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ADOPTION OF THORIUM POWER

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Abstract

Current energy generation methods used throughout the world are economically, environmentally, and physically unsustainable. Nuclear power generation is a step forward from fossil fuels, as it presents a cleaner and more sustainable option. However, due to cost and safety concerns, uranium is not the ideal nuclear fuel. Thorium is a cleaner, safer, cheaper, and more abundant alternative to uranium. This paper examines the viability of the use of thorium as a supplemental or replacement nuclear fuel. The following criteria are used to evaluate thorium's potential: environmental impact, economic feasibility, and the risk of nuclear weapons proliferation. To address these factors, this paper reviews the history of thorium and uranium fuel, the nuclear technology that is currently accessible, fuel availability, and the effects of radiation and waste from various aspects of the fuel cycle. The paper serves as a compilation and assessment of current opinions and facts about the viability of thorium energy generation as it compares to uranium energy generation.

Glossary of Terms

BWR – Boiling Water Reactor

CANDU – Canada Deuterium Uranium (reactor)

D_2O – Deuterium oxide, or heavy water

DU – Depleted uranium

GFR – Gas-cooled Fast Reactor

HEU – High-enriched uranium

HTGR – High Temperature Gas-cooled Reactor

HWR – Heavy Water Reactor

LEU – Low-enriched uranium

LFR – Lead-cooled Fast Reactor

LFTR – Liquid Fluoride Thorium Reactor

LMFBR – Liquid Metal Fast Breeder Reactor

LWBR – Light Water Breeder Reactor

LWR – Light Water Reactor

MSBR – Molten Salt Breeder Reactor

MSR – Molten Salt Reactor

MTR – Materials Testing Reactor

PBMR – Pebble Bed Modular Reactor

PHWR – Pressurized Heavy Water Reactor

PWR – Pressurized Water Reactor

RTR – Radkowsky Thorium Reactor

SCWR – Super Critical Water-cooled Reactor

SFR – Sodium-cooled Fast Reactor

THTR – Thorium High Temperature Reactor

TMSR – Thorium Molten Salt Reactor

VHTR – Very High Temperature gas Reactor

Introduction

Ever since the advent of the Industrial Age, nations in all stages of development have relied heavily on fossil fuels as a power source. Today these fuels are still widely used, despite a dwindling supply. Traditional fossil fuels also present a worrying number of issues in the world. These include threats of severe negative consequences to the environment, political structures, and economic stability.

The 1940's provided a potential solution with the advent of nuclear technology, a breakthrough that has since revolutionized the field of energy generation and set remarkable benchmarks for fuel efficiency and environmental sustainability by means of uranium-235 (U-235). However over the past 60 years it has become increasingly clear that U-235 is not the ideal solution to the world's growing energy demand. The use of U-235 has threatened to destabilize regions of the world by advancing weapons proliferation. Traditional nuclear plants also generate dangerous waste products that pose greater threats to environmental sustainability than many have thought possible. Therefore, the question remains: what fuel could possibly be utilized to help the world through the difficult transitions that lie ahead to an interconnected global society? What power source could be utilized in the near future to provide clean, safe power for the masses?

The answer may still lie in nuclear technology, in another fertile element relatively unknown to the general population: thorium. A radioactive element like uranium, thorium addresses the issues associated with uranium nuclear plants by decreasing both the quantity of hazardous nuclear waste and the potential for nuclear weapons proliferation.

Methodology

This paper sets out to address what we consider to be the three most significant disadvantages of uranium as a nuclear fuel: the costs associated with the fuel in mining, processing, and use in reactors; environmental impacts; and risk of nuclear weapons proliferation. We also see history as an important analytical tool, as we can point to various events and decisions in history that both led to uranium's use as fuel and have cast doubt on the sustainability of nuclear energy. By reflecting on this history, one can discern how thorium could address many of the concerns encountered.

The assumption has been made that nuclear energy of any type generally presents a cleaner, cheaper fuel than most, if not all, fossil fuels. Therefore we will spend the majority of the paper comparing thorium with uranium, as it is the obvious alternative fuel.

The History of Commercial Nuclear Power

Since the inception of commercial nuclear power, more than 500 nuclear reactors have been constructed in 32 countries [Cuttler 2009]. Of these reactors, 435 are still operational, accounting for nearly 370GW of electricity. As of 2012, 63 new reactors are being planned [International Atomic Energy Agency 2011]. It is estimated that 55 countries will have operating nuclear reactors by 2030 [Cuttler 2009]. The history of nuclear power development began with Enrico Fermi, who headed a University of Chicago team that built the first solid-fuel nuclear reactor in 1942 using graphite and uranium blocks. The same team constructed the first liquid-fuel reactor just two years later, using aqueous uranium sulfate as fuel [Hargraves 2010]. It is significant that this discovery happened during World War II, as it led to the utilization of nuclear reactors as factories for the production of weapons-grade plutonium [Penny 2010].

