
|---|---|---|---|
| Natural Gas (Combined Cycle) | 57.10 | Nuclear | 92.40 |
| Coal | 40.50 | Geothermal | 69.10 |
| Natural Gas (Internal Combustion) | 15.10 | Other Gas | 64.60 |
| Natural Gas (Steam Turbine) | 14.20 | Other Biomass | 62.50 |
| Petroleum (Steam Turbine) | 13.90 | Wood | 57.80 |
| Natural Gas (Gas Turbine) | 11.60 | Hydroelectric | 40.70 |
| Petroleum (Internal Combustion) | 1.80 | Wind | 35.30 |
| Petroleum (Gas Turbine) | 1.20 | Solar - Photovoltaic | 24.20 |
| | | Solar – Thermal | 20.60 |

Source: U.S. Energy Information Administration (EIA), Electric Power Annual 2020 Report, U.S. Department of Energy, Washington, DC 20585, March 10

Nuclear Reactor designs have continuously been improved, resulting in Generation IV reactors (Gen IV) as a set of theoretical nuclear reactor designs that offer significant advances in safety and reliability, proliferation resistance, sustainability of nuclear fuel utilization and economics [22]. Gas-Cooled Fast Reactor Systems (GFRs) and Very-High-Temperature Reactor Systems (VHTRs) are two technologies. The GFR has the advantage of a high-temperature reactor with a core and fast spectrum, which means that the core can be designed to be smaller [23]. The VHTR concept utilizes a graphite-moderated core with an outlet temperature of around 1000°C, with the reactor core being either a prismatic block or a pebble bed reactor design [22]. Other advanced reactor types include small modular reactors (SMRs), liquid metal fast breeder reactors and molten salt reactors.

One of the issues in providing a secure nuclear energy supply is the sustainability of nuclear fuel supplies that can be maintained efficiently [24]. Possible solutions to these challenges are additional uranium resources from seawater, combined with thorium fuel resources and some fusion reactors, using spent fuel as a recycling fuel resource and fuel breeding resource.

As noted earlier, the primary arguments against fission power are operational safety, proliferation and radioactive waste management [25]. The main concern for the operation of nuclear reactors is the possibility of a severe accident that may contaminate a whole region or across continents with radioactive materials [26]. However, a study of available literature after Chernobyl, Three Mile Island NPP and the Fukushima accidents shows that radiation did not affect the people. Instead, it was the psychological fear caused due to evacuation after the accidents [27]. The accident at Chernobyl was a major disaster due to poor design and construction and gross disregard for the operating procedures by the operation team. The Chernobyl type of reactor is no longer in use. The accident at Three Mile Island NPP in the USA and Fukushima accident in Japan did not result in any public exposure due to the presence of a containment building around the reactor vessels. No adverse health effects among Fukushima residents have been directly attributable to radiation exposure from the Fukushima accident [28]. These accidents notwithstanding, available statistics from different power plants indicate that the death rate per-terawatt-hour (TWh) generated by nuclear plants is very low and comparable to those from wind, hydro and solar (0.02-0.07). The death rate for fossil fuel plants ranges from 18.43-32.72 [29]. Lelieveld et al. [30] indicate that fossil fuel combustion alone was responsible for 3.61 million (with a 95% confidence interval of 2.96-4.21 million) avoidable deaths per year globally. The United Nations Scientific Committee on the Effects of Atomic Radiation [31] report on the Chernobyl accident indicates that 134 plant staff and emergency workers received high doses of radiation. The high radiation levels resulted in acute radiation syndrome (ARS) with 62 fatalities as of 2006 (28 plant staff and emergency workers, 19 ARS survivors have died and 15 from 6,000 thyroid cancers observed among people who were children or adolescents at the time of the accident). Kharecha et. al [32] estimated that commercial nuclear reactors around the world prevented 1.84 million air pollution-related deaths (mainly offsetting particulate matter) from 1971 to 2009 and projected that nuclear power could save an additional 420,000 to 7 million deaths by 2050 if nuclear power expands to substitute for fossil fuels.

For safeguard and proliferation resistance considerations, the International Atomic Energy Agency guidelines are that civilian reactors can employ uranium enrichment to not more than 20% by mass, the limit of Low Enrichment Uranium (LEU) [33]. Many SMRs incorporate methods that provide intrinsic resistance to the proliferation of nuclear material for use in explosives or nuclear weapons. In addition, SMRs eliminate on-site refuelling. On-site lack of refuelling is quite attractive because of the elimination of the refuelling mechanism, which lowers construction and operation costs and eliminates the possibility of fuel tampering and diversion for clandestine or weapon purposes providing a non-proliferation assurance [34]. The compact nature of integral reactors and the provision of double contaminate are additional barriers to proliferation [35]. IAEA [36] discusses other ways to enhance the proliferation resistance of SMRs.

Like other types of electricity generation, nuclear power produces radioactive waste that will remain radioactive for many years. However, this hazard (radioactivity) will reduce over time, owing to the radioactive decay of the radioactive isotopes within the waste to stable isotopes. This process can take at least one million years; for example, the non-fissile isotope 238U has a half-life of 4.5 billion years. Therefore, managing nuclear waste is one of the most significant and long-term challenges our society faces. Three nuclear waste sources are the spent fuel, the contaminated internal reactor structure, and the mechanical equipment. Equally important is the disposal of contaminated equipment after decommissioning the nuclear reactor [27]. In addition to NPP, research, medical and industrial applications also generate nuclear waste.

Nuclear waste management and disposal throughout the world are carried out based on the guidelines of the International Atomic Energy Agency [37]. Nuclear wastes are classified according to their radioactivity: low-, intermediate-, and high-level. Low-level nuclear waste is (90% by total volume), intermediate-level waste (7%) and high level (3%). IAEA [38] presents a more detailed classification of nuclear wastes. On average, the waste from a reactor supplying one person’s electricity needs for a year would be about the size of a brick. However, only 5g of this is high-level waste which about the same weight as a sheet of paper [27]. According to Corkhill et. al [39], the average yearly waste output from nuclear power in the UK, including decommissioning is about 4000m$^3$ per year. Coal power stations, by comparison, generate about 130,000m$^3$ of ash and sludge per year, in addition to 1.45million m$^3$ of carbon dioxide ($CO_2$). Although high-level waste accounts for just 3% of the total volume of waste, it contains 95% of the total radioactivity. Typically, spent fuel is stored underwater for at least five years. After that, the waste is moved to dry storage in deep geological disposal locations, which is agreed to be the best solution for final disposal. Geological repositories for high-level waste are done to ensure that harmful radiation would not reach the surface even in the event of severe earthquakes or over time. The geologic disposal concept typically relies on a multi-barrier system, composed of a waste form, waste canister, engineered barrier, and natural barrier [40]. Further discussions on nuclear waste are available elsewhere [41-43].

