NUCLEAR ENERGY

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Summary

Nuclear power plants have many applications in our every day world. A significant fraction of the global electricity supply is produced by the world's 400+ (as of June, 2001) nuclear power plants. Other nuclear reactors produce radioactive isotopes for research and medical treatment or generate radiations used in other scientific research. Nuclear energy also promises to help reduce the emissions of greenhouse gases, and some have noted that nuclear energy may be the best way to supply the growing demand for electrical energy without further contributions to global warming. However, nuclear energy is not an unmixed blessing.

Nuclear power plants have also been decried as being costly, unsafe, and environmentally unfriendly. Several accidents have tarnished nuclear power's image, and a few of these have resulted in fatalities. Nuclear reactors generate both high-level and low-level radioactive waste, and the ultimate disposal of these wastes is subject to a great deal of public scrutiny and generates considerable concern. The fears of the public and the environmentalists are further heightened by widespread fear of radiation and its potential long-term effects on the public health. Nuclear power cannot be ignored as a potential source of global energy because of its undeniable benefits; neither can it be embraced unquestionably, for the reasons noted above.

In this article, many of the issues surrounding nuclear energy will be discussed. This discussion will include a brief description of the manner in which nuclear reactors are currently used, a more detailed description of the nuclear fuel cycle and the theory underlying nuclear reactor operations and design, and a discussion of the scientific basis for many of the public health concerns raised by nuclear power. Finally, we will discuss some of the political and environmental issues surrounding nuclear energy, comparing nuclear reactors to other energy sources in an effort to provide an unbiased comparison of the benefits and drawbacks they provide.

1. Introduction

1.1 A Brief History of Nuclear Reactors and Their Uses

The first man-made nuclear reactor was constructed at the University of Chicago by a team led by Enrico Fermi in 1943. Built as part of the Manhattan Project, this nuclear reactor was designed and constructed explicitly for research leading to the eventual construction of the world's first nuclear weapons. Although much scientific research suggested that uranium could be used to generate a self-sustaining nuclear chain reaction, until Fermi's reactor achieved criticality, this had not been demonstrated in practice. Using knowledge from this reactor, other scientists were able to develop not only nuclear weapons, but also built the first plutonium production reactors, used to create fuel for other atomic bombs. Thus, from the very start, nuclear reactors became intimately associated with nuclear weapons; an association that has since haunted all discussion of nuclear energy.

Following the end of World War II, the United States, the Soviet Union, Canada, and Great Britain were the first nations to continue exploring the potential of nuclear energy for both civilian and military purposes. In particular, the United States and the Soviet Union, spurred on by the Cold War, led the way in designing and building increasingly sophisticated designs for both nuclear reactors and nuclear weapons, as well as devising an increasing number of uses for nuclear power in other settings. This led to development and construction of small reactors for use in research, somewhat larger reactors used to produce radio-labeled compounds for research and medical purposes, and the investigation of "portable" nuclear reactors for generating power in near-combat or remote locations. In addition, nuclear reactors were utilized by several navies, where they revolutionized submarine warfare.

The world's first commercial nuclear power plant went into operation in late June, 1954 in the Russian city of Obninsk, near Moscow. This was followed in 1956 by the British plant in Calder Hill, and in 1957, the first American commercial nuclear power plant went on-line in Shippingport, Pennsylvania. The 1950s, and to a lesser extent the 1960s, was an age of nuclear optimism, particularly in the US and the Soviet Union. The widespread use of nuclear power was seen as a nearly unlimited source of inexpensive, reliable power that would help to lift much of the world out of poverty while simultaneously providing fresh water via desalinization plants, new drugs from research using radioisotopes, both at reduced environmental impact from reduced emissions. However, the continued development of nuclear weapons, their testing in the atmosphere, and the growing awareness of the potential for radiation injury became concerns. In the 1960s, with the growing strength of the global environmental movement, these concerns were voiced to governments with increasing volume. One milestone along this path was Linus Pauling's successful campaign to halt atmospheric nuclear weapons testing, which was given enhanced visibility by his subsequent Nobel Peace Prize for his efforts. However, it was not until 1979, with the accident at the US nuclear power plant at Three Mile Island (TMI) that the anti-nuclear power movement really took off.

Although the TMI accident resulted in exceedingly low radiation exposure to the general public, the reactor core was destroyed, and the perception was that it represented a narrowly-averted disaster. Coming on the heels of the successful (although technically inaccurate) movie "The China Syndrome", the accident was an unmitigated disaster for the US nuclear power industry. Seven years later, much more serious accident at the Soviet (now Ukranian) Chernobyl nuclear reactor gained global notoriety, the political results of which are still felt today.