Under the direction of Admiral Hyman Rickover of the US Navy, nuclear energy was also developed for use in submarines following WWII [Hargraves 2010; Kazimi 2003]. In fact, both uranium and thorium were considered as fuel options [Kazimi 2003]. Uranium was ultimately chosen as the standard nuclear fuel because uranium-235, unlike thorium, is fissile, and so it was very easy to use in submarines. In addition, uranium fission produces plutonium-239, which can be used to make nuclear weapons [Hargraves 2010]. At the time, the possibility of weapons proliferation was a benefit and thus a deciding factor for Rickover. He decided that the first US nuclear submarine, the *USS Nautilus*, would be powered by uranium oxide fuel. The submarine took to sea in January 1955 [Hargraves 2010].

In 1957, the first commercial nuclear power plant in the US went online at Shippingport Atomic Power Station in Shippingport, PA. This reactor was modeled after the *Nautilus* and was also fuelled with solid uranium oxide [Hargraves 2010]. The year before, the United Kingdom's first commercial nuclear reactor went online at Calder Hall [Penny 2010]. The first reactor ever to produce commercial electricity had gone online in 1954 in Obninsk, USSR [Kara 2008]. Alvin Weinberg, the director of Oak Ridge National Laboratory from 1955-1973, says about nuclear power development, "At the very beginning of nuclear power, we had to choose which possibilities to pursue, which to ignore" [Hargraves 2010]. The choice to fuel the first commercial reactors with uranium oxide resulted in uranium becoming the standard fuel for nuclear power plants across the globe.

The period between the end of World War II and the end of the 1970's was a period of intense development of commercial nuclear power. Several countries adopted the technology during this time, including the United States, the United Kingdom, France, Germany, and Sweden. North America experienced the largest growth of nuclear technology in the 1970's, when Canada and the United States were constructing peak numbers of reactors. During that time the USSR also constructed the vast majority of Russia's nuclear power infrastructure, and the technology spread to the Soviet bloc in Eastern Europe and some of Central Europe [World Nuclear Association 2012].

In the case of France and Germany, nuclear energy was not a significant source of electricity until the oil crisis of 1974. After this catastrophe, it was apparent that fossil fuels were not an economically stable source of energy, thereby encouraging the development of an energy source that was not so volatile [World Nuclear Association 2011e; World Nuclear Association 2011f].

Shortly after this commercial nuclear boom, the incidences at Three Mile Island and Chernobyl resulted in a loss of approval of nuclear power. The Three Mile Island accident was caused by an equipment failure and a series of operator errors on March 28, 1979. A failure in the coolant system prompted a series of warnings and indicators that were misinterpreted by the operators of the plant [Feeney 2011]. As a result, 50% of the fuel melted, and radiation was released into the containment structure [Cuttler 2009]. However, “the radiation dose to the surrounding populace averaged only 1 millirem, and was 100 millirems at the site boundary. For comparison, chest x-ray exposure is about 6 millirems, and the natural background radiation dose was between 100 and 125 millirems per year in the area” [Feeney 2011].

On April 26, 1986, a failed reactor test in Chernobyl, Ukraine caused a reactor core to melt down. Six tons of radioactive nuclear fuel leaked out of the reactor. This leak represented 50-60% of the reactor’s total radioactive material. It was made clear to investigators of the accident that the reactor did not have enough safety features or adequate safety protocol to prevent the release [Cuttler 2009]. According to a 1987 news article, “31 people were killed, 300 suffered acute radiation illness, and a total of 18,000 were briefly hospitalized. Soviet officials have said that a total of 135,000 people had to be evacuated from the area” [*United Press International* 1987].

Public opinion was drastically shifted as a result of these accidents. Prior to the Three Mile Island accident, 61% of the American public was in favor of the use of nuclear power. A poll conducted in May of 1986 (just after the Chernobyl disaster) showed that only 19% of people were in favor of nuclear power [Holyk 2011].

The Chernobyl meltdown caused opposition to nuclear power to rise “from 65% to 83% in Britain, from 46% to 83% in West Germany, from 40% to 74% in Yugoslavia, from 33% to 64% in Finland, and from 67% to 78% in the United States” [*United Press International* 1987]. French citizens were still only 52% opposed to nuclear power after the incident, a fact that is attributed to the high French investment in nuclear power.

World governments reacted in similar fashion. After the Chernobyl accident, Austria, Sweden, and the Philippines discontinued the use of nuclear power, and Greece discontinued nuclear research [*United Press International* 1987]. In contrast, not all reactions to Chernobyl were overtly negative. In a 1986 economic summit meeting in Tokyo, seven leaders of the Western world “declared that ‘properly managed’ nuclear power [would] continue to produce an increasing share of the world’s electricity” [Blix 1986]. Soviet Premier Mikhail Gorbachev later stated that the economic future can “hardly be imagined without the development of nuclear power” [Blix 1986].