Finally, the traditional thermal power plants convert heat from fossil fuel combustion or nuclear fission into steam which rotates turbines that convert mechanical energy into electricity. While reliable power sources, both methods come with environmental impacts through emissions or radioactive waste. One way of producing this heat without hazardous by-products is through atomic fusion. Fusion occurs when two hydrogen atoms smash together and fuse into a single helium atom. Fusion generates a large amount of energy without producing radioactive fission products. However, fusion is still a research field with a crucial role being played by the International Thermonuclear Experimental Reactor (ITER), under construction in Cadarache in France. Elhegazy et. al [11] and Wagner [25] present a more recent overview of the leading research topics and trends within the NPP research domain with available opportunities and obstacles.

## III. Food and Agriculture

This section presents some of the uses of radioisotopes and radiation in the food and agriculture industry.

### A. Livestock Productivity and Health

Nuclear techniques improve livestock feeding, fertility, and health. Radioisotopes are used to modify biological processes that control growth, reproduction, and disease resistance in various farm animals to increase productivity. Tracer techniques are also utilized by animal nutritionists to determine the nutritional values of items used in animal feeds. These techniques use isotopes such as 14C, 125I, 51Cr, and 15N to tag feed ingredients, amino acids, and other metabolites. For example, isotopic methods have been developed to increase the growth rates and yields of milk and meat besides improving the quality of cattle [44].

Radioimmunoassay (RIA) kits have been used to analyze small ligands such as tyrosine, progesterone and cortisol. Highly sensitive RIA employing 125I or 3H has been developed and used to measure the minute quantities of reproductive and other hormones circulating in the blood that regulate reproduction. The following are possible with RIA: determining the appropriate breeding time for animals, diagnosing pregnancy earlier, and determining if animal insemination was timely done. Other possibilities include devising corrective reproductive disorders measures and improving the efficiency of artificial insemination and embryo transfer programs. However, the short life of RIA kit reagents is a significant problem besides those associated with cost and the regular supply of kits, especially for developing countries [44].

Nuclear techniques have played a significant role in the field of animal health. Ionizing irradiation from 60Co sources has been used to eradicate the virulence of some parasites to produce cost-effective and safer vaccines. In the UK alone, the commercial use of an irradiated vaccine against lungworm disease in calves saves millions of livestock producers each year

[45]. Radioactive Iodine (131I) is most valuable for treating small functional nodules of metastatic disease that are hard to find or treat surgically [44]. Radiation therapy in dogs and cats is given mainly to treat primary brain tumours (total dose of 45 Gy in 3.75 Gy fractions over 28 days) [46].

Conventional disease diagnosis methods, which involve the isolation and direct detection of microorganisms using microscopy and immunoassays, are usually time-consuming. At the same time, nucleic acid hybridization techniques are advancing in terms of speed and sensitivity. This hybridization approach is unique in that it concentrates on the organism's DNA rather than its products, such as proteins. The most frequent label used in DNA probe technology is a radioactive one (32P, 35P, 125I) that is inserted directly into the nucleic acid using one of several available procedures. After hybridization, the duplex (probe-target) is detected by liquid scintillation counting or autoradiography. Technetium 99m is also now commonly used to diagnose hyperthyroidism in dogs and cats, chronic lameness in horses, and portosystemic shunt in the liver.

Radioactive amino acids can be used to metabolically label tissue culture cells. The most often used radioactive precursor for labelling protein is (35S) Methionine because its decay is easier to detect and it is easily absorbed into protein, with linear incorporation throughout a wide range of additional label. Other amino acid labels utilized include (3H) proline, (35S) cysteine and (3H) leucine [47].

### B. Fertilizers

Fertilizers are expensive and can damage the environment if not correctly used. Therefore, the concerns on the efficient use of fertilizers are justifiable for both developing and developed countries. Nuclear-related technologies are employed to optimize the use of soil resources (nutrients and water), increase crop productivity, and optimize the impact on the environment of the excessive use of fertilizers. 15N is used to quantify the amount of biologically fixed nitrogen in field-grown legumes, and the dynamics of 15N applied to soil for crop production. 32P is also used to determine how plants utilise nutrients, allowing better fertilizer application management. An accurate measurement of soil moisture content using nuclear (soil moisture neutron probe) is essential for establishing the optimal soil-water balance for irrigation scheduling under different irrigation systems and soil management practices [44].

## C. Increasing Genetic Variability

Radiation can cause mutations and genetic diversity, which are then used to select desired mutants with improved agronomic qualities. Additionally, seedlings can be irradiated using nuclear techniques. Gamma or neutron irradiation is used in conjunction with other methods to produce new genetic types of cereals, oil seed crops, roots and tuber crops.

New agriproducts resistant to pests have been developed, and the products do well in severe climatic conditions. The agro products include garlic, bananas, peppers and many more. In addition, Mali produces irradiating rice seeds and sorghum varieties that are better desired [42].

## D. Food Preservation

Some 25-30% of the food harvested in many countries is lost due to spoilage by microbes and pests. Therefore, the reduction of spoilage due to infestation and contamination is of the utmost importance. This loss is especially so in countries that have hot and humid climates and where an extension of the storage life of certain foods, even by a few days, is often enough to save them from spoiling before consumption. In addition, some countries lose a high proportion of harvested grain due to moulds and insects.

Globally, irradiation technology use for food preservation is growing. Health and safety authorities in more than 40 nations have approved the irradiation of over 60 types of food, ranging from spices, grains, and grain products to fruit, vegetables, and meat. Irradiation technology can replace undesirable chemical fumigants capable of eliminating insects from fruits, grains, legumes, and spices.

In 1983 a global standard by a joint committee of WHO, FAO and IAEA were adopted following thirty years of testing. However, in 1997 another joint committee indicated that the earlier set upper limit on radiation dose for foods was unnecessary. In addition to reducing post-harvest food spoilage, the increased use of food irradiation is due to concerns about the stringent quality standards for food-borne diseases and the growing international trade in foodstuffs.

Food irradiation means that raw foods are exposed to high levels of gamma radiation which kills bacteria and other harmful organisms without affecting the nutritional value of the food itself or leaving any residue. It is the only means of killing bacterial pathogens in raw and frozen food. Table 2 shows typical applications of irradiation.