As of this writing (June, 2001), the global outlook for nuclear energy is mixed. Japan, France, and to a lesser extent Russia, Canada, and Great Britain seem to have mature and relatively politically secure nuclear power capabilities. Several European nations, however (including Sweden and Germany) have announced plans to eliminate nuclear power plants, although the source of alternate energy has not yet been announced. Still other nations (particularly China and, to a lesser extent, Iran) are embarking on large programs to increase their dependence on nuclear energy, and the US stance remains mixed and undecided.

1.2 Nuclear Reactor Theory and Operations – A General Description

Nuclear reactors generate energy by fissioning (splitting) atoms of uranium. This simple statement hides a great deal of physics and engineering. The physics describes why splitting atoms produces energy and how this fissioning can be maintained for prolonged periods of time, and the engineering is necessary if this energy is to serve any useful purpose.

It is not immediately obvious that simply splitting a uranium atom should release energy. After all, splitting a log, or a stone, or any other object we are familiar with requires energy – swinging an ax is hard work. Similarly, there is no obvious reason that fissioning one atom should result in a second atom splitting, just as it is not readily apparent why uranium must be used instead of, say, lead or iron. A brief foray into nuclear structure is necessary to understand this, but the description is neither mathematical nor abstract.

All atoms are composed of a central nucleus surrounded by a cloud of electrons. The electrons do not concern us for the purposes of this discussion. The nucleus, in turn, is made up of protons with a positive electrical charge and neutrons with no charge, all confined to a very small space. Similar electrical charges repel one another, and the protons in the nucleus are subject to strong forces that try to force the nucleus apart. What holds atoms together is a force, called the strong nuclear force, and this force is carried by the neutrons. The neutrons are the duct tape that helps to hold the protons together. However the strong force only works over very short distances, so as atomic nuclei become larger, the strong force loses its ability to hold onto all of the protons. This means that, in general, large, heavy atoms are inherently less stable than small, light atoms. Another way to look at it, using the duct tape analogy, is that a piece of tape has a finite length. If we use a 30 cm piece of tape to hold together a few sticks, it will serve quite well. However, as the group of sticks grows, the tape is less able to wrap around to hold them all, and the entire bundle becomes less stable and easier to tear or fall apart.

Uranium is the largest atom that exists in abundance on Earth. There are small amounts of plutonium that are present naturally, and large amounts of plutonium and even heavier elements are formed in stellar explosions, but they are not long-lived and are uncommon on Earth. This means that uranium is also the atom most likely to fall apart on its own (called spontaneous fission) or to be forced apart (induced fission) by adding a neutron to the atomic nucleus. The addition of an extra neutron to the atomic nucleus also adds energy to the nucleus, making it vibrate. If an atom is teetering on the edge of stability, as is the case with the uranium atom, this added energy and vibration can cause it to fly apart, or fission.

Uranium also comes in several "flavors", or isotopes. The chemical properties of an atom are determined by the number of protons in the nucleus. Every atom with 82 protons (lead) is chemically identical, as is every atom with 92 protons (uranium). However, atoms of the same element can have different numbers of neutrons present, giving them a variety of atomic weights and different atomic properties. In the case of uranium, 99.2 percent of the uranium in the world has 92 protons and 146 neutrons, giving it an atomic weight of 238 (written as ^{238}U, or U-238). About 0.72 percent has three fewer neutrons; ^{235}U. In spite of having the same chemical properties, U-235 and U-238 have different nuclear properties, and U-235 is more likely to absorb passing neutrons than is U-238. When this happens the strong nuclear force, already stretched thin by the sheer size of the nucleus, can no longer hold the atom together and it falls apart. As the atom fissions, it produces two fission fragments (which are radioactive), two to three neutrons, gamma rays, and energy. The energy released is what we harness to make electricity, the neutrons go on to cause other fissions, and the fission fragments become radioactive waste that, in most cases, remains locked within the fuel.

As noted above, between two and three neutrons are released from each fission. Some of these neutrons go on to be absorbed by the water, steel, and lead of the reactor plant and are lost to the plant. Others are absorbed by uranium atoms, but do not cause fission, and still others escape the reactor altogether. The entire secret of nuclear reactor design is to arrange the fuel in such a way that, for each atom of uranium that fissions, exactly one neutron is produced that goes on to create another fission. When this happens, the total number of fissions in the reactor at any time is constant, so the production of energy is constant. Making this happen requires a certain mass of uranium arranged in a certain configuration, called the "critical mass" and "critical geometry". When you achieve such conditions, the nuclear reactor is said to be "critical". Put another way, ***all*** nuclear reactors are critical when they are operating, and nuclear criticality in an operating nuclear reactor is hardly an emergency (as a corollary, those who understand this fact are usually amused by television shows or movies in which someone announces in a panic-stricken voice that "the reactor is critical" – this just indicates that the writer is not terribly knowledgeable about nuclear reactors, and suggests that their writing should be viewed with some degree of skepticism).