Hans Blix made the point in a 1986 article that the Chernobyl disaster, and other such accidents, could be a great learning experience rather than a cause of opposition. Nuclear workers voiced their opinion that the risks of nuclear power generation are acceptable, and could be compared to the risks associated with air travel. Even at this time, nuclear power was heavily ingrained in the world power makeup, as 15% of all energy was generated through fission, and some countries were heavily invested. Therefore, Blix said, nuclear power was “not going anywhere” [Blix 1986]. In response to the question of proliferation risk, Blix pointed out that “nuclear weapons technology is sufficiently well known today for any state with a developed industrial and scientific infrastructure to manufacture such weapons if it is prepared to devote the necessary time and resources to their manufacture" [Blix 1986]. He later added that "the first and foremost barrier to horizontal proliferation thus lies in the political will of governments to forego the nuclear weapons option and their readiness to enter commitments to that effect" [Blix 1986].

Between 1986 and today, nuclear power slowly came back into public acceptance. No major nuclear accidents occurred between the Chernobyl explosion and the Fukushima disaster. For this reason, it is clear that the public became more confident about nuclear power. In a February 2011 survey, 67 percent of Americans considered nuclear power plants to be very safe, compared with 34 percent in 1987 [Bisconti Research Inc. 2011]. NC State University indicates that this trend exists in a similar fashion in Europe, where the only exceptions are France and Japan. French opinion on the subject remains consistent, while Japan experienced a drop of public approval due to minor nuclear accidents and a distrust of public officials [Vohlers et. al.]. In short, people had only just begun to forgive the nuclear industry for Chernobyl when another accident occurred halfway across the world [Moulds 2011].

On March 11, 2011, a large earthquake struck Japan, forcing the shutdown of the nuclear reactors at the Fukushima power plant. While the shutdown was successful, the earthquake's resulting tsunami caused a power failure, which took the plant's cooling systems offline. Four reactors then overheated and released radioactive material to the environment [Butler 2011]. The scope of the disaster is still not fully known.

The Fukushima incident comes after a 25-year record of nuclear safety since the Chernobyl accident. In this period of time, nuclear power was enjoying a surge in confidence.

Members of the European Union used nuclear power to generate 31% of their electricity in 2010, and efforts were being made to increase this percentage through increased nuclear capacity. While Germany and Sweden had been tapering off their nuclear dependence, and Italy and Poland had sworn off nuclear power, these countries were looking into an increased nuclear capacity before the 2011 accident [*Forbes* 2011].

The accident at Fukushima had a noticeable effect on the Asian nuclear scene. Japan has halted plans to build new reactors, and has instead begun reevaluating its nuclear strategy. As it stands, Japan generates 30% of its total electricity from nuclear power [Dempsey 2011]. China has put plans for 110 new reactors on hold [Moulds 2011]. Kenya, which is aggressively pursuing a nuclear power program, has been met with questions regarding the safety of its infrastructure and the ability of its population to create a nuclear energy system essentially from scratch [Mugoh 2011]. Kenya has not stopped its program but has instead looked at Fukushima as a valuable learning experience and safety guide [Mugoh 2011].

Most major European powers have been swayed in some way by the incident in Japan. Italy has in the past relied mostly on natural gas to fulfill its energy needs, along with nuclear-generated electricity that it buys from France. The country generates no nuclear energy of its own. Italians voiced their opinion of nuclear energy in the 2010 Eurobarometer survey, in which 62% of the population opposed an Italian nuclear generation program. The anti-nuclear movement in Italy is very vocal, and it cites seismic activity in Italy as a reason to stay away from nuclear power [*Forbes* 2011].

Germany has closed seven of its seventeen nuclear plants as a result of the Japanese disaster [Moulds 2011]. Germany considers nuclear power to be a “bridge technology,” as the country plans to utilize the technology only until it can develop a more favorable energy source [Dempsey 2011]. New technology notwithstanding, Germany plans to completely replace nuclear power as an energy source by 2022 [Butler 2011]. Surely, German apprehension is motivated by the country's "nearly 50-year status as the likely nuclear battlefield between the Cold War superpowers" [*Forbes* 2011].

The current UK government looks favorably upon nuclear power and wishes to build about ten additional reactors by 2020 [*Forbes* 2011]. This new reactor development comes with the caveat that all new nuclear plants must be privately funded without any government subsidy [Butler 2011]. The country currently only generates 18% of its power from nuclear energy and has built only one reactor since 1986. This lack of nuclear development has come as a result of sizeable opposition by British citizens. However, the Norwegian natural gas that Britain has relied upon for decades is dwindling, and a new approach to energy generation is being seen as more and more necessary. The UK sees the Fukushima disaster as a lesson in preparedness, and British Energy and Climate Change Secretary Chris Huhne has ordered an investigation on the lessons of Fukushima as they apply to the UK [*Forbes* 2011].