Table 2: Food irradiation applications

| Dose (Gy) | Application | Example Foods |
|---|---|---|
| Low dose (up to 1k) | Inhibition of sprouting | Potatoes, onions, garlic, ginger, yam |
| | Insect and parasite disinfestation | Cereals, fresh fruit, dried foods |
| | Delay ripening | Fresh fruit, vegetables |
| Medium dose (1-10k) | Extend shelf life | Fish, strawberries, mushrooms |
| | Halt spoilage, kill pathogens | Seafood, poultry, meat |
| High dose (10-50Gy) | Industrial sterilization | Meat, poultry, seafood, prepared foods |
| | Decontamination | Spices, etc |

Radiation is also used to sterilize food packaging. For example, in the Netherlands, milk cartons are freed from bacteria by irradiation. The four primary components of commercial irradiators are a source of radiation, a method of product conveyance, protectors for personnel against irradiation and the environment to radiation and safety systems. Ionizing radiation is penetrating energy; therefore, products are packaged before irradiation. Two of the available irradiators for food processing are:

- **Electron Beam Irradiators**:

These employ a radiation chamber. Accelerators generate electron beams and accelerate the electrons in the direction of the food product to be irradiated. Electrons have limited penetration through food products because they have mass. Penetration on typical food products is about 3.8cm or about 8.9cm if irradiation is on both sides of the food product [48]. The electric charge on an electron enables accelerated electron streams to undergo scanning by magnets and tracking within the product. For example, commercial food electron beam irradiators are known to accelerate the electrons to 10MeV [49]. Furthermore, this possesses massive concrete, steel or lead shields.

- **Gamma Irradiator**:

Radioactive isotopes like 137Cs (Cesium) or 60Co (Cobalt) are the photon source in gamma irradiators. Unlike electron beams generated on-site using electricity, cobalt-60 is generated off-site in nuclear reactors and moved to the site in "casks," particularly shipping containers. Cobalt-60 is solid radioactive metal in two welded stainless-steel encapsulations, creating a "Sealed Source". The Cobalt-60 (Co60) is contained in the sealed source, but the photons pass through to the food product. Since Co60 photons are massless, they can penetrate deep into the food product. The photon can penetrate more than 60cm of food product if irradiated on both sides. Massive concrete or steel structures Gamma irradiators encapsulate since radiation from Co60 is continuous and cannot be turned "off". The radiation source is immersed in a pool of water when it is not in use to enable personnel to access the chamber. The shielding water does not become radioactive. Safety interlocks disallow personnel entry to the room when the source is not in the stored position. The products are moved through the room using hanging carriers, totes and roller conveyors.

### E. Insect Control

The limited data available indicate that arthropods may be destroying an estimated 18-20% of the annual crop production worldwide [50]. In developing countries, Crop losses caused by insects is estimated to 25-35% [51]. Stock losses due to tsetse in Africa and screwworm in Mexico have also been sizeable. Modern chemical insecticides were rapidly developed after World War II and provided plant and animal producers with powerful tools for general use against insects. Insecticides provide the primary method of insect control; however, they are only partially satisfactory. Moreover, there are concerns that reliance on pesticides to maintain yields adversely affects the environment and may also lead to the insect's developing resistance to the pesticides themselves. One solution has been the use of sterile insects.

The Sterile Insect Technique (SIT) involves rearing large numbers of insects and then irradiating their eggs with gamma radiation before hatching to sterilize them. Then, the sterile males are released in large numbers in the infested areas. When they mate with females, there are no offspring. Repeated releases will eventually lead to the control or eradication of insect pests of major crops and insect vectors of diseases with a substantially reduced use of insecticides [52].

Many SIT operations against the Medfly (Mediterranean fruit fly) were performed in countries like Mexico, Argentina, and northern Chile. In 1981, Mexico reported complete success using this method. In 1994, two fruit-growing areas of Argentina achieved 95% eradication and 95% success in another and Chile. Moreover, the program was also implemented in southern South America and Africa. Zanzibar was declared tsetse-free in 1997, and Nigeria benefited from the SIT program. Three UN organizations which are IAEA, FAO and WHO as well as the governments concerned promote new SIT programs in many countries.

In addition to SIT, nuclear applications deploy isotopes and radiation to control insects. Isotopes are used as tags or markers, for instance, of chemical molecules, insects, or plants. For example, with these tags, one can follow the fate of insecticides within insects and the environment, incorporating nutrients into the insect; and the movements of insects under field conditions. They also can mark plants on which insects feed so that the quantity of consumed food can be measured and directly correlated with plant resistance. Finally, SIT can also be used to follow parasites and predators of insects, for example, their movements, numbers, and ability to help control insect pests.

## F. Challenges of Nuclear Techniques in Food and Agriculture

The major challenges faced by nuclear techniques in the food and agricultural sector are the issues of human resources, cost of technology and equipment, and government political will and investment. Table 3 highlights these challenges as they affect developing countries.

Table 3: Challenges in Food and Agriculture

| Challenge | Discussion |
|---|---|
| Human Resources | Nuclear techniques in the food and agricultural sector require huge human capital, especially skilled human resources. Most developing countries have limited nuclear technology experts required to drive the industry. An aggressive approach needs to be used to grow the nuclear expertise of professionals needed in the food and agricultural sectors. Efforts should be made to take advantage of resources available at the International Atomic Energy Agency (IAEA), and other international and local organizations |
| Cost of Technology and Equipment | The high cost of technology has kept a lot of developing countries out of nuclear techniques. Radioisotopes used in the food and agricultural sectors are often sourced from developed countries. The logistics of acquiring the radioisotope and in most cases the short half-life may become a challenge. The equipment used in producing radioisotopes and other equipment used |

| | |
|---|---|
| | for analysis is rather very capital intensive. The IAEA has tried to step in to fill this gap, but it is usually not enough |
| Government Political Will | Governments of developing countries, especially countries of Africa, lack the political motivation to allocate enough budget to nuclear-related projects in food and agriculture. Most of these countries even find it difficult to maintain donated resources [53] and, in some cases, donated equipment is either underutilized or abandoned |

## IV. Use of Nuclear Energy in Medicine

Radiation and radioisotopes have medicinal use, particularly for identification (diagnosis) and treatment (therapy) of several medical conditions. In developed countries, about 2% of the population use diagnostic nuclear medicine annually, and the frequency of therapy with radioisotopes is about one-tenth of this [54].

### A. Diagnosis

Nuclear medicine diagnostic techniques use radioactive tracers, emitting gamma rays from within the body. These tracers are generally short-lived isotopes linked to chemical compounds that permit scrutinizing physiological processes [54]. These tracers are injected, inhaled or taken orally. Combined with imaging devices that register the emitted gamma rays from within, they can study the dynamic processes in various body parts. A benefit of nuclear techniques over X-ray techniques is the capability to perform successful bone and soft tissue imaging. In using radiopharmaceuticals, a radionuclide is injected into the patient. Then, the radionuclide activity within the organ is studied either as a two-dimensional picture or with tomography.

With the increased power of modern computers, clinical images can be acquired at multiple angles, creating a replica of the body's cross-section, a technique called computerized tomography (CT). Single-photon emission computed tomography (SPECT) and positron emission tomography (PET) are the most advanced radionuclides forms [55]. SPECT is where a gamma camera detects single photons that can view organs from many angles [56]. In addition, the camera captures an image of the emitted radiation. This image is computer-enhanced and viewed for indications of abnormal conditions.