On an atom-by-atom basis, nuclear fission releases a tremendous amount of energy. Splitting one uranium atom produces about 100 times as much energy as burning one molecule of gasoline, so nuclear energy can produce much higher energy densities than can plants that rely on chemical reactions (such as combustion). However, this energy is useless unless it can be harnessed in a usable form; we cannot simply pump through wires. In the case of nuclear reactors, the energy generated by fission turns into heat, which heats the reactor fuel. The fuel is surrounded by a coolant, usually water, and the heat energy is transferred into the water. The hot water, in turn, is used to produce steam, which turns turbines, which generate electricity. Although the process sounds somewhat laborious, it is no more so than many other forms of electricity generation, and the efficiency of most nuclear power plants (i.e. the ratio of electrical energy to thermal energy) is higher than many competing forms of energy generation.

Technical note – in reality, energy cannot be created, it can only be changed from one form to another. Nuclear reactors release energy already present in an atomic nucleus, turn it into heat energy, and the heat energy is transformed into electrical energy. The total amount of energy contained in the power lines coming out of a nuclear reactor plant is the same as the total amount of energy originally present in the uranium atoms that were fissioned.

1.3 Uses of Nuclear Reactors

Although the most visible and obvious uses to which nuclear reactors have been put, are the generation of electrical energy and the production of materials for nuclear weapons. They have found many other uses in the half-century or so they have been in use. These uses include the production of radioactive isotopes for medical diagnosis and treatment, production of isotopes for research, and desalinating seawater for drinking and industrial purposes. Generating power has already been discussed above, and nuclear weapons are beyond the scope of this chapter, so the next few paragraphs will discuss the use of nuclear reactors for military (non weapons-related), research, and medical purposes.

1.3.1 Military, non-weapons use

The first non-weapons use to which nuclear energy was applied was in nuclear submarines. Every major naval power immediately understood that nuclear energy offered the promise of creating a submarine force that could operate submerged for prolonged periods of time, virtually undetectable. Earlier submarines were hybrid machines – they ran on diesel engines on the surface and on batteries while submerged. Since their batteries could only give a limited amount of service before recharging, diesel submarines were designed to operate on the surface of the ocean, submerging only when necessary to attack or to hide.

Nuclear reactors, unlike diesel engines, do not need air or oxygen to produce power. A nuclear submarine could operate at full power, completely submerged, almost indefinitely. The reactors actually produce more than enough energy to meet the ship's needs, leaving additional energy for distilling fresh water, purifying the atmosphere, and more. In addition, freed from the constraints of a large battery for underwater attacks or evasions (and the diesels to recharge it), much more of the volume could be devoted to carrying weapons, electronics, and crew. The development of nuclear submarines was the most significant revolution in the history of submarines and was one of the biggest innovations in the history of modern naval warfare. Although nuclear power has also been put in use on surface combatants by the US and the Soviet Union (now Russia), its advantages on the ocean's surface are not nearly as pronounced as they are beneath the waves.

In addition to the naval use of nuclear reactors, some nations experimented with "portable" nuclear power plants that could be used to supply energy to military headquarters in remote locations. Another proposed use was in a nuclear airplane, a project begun but abandoned by the US in the 1960s. Others have used nuclear reactors in space. This latter use should not be confused with radio-isotopic thermal generators (or RTGs) which are used on most deep-space missions to the outer solar system. RTGs make use of heat released by radioactive decay, but they do not use nuclear fission for this purpose, they do not generate radioactive fission products or high levels of neutrons.

1.3.2 Medical and research uses

Although only a few isotopes will fission, most can be induced to capture neutrons, protons, or other atomic particles under the appropriate conditions. When this happens, the resulting atom will become radioactive. One example of this is the formation of radioactive carbon in the atmosphere. In this reaction, a cosmic ray neutron will strike a nitrogen atom, ejecting a proton from the nucleus and turning it into a carbon atom. This reaction is written

$$^{14}N + n = ^{14}C + p$$

This reaction is the one that creates the carbon-14 used to date archeological artifacts, tree rings, and many other objects. Similar reactions can be used to create many other isotopes that are widely used in research, to diagnose medical conditions, or to treat cancer and some other diseases. Research performed with the aid of nuclear reactor-generated isotopes includes genetic sequencing, investigation of basic biological functions, the development and understanding of new drugs, and better understanding of brain functions.