Sweden imposed a government ban on nuclear power in 1980 following the Three Mile Island incident. The ban was overturned in 2010 by a 174-172 vote. Nuclear power in Sweden does not have the negative connotation that it has in many other nations, as the country held an independent weapons program in the 1950s along with a policy of neutrality. Since Sweden's hydropower plants are insufficient for the country's needs, and the government does not want to increase greenhouse gas levels, Sweden has turned to nuclear power. The Fukushima incident does not appear to have swayed the Swedish government [*Forbes* 2011].

In Poland, nuclear power is seen as “a way to escape dependence on Russian natural gas exports” [*Forbes* 2011]. Prime Minister Donald Tusk has stated that Poland has “no intention of abandoning its plans for nuclear energy” after the accident in Japan [*Forbes* 2011].

In 2010, France generated 74% of its electricity from nuclear power. This heavy investment, paired with the fact that no French nuclear reactor manufacturer has ever experienced an accident, makes France the “most committed nuclear power user” [*Forbes* 2011]. French nuclear development slowed as a result of the two twentieth century accidents, as France has only built three new plants since 1979. Due to a 2010 figure of 37% public opposition to nuclear power in France, no additional development appears to be on the horizon for France [*Forbes* 2011].

In a meeting on March 15, 2011, the EU energy ministers unanimously agreed to test the earthquake endurance of all European reactors as well as the safety of the reactors in the event of tsunamis, heat waves, power cuts, and terrorism [*Forbes* 2011].

A 2011 article in Environmental Magazine identifies five frames through which the public sees nuclear power and its use. The first frame is that of “progress.” Through this frame, we see nuclear power as a technological marvel that can either lead us to good and peaceful energy generation or to warfare. Second, society sees nuclear power in a light of “energy interdependence.” This frame appeared during the oil shortage of the 1970’s but is certainly just as relevant as ever in modern context [Butler 2011].

The third frame encompasses three perspectives, each of them anti-nuclear in nature. The first of these, entitled “soft paths,” demands a view of nuclear power that is based on where it leads society in terms of energy wasting and environmental insensitivity. “Public accountability" is the second piece of the third frame, and it "emphasizes an anti-corporate message." The "not cost-effective" piece rounds out the third frame and is self-explanatory [Butler 2011].

The fourth frame, described by the word "runaway," calls for society to "grin and bear" nuclear power instead of opposing it. The final frame is of a "devil's bargain." This frame combines the "progress" and "energy interdependence" narratives with the "runaway" frame [Butler 2011].

Table A1 lists news reports regarding the Fukushima disaster and how they fit into the framework described above.

Development of Uranium Reactors: A General Overview

Uranium reactors are categorized by generation. The first generation consisted of prototypes, which were designed to be cheap to build and to operate [Penny 2010]. Generation II saw the advent of more advanced designs such as the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) [Penny 2010]. These were the first of the commercial reactors; in fact, most of today's operating nuclear reactors are of this second generation [Kara 2008]. Generation III reactors are essentially Generation II reactors with improved thermal efficiency and safety features [Penny 2010]. Presently, many are being built or planned, and some are in operation [Kara 2008].

Meanwhile, engineers are already studying a new generation of reactor designs. These Generation IV designs are intended to be starkly different from the more familiar designs of the second and third generation because of heightened concerns associated with nuclear energy production. These concerns include energy sustainability, increased safety, waste reduction, proliferation-resistance, and cost-competitiveness [Penny 2010]. Research and development of these designs was endorsed by the US Energy Act of 2005 [*US Congress* 2005]. Just five years before, the United States launched the Generation IV initiative in an effort to increase international cooperative efforts toward the study of these designs. Members include the US, the UK, Japan, France, China, Canada, and Brazil [Kara 2008].

In 2002, The Generation IV International Forum (GIF) narrowed its focus to six reactor designs that could be implemented commercially by 2030 [Kara 2008]. Both uranium and thorium may be used in Generation IV reactors, but uranium is currently preferred because it is the more familiar fuel. More is known about its performance in reactors, the fuel cycle infrastructure already exists, and fuel is still available [The Generation IV International Forum 2010].

Generation IV reactors generally have not been designed specifically for thorium. An exception is the MSR, which has been effective when thorium fuel is utilized. This design, along with fast breeder reactors and high temperature reactors, would be the best options for thorium fuel [Kara 2008].

Table 1 summarizes the different types of Generation IV designs under investigation as of 2007.