On the other hand, PET is a more accurate but complex technique using isotopes produced in a cyclotron. An injection initially introduces a positron-emitting radionuclide; this then accumulates in the target tissue. As the radionuclide decays, positrons are emitted, which combine with a nearby electron resulting in the simultaneous emission of two identifiable gamma rays in opposite directions [57]. PET cameras detect these emissions and indicate their origin. PETs are used widely in oncology, with fluorine-18 as the tracer. It is also well-used in cardiac and brain imaging. Combining PET with CT scans for co-registration of the two images (PETCT) enables a 30% better diagnosis than the traditional gamma camera alone [57].

Technetium-99m, a widely used diagnostic radioisotope, provides the patient with a low radiation dose. The radioisotope has a half-life of six hours. Such radioisotopes are ideal for tracing many bodily processes with minimum discomfort to the patient. They are widely used to identify tumours and study organs such as the heart, liver, lungs, kidneys, bone structure and monitor blood circulation [58].

**B. Therapy**

Radioisotope usage in therapy is essential but comparatively few. Cancerous growths are sensitive to damage by radiation [54]. Therefore, external irradiation or teletherapy using a radioactive cobalt-60 source can be performed using a gamma beam. Also, internal radionuclide therapy or brachytherapy is accomplished by planting a small gamma or beta emitter source in the affected area. Brachytherapy is becoming the primary means of treatment. Many therapeutic procedures relieve pain.

Iodine-131, probably the most successful in cancer treatment, is used to treat thyroid cancer and non-malignant thyroid disorders [56]. Iridium-192 wire implants are used primarily in the head and breast to give precise doses of beta rays to limited areas, then removed. A new treatment uses samarium-153 complexed with organic phosphate to relieve the pain of secondary cancers lodged in the bone [58].

Lutetium-177 dilatate or octreotide is used to treat tumour types such as neuroendocrine and is effective when other treatments fail. Four treatments deliver 32GBq (1GBq = 109 becquerels = 0.027Ci). After about four to six hours, the exposure rate of the patient has fallen to less than 25 microsieverts per hour at one metre, and the patients can be discharged from hospitals. Lu-177 is essentially a low-energy beta-emitter (with some gamma), and the carrier attaches to the surface of the tumour.

A new field is targeted alpha therapy (TAT) or alpha radio-immuno-therapy, especially for controlling dispersed cancers. The alpha emissions are very energetic; they have a short range. The implications are that a significant fraction of that radiative energy goes into the targeted cancer cells once a carrier, such as a monoclonal antibody, has taken the alpha-emitting radionuclide Bi-213 to the right places [54]. Clinical trials for leukaemia, cystic glioma and melanoma are underway. In addition, TAT using lead-212 is increasingly essential for treating pancreatic, ovarian and melanoma cancers.

### C. Biochemical Analysis

Detecting the presence or absence of some radioactive materials, even when they exist in low concentrations, is a straightforward process. Radioisotopes can therefore be used to label molecules of biological samples in vitro (out of the body). Pathologists have devised hundreds of tests to determine the constituents of blood, serum, urine, hormones, antigens and many drugs using associated radioisotopes. These procedures are known as radio-immuno-assays, and although the biochemistry is complex, kits manufactured for laboratory use are easy to use and give accurate results. These procedures measure low concentrations of hormones, enzymes, hepatitis virus, some drugs and a range of other substances in a sample of the patient's blood [58]. The patient never meets the radioisotopes used in the diagnostic tests. Annually, about 40 and 15 million diagnostic tests are performed in the USA and Europe.

**D. Sterilization**

Gamma irradiation, rather than heat sterilization, is widely used to sterilize medical products that might react adversely to the heat sterilization process. The products include syringes, gloves, clothing, cotton wool, burn dressings, heart valves, bandages, plastic and rubber sheets, and many other surgical instruments [58]. Cobalt-60 is the main isotope used since it is an energetic gamma emitter. Large-scale irradiation facilities for gamma sterilization are in many countries.

The benefit to humanity of sterilization of medical products and supplies by radiation is tremendous. The sterilization method is safer and cheaper than other methods, and doing it is best before product shipping. Furthermore, the sterile shelf life of the article is then practically indefinite, provided the package is not damaged [54]. The ionizing and non-ionizing radiation methods are generally used for sterilization. Ionizing radiation uses short-wavelength, high-intensity radiation to destroy microorganisms. For example, this radiation can come in gamma or X-rays that react with DNA resulting in damaged cells. Non-ionizing radiation uses a longer wavelength and lower energy. As a result, non-ionizing radiation loses the ability to penetrate substances and can only be used for sterilizing surfaces [59]. The most common form of non-ionizing radiation is ultraviolet light, which is used in various ways throughout industry.

One industrial application of non-ionizing radiation is the breakdown of ozone ($O_3$). By adding ozone to water, bacteria are unable to sustain life. Unfortunately, ozone also destroys process media. Therefore, ozone must decompose so water can be used for its designated purpose. Since ozone is very sensitive to ultraviolet light, pass the water stream under UV bulbs. This reaction breaks the oxygen-oxygen bonds and results in the safe process of water [59] and this can be presented as in Figure 3.


Figure 3: Non-ionizing radiation

Radiation sterilization offers several advantages over conventional heat sterilization. It does not degrade the media during the sterilization process, making it suitable for thermally labile materials. In addition, it leaves no chemical residue, allows precise and uniform dose distribution, and enables the media to be used immediately after sterilization. However, this method also has some limitations. It is generally more expensive than heat sterilization and requires highly specialized equipment, which may limit its widespread application.

## V. Nuclear Technology in the Process Industry

### A. Process Heat

Nuclear reactors can provide heat for multiple uses, including heating homes and commercial and industrial buildings safely and with minimum impact to the environment. There are two forms of heat consumption levels:

- **Low-temperature heat:** includes hot water or low-quality steam for district heat, desalination, and other purposes
- **High-temperature heat:** can either be heat for processing steam for various chemical and manufacturing applications or heat for converting fossil fuels and hydrogen production.

For process heat some of the applications are [60]:

- **Recovery of oil from tar sands:**

Since 2003 various proposals have been made to use nuclear power to produce steam for the extraction of oil from Alberta's northern tar sand deposits and electricity and for the major infrastructure involved. One proposal from Energy Alberta Corp. suggested that a single CANDU 6 reactor (about 1800 MWt) configured to produce 75% steam and 25% electricity would replace 6 million $m^3$ per day of natural gas and support the production of 175-200,000 barrels per day of oil. It would also save the emission of 3.3 million tonnes of $CO_2$ per year.