Nuclear reactors are also used as a source of neutrons for other research purposes. Neutrons can be used to probe the structure of matter and to investigate the chemical composition of geologic specimens (also called rocks). Cell cultures can be exposed to radiation from nuclear reactors to learn more about how DNA is damaged and repaired, nuclear reactor-produced neutrons have also been used to help treat some forms of cancer, and chemical compounds containing radioactive atoms created in nuclear reactors are used in research and in the diagnosis or treatment of disease.

1.4 Desalinating seawater

The primary product of nuclear fission is heat, and this heat can be used for purposes other than generating electricity. Nuclear desalinization plants use this heat to boil salt water because the steam that is produced can then be condensed to form fresh water for drinking. Nuclear desalinization is not a new technology; nuclear submarines and surface ships do this routinely to produce drinking water for their crews and fresh water for the engineering plant. However, this technology is not used for making public drinking water because of public response against nuclear reactors. The International Atomic Energy Agency has given this subject much study and has written several excellent fact sheets that are worth reading. Nuclear energy is not the least expensive method available for making fresh water, but it is one of the only technologies that can produce millions of gallons of fresh water daily, in virtually any part of the world that is near an ocean.

2. The Nuclear Fuel Cycle

As mentioned above, natural uranium cannot sustain a nuclear chain reaction; for this to occur, the fraction of U-235 present in the uranium must be increased from 0.72 percent to at least one percent of the total number of uranium atoms present. In reality, the uranium must be enriched further yet, because commercial nuclear reactors use fuel containing from three to six percent U-235. Some nuclear reactors, primarily those used for research, make use of fuel enriched to 20 percent U-235, and some military nuclear reactors use fuel that is nearly pure U-235 (similar to the concentrations used in some older nuclear weapons). As an aside, this means that commercial and research nuclear reactors cannot explode like nuclear bombs – it is physically impossible for them to do so because of the relatively low concentrations of fissionable uranium. This is not to say that nuclear reactors cannot experience accidents; the Chernobyl accident spread large amounts of radioactive contamination over a large area, and the reactor core at Three Mile Island was destroyed in its accident (although the release of radioactivity at TMI was minor). However, stories of commercial nuclear reactors exploding like atomic bombs are wildly inaccurate.

The process of making fuel for nuclear reactors begins when the uranium ore is mined and processed, continues through the process of uranium enrichment, and culminates with fabrication of the nuclear reactor fuel. Eventually, the U-235 in the reactor fuel is fissioned to the point at which nuclear reactions no longer occur, and the reactor is refueled so it may continue operating. The spent fuel is then either stored on site, sent for disposal, or recycled. This whole process is called the nuclear fuel cycle and is the subject of this section.

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Biographical Sketch

Andrew Karam began his radiation safety career in the Naval Nuclear Power Program, in which he was enlisted from 1981 – 1989. Following completion of his training, Andy served nearly three years as a staff instructor before reporting to the USS Plunger (SSN 595), a fast-attack submarine stationed in San Diego. During the next 3 ½ years, Andy completed 2 extended deployments to the Western Pacific and served as Leading Engineering Laboratory Technician for over two years.

Following his discharge from the Navy, Andy returned to the Ohio State University, where he completed an undergraduate degree in Geology in 1993. It was during this period that he decided to make a career of health physics.

Taking a job at the Ohio Department of Health, Andy worked primarily with DOE sites and other contaminated sites. This work fascinated him, and was one of the factors leading him to become a professional health physicist. This work, too, led him to join an environmental consulting firm, where he was the Manager of Radiological Services.

In 1996, Andy returned to graduate school to complete his MS in Geology. In keeping with his recent past, he worked full-time for the OSU Radiation Safety Office while taking classes and completing his thesis. In 1998, after completing his degree, Andy accepted a position as Radiation Safety Officer at the University of Rochester, where he has worked for nearly three years. He completed his Ph.D. in Environmental Science in 2001, again graduating from the Ohio State University.

Andy is active professionally as a past President of the Western NY Chapter, an associate editor for the HPS Newsletter, and editor of the HPS Medical Section's electronic newsletter. Andy is also a periodic contributor to ORS and the Health Physics Journal, he has contributed pieces for several other magazines and journals in the US, Europe, and Iran, and he has presented a number of lectures, papers, and posters at meetings in the US, Europe, and Asia.

Outside of work, research, and other professional activities, Andy enjoys time with his family; Kathy, Alexander, Ben, and assorted cats. He also enjoys reading, writing, photography, travel, and cooking.