System	**Neutron Spectrum**	**Coolant**	**Operating Temperature (°C)**	**Fuel Cycle**	**Size (MW_e)**
GFR	Fast	Helium	850	Closed	1200
LFR	Fast	Lead	480-800	Closed	20-180 300-1200 600-1000
MSR	Epithermal	Fluoride salts	700-800	Closed	1000
SCWR	Thermal/fast	Water	510-550	Open/closed	300-700 1000-1500
SFR	Fast	Sodium	550	Closed	30-150 300-1500 1000-2000
VHTR	Thermal	Helium	900-1000	Open	250-300

Table 1: Generation IV Reactors [Kara 2008]

The Gas-cooled Fast Reactor (GFR) has a self-generating core and high efficiency. It operates at very high temperatures, and on-site fuel reprocessing is feasible [Kara 2008].

The Lead-cooled Fast Reactor (LFR) can be operated as a breeder, as a burner of actinides from spent fuel, or as a burner/breeder hybrid if thorium fuel is used. It could be commercially viable by 2025 [Kara 2008].

The Molten Salt Reactor (MSR) design has the unique feature of using liquid fuel. It can be used to burn transuranic elements from spent LWR fuel and has breeding capabilities. It also produces very little waste [Kara 2008].

The Supercritical Water-cooled Reactor (SCWR) operates at high temperature and high pressure. The plant design is simple and economical because the water is a one-phase coolant. A prototype of this design is expected by 2022 [Kara 2008].

The Sodium-cooled Fast Reactor (SFR) is characterized by a liquid sodium coolant and very high power density. This design has been researched extensively by many countries, and deployment may be possible by 2020 [Kara 2008].

The Very High Temperature Reactor (VHTR) uses a helium coolant and a graphite moderator, and it has the potential for hydrogen production [Kara 2008]. The Pebble Bed Modular Reactor (PBMR), which in many ways parallels the VHTR, is being studied in South Africa. These studies may help with the design and optimization of the VHTR [Ion 2003].

In general, the SFR and VHTR are the most popular designs among the GIF. The LFR and MSR are not as widely researched [Kara 2008]. The United States is especially interested in the SFR and VHTR. The VHTR holds the priority because of its potential to produce hydrogen. The Idaho National Laboratory is the frontrunner for Generation IV activities in the US [US Department of Energy].

Research and Development of Thorium Nuclear Power

Although uranium had been established as the standard fuel in commercial reactors by 1957, scientists continued to study thorium-based fuels. Between 1945 and 1960, in the wake of the Manhattan Project, many US laboratories studied the thorium fuel cycle with the goal of using uranium-233 in nuclear weapons [Lung 1998]. President Eisenhower's Atoms for Peace Program, which lasted from 1955 to 1975, encouraged further research into thorium as a complement to uranium in commercial reactors [Lung 1998]. Several US companies and institutions supported thorium research during this time, including the Oak Ridge National Laboratory, General Atomics, Babcock and Wilcox, Allis Chalmers, and Westinghouse [Lung 1998]. Thorium research was not limited to the United States, however. Table 2 gives statistics of experimental and commercial thorium reactors as well as where they were constructed.

Name	**Country/ Corporation**	**Period of Operation**	**Type**	**Thermal Power (MWt)**	**Electrical Power (MWe)**	**Coolant**	**Purpose**
AVR	Germany	1967-1988	HTGR	46	15	Helium	Experimental
THTR	Germany	1985-1989	THTR	750	300	Helium	Commercial
Lingen	Germany	1973	BWR	-	60	Helium	Irradiation testing
Dragon	UK, Norway, Switzerland, Sweden	1966-1973	HTGR	20	-	Helium	Experimental
Elk River	US/ Allis Chalmers	1963-1968	BWR	-	24	Light water	Experimental
Indian Point	US	1962-1980	PWR	-	285	Light water	Experimental
Peach Bottom	US/General Atomics	1966-1972	HTGR	-	40	Helium	Experimental
Fort St. Vrain	US/General Atomics	1976-1989	HTGR	842	330	Helium	Commercial
Molten Salt Reactor Experiment (MSRE)	US	1964-1969	MSBR	7.5	-	Molten salt mixture	Experimental
Shippingport	US	1977-1982	LWBR, seed-blanket assembly	-	100	Light water	Commercial
SUSPOP/ KSTR	Netherlands	1974-1977	Used uranium/ thorium oxide micro-particles	1	-	-	Commercial
NRU and NRX	Canada	-	MTR	200	-	Heavy water	Research
KAMINI	India	Operational	MTR	30	-	Demineralise of water	Research
KAPS	India	-	PHWR		220	Heavy water	Commercial
FBTR	India	Operational	LMFBR	40	13.2	Liquid sodium	Breeder (uses weapons-grade Pu)

Table 2: Statistics of Thorium Reactors (Sources: Penny 2010, Lung 1998, Kazimi 2003)

Many of these reactors operated successfully, which heightened enthusiasm regarding the thorium fuel cycle [Lung 1998; Penny 2010]. In fact, thorium was touted as a promising new fuel at the International Fuel Cycle Evaluation Conference of 1978, and conference officials even predicted that it would one day be utilized as extensively as uranium [Lung 1998].