- **Oil refining:**

Apart from separating the different components of crude oil by two distillation processes, an oil refinery typically breaks down the residual heavy or long-chain hydrocarbons in a catalytic cracker by adding hydrogen. Hydrogen is produced by steam reforming of the natural gas and gives rise to a lot of carbon dioxide. The hydrogenation of heavy crude oil is a major use of hydrogen today. Overall, about 15-20% of the energy value of crude oil is used in producing refined products.

In the short term, some of the electricity generated by nuclear power could be used for high-temperature electrolysis for hydrogen production. (Heavy water and oxygen could be valuable by-products of electrolysis). In future, a major possibility is the decomposition of water by direct use of heat from nuclear energy, using a chemical process enabled by high-temperature reactors. The hydrogen produced can also be used for agricultural fertilizers.

There are other possibilities for producing hydrogen. In the iodine-sulfur (IS) process iodine combines with $SO_2$ and water to produce hydrogen iodide which then dissociates into hydrogen and iodine [61]. This is the Bunsen reaction and is exothermic as in Equation (2) occurring at low temperature of 120°C.

$$I_2 + SO_2 + 2H_2O \Longrightarrow 2HI + H_2SO_4 \quad (2)$$

The HI then dissociates to hydrogen and iodine at about 350°C, the reaction is endothermic as in Equation (3).

$$2HI \Longrightarrow H_2 + I_2 \quad (3)$$

This can deliver hydrogen at high pressure. Combining all this, the net reaction is as Equation (4).

$$H_2O \Longrightarrow H_2 + 0.5O_2 \quad (4)$$

All the reagents other than water are recycled, and there are no effluents. The Japan Atomic Energy Authority (JAEA) has demonstrated laboratory-scale and bench-scale hydrogen production with the IS process, up to 30 litres/hr. The Sandia National Laboratory in the USA and the French CEA are also developing the IS process intending to use high-temperature reactors for it. The economics of hydrogen production depends on the efficiency of the method used. The IS cycle coupled to a modular high-temperature reactor is expected to produce hydrogen at $1.50 to $2.00 per kg. The oxygen by product also has value [62].

## B. Smoke Detector

One of the most typical uses of radioisotopes today is in household smoke detectors. Smoke detectors contain americium-241, a decay product of plutonium-241 originating in nuclear reactors. Americium-241 emits alpha particles and low-energy gamma rays. The alpha particles emitted by the Am-241 collide with the oxygen and nitrogen in the air in the detector's ionization chamber to produce charged particles (ions). A low-level electric voltage across the chamber is used to collect these ions, causing a steady small electric current to flow between two electrodes. However, when smoke enters the space between the electrodes, the particles attach to the charged ions, neutralizing them and causing the number of ions present and the electric current to fail, which sets off an alarm [63].

The radiation dose to the occupants of a house from a domestic smoke detector is essentially zero and, in any case, much less than that from natural background radiation. The reason is that the alpha particles are absorbed within the detector, while the gamma rays escape harmlessly. The small amount of radioactive material in these detectors is not a health hazard and is disposed of with regular household waste.

### C. Environmental Tracers

Radioisotopes are essential in detecting and analyzing pollutants because small amounts of a radioisotopes are detectable. In addition, the decay of short-lived isotopes means that no residues remain in the environment. Many pollution problems, such as smog formation, sewage dispersal from ocean outfalls, sulphur dioxide contamination of the atmosphere, and oil spills have been monitored using nuclear techniques.

### D. Industrial Tracers

Radioisotopes have found a wide range of applications in the industry because they are detectable in minute quantities. For example, manufacturers use Radioisotopes as tracers to monitor fluid flow and filtration, detect leaks, and gauge engine wear and corrosion of process equipment. Small concentrations of short-lived isotopes can be detected whilst no residues remain in the environment [54]. By adding small amounts of radioactive substances to materials used in various processes, mixing and flow rates studies are possible for a wide range of materials, including fluid-like substances, and to locate leaks. Tracers added to lubricating oils can help measure the rate of wear of engines, plants and equipment. Tracer techniques have been used in plant operations to check equipment performance and improve efficiency, resulting in savings in energy and better use of raw materials.

### E. Instruments

The use of nuclear energy exists in many instruments. For example, all industries use gauges containing radioactive sources to check gases, liquids and solids levels. Furthermore, these instruments measure the amount of radiation by material from a source. These gauges are most useful where heat, pressure or corrosive substances, such as molten glass or metal, make it challenging to use gauges that require direct contact with the material [54].

When it is desirable to avoid contact between the gauge and the material, continuous sheets of material, such as paper, plastic film, metal, and glass, to mention a few, the manufacturing process uses a radioisotope thickness gauge. Density gauges have found use in detergent manufacture where automatic control of a liquid, powder or solid is necessary.

Radioisotope instruments offer several significant advantages. They enable measurements to be performed without physical contact with the material or product being measured, making them suitable for various industrial applications. In addition, isotope sources require very little maintenance, reducing operational effort and downtime. Furthermore, these instruments provide an excellent cost benefit ratio, as the savings they generate often allow the initial investment to be recovered within a few months [58].

## F. Radiography

Radiography involves using radiation to provide images of internal body organs such as tissues, organs, bones, and blood vessels. Those that emit gamma rays are more portable than X-ray machines and may give higher-energy radiation. Therefore, Radioisotopes can check new gas and oil pipeline welds, with the radioactive source placed inside the pipe and the film outside the welds. Figure 4 illustrates other forms of radiography (neutron radiography/ autoradiography) based on different principles; this can measure the thickness and density of materials or locate components that are not visible by other means [58].

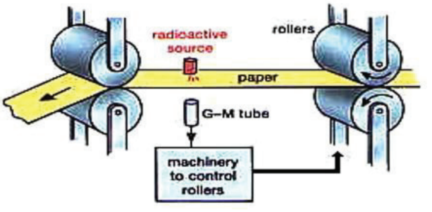


Figure 4: Paper thickness control

## G. Radiometric Dating

Examining the relative abundance of some naturally occurring radioisotopes is essential. Radiometric Dating helps determine the age of rocks and other geological, anthropological and archaeological information. Radiometric dating, sometimes called radioactive dating, is simply a nuclear method based on the decay rate of the radioactive isotopes of the material. Different methods exist for Radiometric Dating using both natural and manufactured materials.

The Uranium-Lead dating is a widely used method for dating materials containing uranium traces. The Uranium-Lead dating method uses U-238 or U-235, which are unstable and decay to a stable isotope of Pb-206 or Pb-207. Although U-238 and U-235 decay at different rates, they have different half-lives, and the different decay rates make this radiometric dating method more reliable and accurate.