However, some experiences with thorium power stunted its development and prevented widespread commercial adoption. There were “costly technological incidents” at the THTR reactor in Germany, which was built after the success of its AVR reactor [Lung 1998]. An obstruction in the fuel assembly caused radioactive dust to leak into the atmosphere, and the reactor was subsequently shut down. As this occurred shortly after the Chernobyl incident, it was decided to forego further thorium research in Germany in an effort to be consistent with the public’s distrust of nuclear power [Penny 2010].

A similar political climate in the UK stalled thorium research after its Dragon reactor was shut down in 1973. Although the experimental reactor performed successfully, the decommissioning process was very expensive, leading political officials to doubt thorium’s promise [Penny 2010].   In general, several factors discouraged additional thorium research around the 1980s [Lung 1998]. At the time, thorium simply could not compete economically with uranium because thorium technology was not as well understood or as well established as uranium technology [Kara 2008]. The success of the early thorium experiments was simply not enough to guarantee increased commercial use; the nuclear industry would have had to use considerable funds to adapt to the unique problems of the thorium fuel cycle [Lung 1998].

Thus, it would have taken a substantial effort to establish thorium as a commercial fuel, and politics were not leaning toward the development of any new nuclear technologies after the catastrophe at Chernobyl in 1986. There was also increasing concern regarding the proliferation risk associated with the reprocessing of spent thorium fuel [Kara 2008]. Without political support and funding, there was very little hope that thorium technology could be further developed at this point [Kara 2008].

The only country that continued to investigate the thorium fuel cycle is India, which has a long history of support for thorium-based nuclear power. Experiments have been constantly conducted for at least the past 20 years, with plans for a three-stage nuclear program set in 1993 [Chidambaram 1994]. This behavior was not unexpected, as India's natural reserves of thorium are quite abundant, estimated to have the capacity to power the entire country for 244 years. In addition, they lack many other traditional fossil fuels as well as a useful supply of uranium [Chidambaram 1994]. India's plan has always been to be fuel-independent and to not have to rely on other nations to supply resources or power to maintain a stable energy infrastructure.

In 1969, India developed its first nuclear reactor at Tarapur, in the Maharashtra province [Chidambaram 1994]. As of 2001, there were sixteen such reactors around the country. India's hopes for a nuclear future involve a three stage plan to construct a thorium-based energy solution. The first stage is a series of pressurized heavy-water reactors, the second is a set of liquid-metal fast breeder reactors, and the third will be to create thermal breeder reactors that will run off an optimal uranium-233 and thorium-232 fuel cycle [Chidambaram 1994].

India is currently just entering the second stage of their plan. The only commercial thorium powered nuclear reactor currently in operation is a heavy-water reactor at the Bhabha Atomic Research Centre (BARC) in Mumbai. The plant is owned and operated by the Nuclear Power Corporation of India Ltd., a government-owned subsidiary [Rahman 2011]. The plant is a heavily modified Radkowsky design and the reactor was built specifically for thorium use. It contains specially designed safety features. These include removing core heat passively through circulation of coolant beneath the reactor, passive shutdown measures to prevent meltdowns, and a neutron poison that is automatically injected into the uranium seed to stop the reaction if there is a failure. These safety features allow the reactor to be built close to the population with minimal risk to the residents [Chidambaram 1994].

The designers claim that the reactor will be operational for about one hundred years at an output of 300 megawatts, the current power output. This is in stark contrast to standard reactors, which have a design life of about 40 years. Fuel will have to be replaced twice in the lifetime of the reactor, which could occur in standard annual shutdowns [Singh 2008].

The fuel cluster in the reactor is comprised of 54 fuel rods arranged in three concentric rings around the central seed rod. The 24 pins in the outer ring have thorium or plutonium for fuel, and the 30 pins in the inner and middle rings have thorium and uranium-233 for fuel. Placing the plutonium pins on the outermost ring minimizes the required amount of plutonium. In total, thorium produces about 60 percent of the reactor's power [Singh 2008]. Although India has a long way to go before they reach stage three, many proof-of-concepts and small scale tests have been performed along the development of their nuclear program, and confidence is high that their plans will be realized.