### H. Challenges of Nuclear Technology in the Process Industry

If not used with safety and security in mind, industrial use of radioactive sources can harm workers and the environment. An example is the exploration and extraction of crude oil. Although radioactive marker bullets determine the relative depth, in most cases, gamma sources are used to find the bullets after completing the well-casing. In addition, radioactive tracers measure the direction and flow of crude oil and water [64]. In some cases, these sources and radioactive tracers, which become waste, are left underground after exploration and exploitation [65]. Because radioactive sources cause pollution to people and the environment, it has become a safety problem for both.

## VI. Nuclear Application for Water Resources

A sustainable potable water supply is crucial for any new development, whether agricultural, industrial, or human settlement. [66]. Freshwater is scarce in many parts of the world and becoming scarcer in others. Isotope hydrology techniques offer an accurate way of tracking and measuring underground water resources. These techniques provide essential analytical tools for managing and conserving existing water supplies and identifying new, renewable water sources. They also answer questions about groundwater's origin, age, and distribution and the interconnections between ground and surface water and aquifer recharge systems, permitting the planning and sustainable management of these water resources [67].

Surface waters can give information about leakages through dams and irrigation channels, the dynamics of lakes and reservoirs, flow rates, river discharges, and sedimentation rates. From Afghanistan to Zaire, some 60 developed and developing countries have used isotope techniques to investigate their water resources in collaboration with IAEA [63]. Neutron probes [68] can measure soil moisture very accurately, enabling better management of land affected by salinity, particularly irrigation [69].

## VII.Emerging Applications

The transportation sector is one area the nuclear industry is looking into in the future. Nuclear technology usage for the propulsion of ships and submarines dates to the mid-1950s when the United States developed the nuclear submarine. Later in the year 1959, the Soviet Union developed and launched the Lenin icebreaker [62,70,71]. Since then, nuclear-powered vessels have been associated with the armed forces. In recent years, much thought and research have gone into using nuclear-powered commercial cargo vessels and big commercial passenger ships. The fear and challenge have been the environment and the risk of radiation leaks to aquatic life, personnel or passengers onboard nuclear-powered commercial vessels. The International Commission on Radiological Protection (ICRP) states that if a reactor exists on a ship, all crew are considered radiation workers.

Furthermore, radiation exposure to the crew must not exceed five rems per year [71]. This exposure should be far less with passengers as their exposure should be at most half a rem per year. The ships must have a design to keep the accommodation area away from the reactor, so the passengers do not receive more than the minimum recommended half a rem per yearly dose for a 4-moth trip. Much research on small modular reactors (SMR) for the propulsion of commercial ships and vessels indicates that the vessel travels 50 per cent faster than oil-fossil ships of the same size. Small modular reactors (SMR) on commercial sea vessels will also help ships stay longer without fearing refuelling and significant maintenance.

Radioisotope thermal generators (RTG), also called nuclear batteries, generate usable electrical energy from the waste heat of a radioactive decay process. Radioisotope thermal generators are fitted in remote structures/machines that cannot get energy efficiently by any other means, such as satellites, lighthouses or space-bound objects. Figure 5 shows the RTG design made up of nuclear fuel, decays, and a set of thermocouples that converts heat energy to electric energy [72]. Several criteria should be considered when selecting a suitable radioisotope thermoelectric generator (RTG) fuel. The fuel should produce high-energy radiation and generate sufficient decay heat for power production. In addition, it should possess a long half-life to ensure long-term energy generation and have a high heat density (power-to-mass) ratio to maximize energy output while minimizing the fuel mass [73].

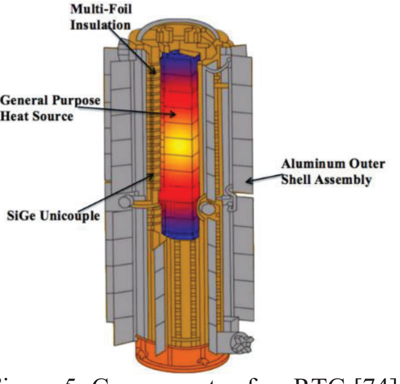


Figure 5: Components of an RTG [74]

The third condition is essential because of the remote location and lifespan. Blanke et al [73] showed that out of 1300 radioisotopes, only 47 qualified for use in RTGs. Out of the 47 radioisotopes that qualify, the most used for RTGs are Plutonium-238, Strontium-90, and Curium-244, with Plutonium-238 being the most used fuel. The last condition for choosing an acceptable radioisotope is mainly the issue of size and efficiency; a compact RTG is desirable. Even if a particular radioisotope passes all other conditions but still requires much fuel to produce electricity, it is undesirable. Doing further research and handling all safety, security and safeguards issues makes domestic use of the RTGs possible. Electric cars, trains, and homes can use RTGs for light.

Another emerging application is the production of green hydrogen. Although hydrogen can be readily obtained from oil refining and ammonia production, nuclear power plants can produce a more significant amount of hydrogen, thereby reducing the emission of $CO_2$. In addition, hydrogen obtained from nuclear power plants can be used to build hydrogen fuel cells that can power cars. Accomplishing this would replace the use of fossil fuels, which would further reduce the emission of $CO_2$.

## VIII. Conclusion

Our daily lives are enriched using radioisotopes and radiation, often without our awareness. These technologies are woven into the fabric of our routines, from the water we wash with, the clothes we wear, the food we eat, to our means of transportation, the bridges we cross, and the paper we use. But perhaps most significantly, nuclear technology plays a pivotal role in medicine, from the drugs we take to the medical tests that ensure our well-being. Additionally, radioisotope techniques are instrumental in maintaining a clean environment.

## IX. References

[1] R. Rhodes, *The making of the atomic bomb*. Simon & Schuster. 1986.

[2] I. Chernus, *Eisenhower's atoms for peace* (1st ed). Texas A&M University Press. 2002.

[3] IAEA. *Nuclear Power Reactors in the World, Reference Data Series* No. 2, 2022 edition. International Atomic Energy Agency, Vienna 2022.

[4] Cobb, J. World nuclear performance report 2016. A new study by *World Nuclear Association. Atw. Internationale Zeitschrift fuer Kernenergie, World Nuclear Association*., 61(8), 522-525, 2016.

[5] Michal, R. Fifty years ago in December: Atomic reactor EBR-I produced first electricity. *Nuclear News*, 44(12), 28-29, 2001.

[6] Semenov, B. A. Nuclear power in the Soviet Union. *IAEA Bulletin*, 25(2), 47-49. 1983.

[7] IAEA *Nuclear Technology Review 2022*, Report by the Director General, GC (66)/INF/4, IAEA, Vienna, 2022.

[8] Ritchie, H., Roser, M., & Rosado, P. 2020. *Energy*. [Online] Our World in Data. <https://ourworldindata.org/electricity-mix> [Accessed 22 September 2022].

[9] Sims, R. E. H., Rogner, H.-H., & Gregory, K. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy*, 31(13), 1315–1326, 2003.

[10] Ghenai, C., & Janajreh, I. Comparison of resource intensities and operational parameters of renewable, fossil fuel, and nuclear power systems. *Int. J. of Thermal & Environmental Engineering*, 5(2), 95-104, 2013.

[11] Elhegazy, H., & Kamal, M. Implementing nuclear power plants (NPPs): State of the art, challenges, and opportunities. *Innovative Infrastructure Solutions*, 7(1), 11, 2022.

[12] Iwata, H., Okada, K., & Samreth, S. Empirical study on the environmental Kuznets curve for CO2 in France: The role of nuclear energy. *Energy Policy*, 38(8), 4057-4063, 2010.

[13] Baek, J. A panel cointegration analysis of CO 2 emissions, nuclear energy and income in major nuclear generating countries. *Applied Energy*, 145, 133-138, 2015.

[14] Hassan, S. T., Danish, Salah-Ud-Din Khan, Awais Baloch, M., & Tarar, Z. H. Is nuclear energy a better alternative for mitigating CO2 emissions in BRICS countries? An empirical analysis. *Nuclear Engineering and Technology*, 52(12), 2969-2974, 2020.

[15] Azam, A., Rafiq, M., Shafique, M., Zhang, H., & Yuan, J. Analyzing the effect of natural gas, nuclear energy and renewable energy on GDP and carbon emissions: A multi-variate panel data analysis. *Energy*, 219, 119592, 2021.

[16] Danish, Ozcan, B., & Ulucak, R. An empirical investigation of nuclear energy consumption and carbon dioxide (CO2) emission in India: Bridging IPAT and EKC hypotheses. *Nuclear Engineering and Technology*, 53(6), 2056-2065, 2021.

[17] Pata, U. K., & Samour, A. Do renewable and nuclear energy enhance environmental quality in France? A new EKC approach with the load capacity factor. *Progress in Nuclear Energy*, 149, 104249, 2022.

[18] Permana, S., Trianti, N., & Rahmansyah, A. Nuclear energy contribution for net zero emission and national energy mix 2060 in Indonesia. *In Journal of Physics: Conference Series* (Vol. 2243, No. 1, p. 012066, 2022.

[19] WNA. Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources. WNA Report, London. WNA 2011. (World Nuclear Association). https://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf

[20] Papiewski, J. The Differences Between Nuclear Power & Fossil Fuel-Burning Power Plants, 2018.

[21] EIA U.S. Energy Information Administration (EIA), *Electric Power Annual 2020 Report*, U.S. Department of Energy, Washington, DC 20585, March 10, 2020.

[22] Irwanto, D., Permana, S., Pramutadi, A., & Pramuditya, S. Preliminary Design Study of Small Power 30-50 MWt Experiment Power Reactor based on High Temperature Pebble Bed Gas Cooled Reactor Technology. *Journal of Physics: Conference Series*, 1127, 012024, 2019.

[23] Gad-Briggs, A., Pilidis, P., & Nikolaidis, T. Analyses of long-term off-design performance strategy and operation of a high-pressure ratio intercooled brayton helium gas turbine cycle for generation IV nuclear power plants. *Journal of Nuclear Engineering and Radiation Science*, 4(4), 041014, 2018.

[24] Permana, S., Saputra, G., Suzuki, M., Suud, Z., & Saito, M. Reactor core and actinide production evaluation based on different loading material of recyled spent nuclear fuel of LWR in FBR. *International Journal of Hydrogen Energy*, 41(17), 7076-7081, 2016.

[25] Wagner, F. EPS-SIF Energy Summer School 2019: Concluding remarks. *EPJ Web of Conferences*, 246, 00022, 2020.

[26] Michaelides, E. E. *Alternative Energy Sources*. Springer-Verlag Berlin Heidelberg, 2012.

[27] Kalpakkam, India, & Vaidyanathan, G. Electricity Generation Options for India-A Critical Evaluation. *Indian Journal of Science and Technology*, 14(33), 2684-2710, 2021.

[28] UNSCEAR. 2020. *Sources and Effects of Ionizing Radiation. Annex B: Levels and Effects of Radiation ExposureDue To The Accident At The Fukushima Daiichi Nuclear Power Station: Implications of Information Published Since the UNSCEAR 2013 Report*. United Nations Scientific Committee on the Effects of Atomic Radiation. https://www.unscear.org/unscear/uploads/documents/publications/UNSCEAR_2020_21_Annex-B.pdf

[29] Ritchie, H. *What are the safest and cleanest sources of energy?,* 2020.
[30] Lelieveld, J., Klingmüller, K., Pozzer, A., Burnett, R. T., Haines, A., & Ramanathan, V. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences*, 116(15), 7192-7197, 2019.
[31] UNSCEAR. 2008. *Sources and Effects of Ionizing Radiation. Annex D: Health Effects due to Radiation from the Chernobyl Accident.* United Nations Scientific Committee on the Effects of Atomic Radiation. https://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_D.pdf
[32] Kharecha, P. A., & Hansen, J. E. Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power. *Environmental Science & Technology*, 47(9), 4889–4895, 2013.
[33] IAEA. 2001. IAEA Safeguards Glossary 2001 Edition), Tech. Rep, International Atomic Energy Agency, Vienna, Austria, Jun. 2002. https://www.iaea.org/sites/default/f iles/iaea_safeguards_glossary.pdf.
[34] IAEA, *Status of Small Reactor Designs without On-Site Refuelling*, Tech. Rep., International Atomic Energy Agency, Vienna, Austria, 2007.
[35] Hussein, E. M. A. Emerging small modular nuclear power reactors: A critical review. *Physics Open*, 5, 100038, 2020.
[36] IAEA. Options to Enhance Proliferation Resistance of Innovative Small and Medium Sized Reactors, Tech. Rep. NP-T-1.11, *International Atomic Energy Agency*, Vienna, Austria. 2014.
[37] IAEA. *Radioactive Waste Management Status and Trends*-Number 4, Vienna, 2005.
[38] IAEA. *Classification of radioactive waste*-General Safety guide-No. GSG-1, Vienna, 2009.
[39] Corkhill, C., & Hyatt, N. *Nuclear Waste Management*. IOP Publishing, 2018.
[40] Apted, M. J., & Ahn, J. Repository 101. In Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste (pp. 3–26, 2017. Elsevier.
[41] Lersow, M., & Waggitt, P. Disposal of All Forms of Radioactive Waste and Residues: Long-Term Stable and Safe Storage in Geotechnical Environmental Structures. Springer *International Publishing*. 2020.
[42] WNA. Storage and Disposal of Radioactive Waste, *World Nuclear Association*, 2021. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/storage-and-disposal-of-radioactive-wastes.aspx

[43] Jia, S., Dai, Z., Yang, Z., Du, Z., Zhang, X., Ershadnia, R., & Soltanian, M. R. Uncertainty quantification of radionuclide migration in fractured granite. *Journal of Cleaner Production*, 366, 132944, 2022.