In recent years, thorium power has again come under extensive investigation because of the inherent proliferation resistance of thorium fuel. Fears of nuclear weapons proliferation by countries like North Korea and Iran have necessitated a solution to the proliferation problems of conventional nuclear power [Kazimi 2003]. One potential solution to the proliferation dilemma would be to develop Generation IV reactors that run on uranium fuel, but researchers in many countries are also studying the performance of thorium fuel in these reactors [Penny 2010].

Although France’s nuclear program is based on the use of uranium fuel, there has been some French research on the thorium fuel cycle. Led by Roger Brissot, The Reactor Physics Group of the Laboratoire de Physique Subatomique et de Cosmologie in Grenoble has been conducting MSR experiments since 2002. This marks the start of the Thorium Molten Salt Reactor (TMSR) Project [Hargraves 2010; Evans-Pritchard 2011; Kara 2008]. Japan has also carried out MSR research; their experiments have been going on since the 1980’s [Kara 2008]. The latest project is what is known as the Fuji reactor, which is an MSR that can run entirely on thorium or on a mixed fuel containing thorium and uranium or thorium and plutonium [*Next Big Future* 2007]. As of 2007, the Japanese planned to develop a miniature reactor within 8-9 years and a commercial reactor within 12-15 years [*Next Big Future* 2007]. The projected costs for such a reactor are 20-25% less than for a typical PWR [*Next Big Future* 2007]. However, as of the time of this writing, the project is stalled awaiting significant funding, and a timeline is not in place for construction or completion [Shimazu 2011].

Meanwhile, Canada has been testing the thorium fuel cycle in CANDU reactors. Like the United States, Canada has considered the use of thorium in nuclear reactors since the 1950’s [Hastings 2009]. Atomic Energy of Canada Ltd (AECL) has done extensive research on several aspects of the thorium fuel cycle, specifically fuel fabrication and waste management. They have found that “thorium fuel [shows] comparable or superior performance” compared to uranium oxide in experiments with CANDU reactors [Hastings 2009]. The nature of the CANDU reactor works very well with the thorium fuel cycle. The reactor can run on virtually any type of nuclear fuel and can be refueled while operating at full capacity [Boczar 1998]. AECL is very enthusiastic about their results and suggests that the use of thorium in CANDU reactors would be a good way to guarantee a long-term supply of nuclear fuel [Boczar 1998].

Russia established a program in the early 1990's to develop a thorium-uranium or thorium-plutonium fuel to use in the burning of excess weapons-grade plutonium. The program is a partnership between the Kurchatov Institute and the American company Lightbridge, formerly Thorium Power Ltd [Kara 2008].

Several emerging nuclear powers are also considering thorium fuel. A South African-led consortium is studying the Pebble Bed Modular Reactor (PBMR) and the US and China are both working separately to develop a similar design. There is some concern that the current incarnation of this design would produce large quantities of long-lived radioactive waste [*Next Big Future* 2007].

China also has other plans. The country has launched a research program based on initial American MSR research, and it is working with AECL in Canada to assess the use of thorium fuel in its several CANDU reactors [Pottinger 2011; World Nuclear News 2009]. In addition, Aker Solution, a Norwegian company, is planning to build a sub-critical accelerator-driven reactor in China after buying a CERN accelerator patent [Evans-Pritchard 2011].

Norway itself is more reserved in its plans for thorium implementation. According to a 2008 report published by a Norwegian committee, the option of implementing commercial thorium power should "be kept open in so far it represents an interesting complement to the uranium option to strengthen the sustainability of nuclear energy" [Kara 2008]. To this end, the committee recommended that Norway stay abreast of current thorium research, work with other European nations to research thorium, and be prepared to use thorium to supplement other carbon-free energy sources if needed. Because Norway has abundant thorium reserves, the country is interested in a possible thorium energy solution but currently has no plans to implement the necessary infrastructure [Kara 2008].

Opposition to Thorium Nuclear Power

Opposition to thorium nuclear power is a complex topic. People may stand against thorium because of a distrust of nuclear power, or they may embrace thorium for the same reason. Therefore, nuclear accidents may have either a reinforcing or a diminishing effect on thorium opposition.

For an accurate assessment of where opposition to thorium stands, we can turn to the UK National Nuclear Laboratory. The UK NNL's August 2010 position paper on thorium starts by pointing out that "the only realistic prospect for deploying thorium fuels on a commercial basis would be in existing and new build LWRs" [Hesketh 2010]. The report elaborates that "new build" nuclear power plants (such as the MSR) would only be feasible in the longer term, "of the order of 40+ years minimum" [Hesketh 2010].

The report cites the reasonably-low current price of uranium as the reason that countries have little interest in thorium and little reason to implement the technology. However, India's implementation is described as "understandable" because of the Indian lack of uranium resources and prevalence of thorium. The authors do not believe that seed-blanket thorium PWR's will be cheaper than uranium reactors unless uranium prices ascend a great deal, which does not look likely for the foreseeable future [Hesketh 2010].