[44] Khanal, D. R., & Munankarmy, R. C. Nuclear and related techniques for enhancing livestock and agriculture productivity. *Journal of Agriculture and Environment*, 10, 150-155, 2009.

[45] Dargie, J. D. Helping small farmers to improve their livestock. *International Atomic Energy Agency*, Vienna. 1990.

[46] Lavin, L. M., *Radiography in veterinary technology*. W. B. Saunders Company, Philadelphia, 1999.

[47] IVRI, Practical manual of analytical biochemistry. *Division of Biochemistry and food science*, Indian Veterinary Research Institute, India, 2001.

[48] McKeen, L. Introduction to Food Irradiation and Medical Sterilization. *In The Effect of Sterilization on Plastics and Elastomers* (pp. 1-40). Elsevier, 2012.

[49] Pillai, S. D., & Braby, L. A. Electronic Pasteurization. In G. Tewari & V. K. Juneja (Eds.), Advances in Thermal and Non-Thermal Food Preservation (pp. 195-202). *Blackwell Publishing*, 2007.

[50] Sharma, S., Kooner, R., & Arora, R. Insect Pests and Crop Losses. In R. Arora & S. Sandhu (Eds.), Breeding Insect Resistant Crops for Sustainable Agriculture (pp. 45-66). *Springer Singapore*, 2017.

[51] Nwilene, F. E., Nwanze, K. F., & Youdeowei, A. Impact of integrated pest management on food and horticultural crops in Africa. *Entomologia Experimentalis et Applicata*, 128(3), 355-363, 2008.

[52] Brockerhoff, E. G., Liebhold, A. M., Richardson, R., & Suckling, D. M. *Eradication of invasive forest insects: Concepts, methods, costs and benefits*. New Zealand Journal of Forestry Science, 40 (Supplement), S117-S135, 2010.

[53] Kileo, A., Mdoe, S., Walter, A., & Mkilaha, I. The Role Of Nuclear Science And Technology In Achieving Sustainable Agricultural Development In Developing Countries. *I. International Symposium on Food Safety and Quality: Applications of Nuclear and Related Techniques*. Vienna, Austria: IAEA, 2014.

[54] Bezdek, R. H. *Global market for radiation applications*. Encyclopedia of Nuclear Energy, pp 588-597, 2021.

[55] Brooks, D. J. Positron emission tomography and single-photon emission computed tomography in central nervous system drug development. *NeuroRX*, 2(2), 226-236, 2005.

[56] Plekhanov, V. Traditional Application of Stable and

Radioactive Isotopes. In*: Isotopes in Condensed Matter. Springer Series in Materials Science*, vol 162. Springer, Berlin, Heidelberg, 2013.

[57] Beyer, T., Townsend, D. W., Brun, T., Kinahan, P. E., Charron, M., Roddy, R., & Nutt, R. A combined PET/CT scanner for clinical oncology. *Journal of Nuclear Medicine*, 41(8), 1369–1379, 2000.

[58] Rahman, R. O. A., Kozak, M. W., & Hung, Y. T. Chapter 16: *Radioactive pollution and control. In Handbook of Environment and Waste Management: Land and Groundwater Pollution Control* (pp. 949-1027), 2014.

[59] Behera, B. K. *Conceptual Development of Industrial Biotechnology for Commercial Production of Vaccines and Biopharmaceuticals*. Elsevier. 2023.

[60] Bajus, M. *Converting Power into Chemicals and Fuels, Power-to-X Technology for a Sustainable Future*. John Wiley & Sons, Inc., Hoboken, NJ. 2023.

[61] Hoffelner, W. *Materials for Nuclear Plants: From Safe Design to Residual Life Assessments*. Springer-Verlag, London, 2013.

[62] Hore-Lacy, I. Other nuclear energy applications: Hydrogen for transport desalination ships space research reactors for radioisotopes. *In Nuclear Energy in the 21st Century*. Elsevier. pp 93-110, 2007.

[63] Hore-Lacy, I. *Mankind benefits from nuclear energy and radiation*. Encyclopedia of Nuclear Energy, pp 653-660, 2021.

[64] Ajayi, T. R., Torto, N., Tchokossa, P., & Akinlua, A. Natural radioactivity and trace metals in crude oils: Implication for health. *Environmental Geochemistry and Health*, 31(1), 61-69, 2009.

[65] Avwiri, O., Ononugbo, C., & Egieya, J. Radiometric Assay Of Hazard Indices And Excess Lifetime Cancer Risk Due To Natural Radioactivity In Soil Profile In Ogba/ Egbema/ Ndoni Local Government Area Of Rivers State, Nigeria. *Academic Research International*, 4(5), 54-65, 2022.

[66] Rijsberman, F. R. *Water scarcity: Fact or fiction? Agricultural Water Management*, 80(1-3), 5–22, 2006.

[67] Owusu-Sekyere, E., Jordaan, H., & Chouchane, H. Evaluation of water footprint and economic water productivities of dairy products of South Africa. *Ecological Indicators*, 83, 32-40. 2017.

[68] Holton, J. R., Curry, J. A., & Pyle, J. A. *Encyclopedia of atmospheric sciences*. Academic Press, 2003.

[69] *Encyclopedia of atmospheric sciences* (2nd edition). Elsevier, 2015.

[70] Valentine, H. 2021. *Could a Nuclear-Powered Cargo Ship Transit the Suez Canal?* [Online]. Maritime-executive.com.

[71] SAFETY4SEA. 2021. *Is nuclear power the future of*? <https://safety4sea.com/cm-is-nuclear-power-the-future-of-/>

[72] Jiang, M. *An overview of radioisotope thermoelectric generators.* Introduction to Nuclear Energy PH241-Stanford University-Winter, 2013.

[73] Blanke, B., Birden, J., Jordan, K., & Murohy, F. 2022. *Nuclear Battery Thermocouple-Type Summary Report*. [Online] Large.stanford.edu. Available at: <http://large.stanford.edu/courses/2013/ph241/jiang1/docs/4807049.pdf> [Accessed 19 April 2022]. <http://large.stanford.edu/courses/2013/ph241/jiang1/docs/4807049.pdf> [Accessed 19 April 2022].

[74] Lefsrud, N., Lloyd, E., Mclean, M., Suarez, L., Sumners, Z., Toor, J., & Doner, J. 2022. *Radioisotope thermal generator* - Energy Education. [Online] Energyeducation.ca. Available at: <https://Energyeducation.ca/Encyclopedia/Radioisotope_thermal_generator> [Accessed 19 April 2022]