Furthermore, the NNL points out that the thorium fuel cycle is only sustainable if thorium waste is reprocessed at a remote plant and that this reprocessing “present[s] very large technological, commercial and risk barriers, each with a significant cost component.” Even if the waste is not reprocessed, the thorium fuel cycle is only marginally beneficial over the uranium cycle. As an example, the NNL states that the seed-blanket design only represents a 10% reduction in uranium input [Hesketh 2010].

Since uranium is still required for the fuel cycle, there will always be a significant amount of plutonium produced, even if that amount is reduced. The NNL feels that the proliferation-proof nature of the thorium cycle is “over-stated,” and that “thorium systems are no more proliferation resistant than U-Pu systems though they may offer limited benefits in some circumstances” [Hesketh 2010]. Reduction in the radio-toxicity of waste for the thorium cycle is also thought by the lab to be too small to warrant a change, unless the waste is recycled. In this case, the reduction in radio-toxicity would be significant [Hesketh 2010].

In light of this information, the National Nuclear Lab does not feel that LWR and PWR power suppliers would find a switch to thorium power to be economically wise. The technology would need to be further researched and developed [Hesketh 2010].

Technical Aspects of Thorium and Uranium Mining, Fuel Cycle, and Reactors

Mining and Processing

Uranium

Uranium is mined both above and below the earth's surface. The ore is sent to a mill, crushed into slurry, and is then treated with sulfuric acid to extract pure uranium. Concentrated U_3O_8 (uranium oxide) is precipitated from this reaction. Approximately 200 tons of U_3O_8 are required to run a 1000 MW plant for one year. The U_3O_8 is converted to UF_6 (uranium hexafluoride) before enrichment [World Nuclear Association 2011d].

In the enrichment process, the UF_6 is separated into two streams. One stream passes to the next level, as it is sufficiently enriched in its U-235 level. The second stream, called "tails," is mostly U-238 and is not used for energy generation. Enrichment is typically carried out by using rapidly-spinning centrifuges [World Nuclear Association 2011d].

After the UF_6 is enriched, it is converted to UO_2 (uranium oxide) powder in a separate refinement plant and is then compressed into pellets. These pellets are placed in zirconium alloy or stainless steel tubes, which are sealed and grouped in clusters for use in the reactor core. It takes twenty-seven tons of completed fuel to power a 1000 MW reactor for one year [World Nuclear Association 2011d].

Thorium

The phosphorous mineral monazite is the major source of thorium in the earth's crust. It is found in many types of sand and is mined in an open pit. Monazite is separated from other minerals in the sand by a series of physical and chemical processes, as shown in Figure A2. The products of these processes are 98% pure monazite concentrate and thorium tailings [Penny 2010].

After the pure monazite is extracted from sand, thorium is extracted from monazite. There are two generally used methods to accomplish this. The first is the acid method, in which sulfuric acid is used to obtain a thorium phosphate precipitate and lanthanide sulfate residues. This process produces a large amount of waste and is not considered to be very cost-efficient or safe [Penny 2010].

The other method is alkaline-based. Sodium hydroxide is used to obtain thorium oxide through a series of chemical reactions. The thorium oxide produced from this process is essentially pure [International Atomic Energy Agency 2005]. This method also produces much less waste than the acid method and is especially useful because many thorium reactors use thorium oxide as fuel [Penny 2010].

Research is also ongoing in India to develop an economical and safe method to extract thorium using alkyl amines, a class of nitrogen-containing organic compounds. This method produces 99.8% pure thorium from monazite and 99.4% pure uranium when the process is applied to uranium ore tailings [Penny 2010].

Further processing and refinement is unnecessary once the thorium has been extracted from monazite. In contrast, low grade uranium ore only contains up to 0.25% uranium oxide, and high grade ore is approximately 23% uranium oxide. For this reason, uranium ore must be refined and enriched after extraction, resulting in 75% uranium oxide, otherwise known as "yellow cake uranium." Thorium has only one naturally occurring isotope, so isotopic separation is also unnecessary [Penny 2010].

Fuel Cycle

Uranium

In all uranium power cycles, enriched U-235 is bombarded with neutrons, which causes atoms to split in two. If proper alignment is attained this initial fission causes a chain reaction that emits a large amount of energy [World Nuclear Association 2011d].

Thorium

Properties

Although thorium is radioactive, it is not inherently fissile, which means that it cannot undergo fission alone. However, thorium is a fertile element. As the name suggests, it can be transformed, or 'grown,' by chemical means into an element that can undergo fission. In this case, that fissile element is uranium-233. Once this transformation from thorium to uranium is achieved, U-233 can undergo fission and release energy [Penny 2010].

Three reactions are needed to exact this transformation and are shown schematically in Figure 1.

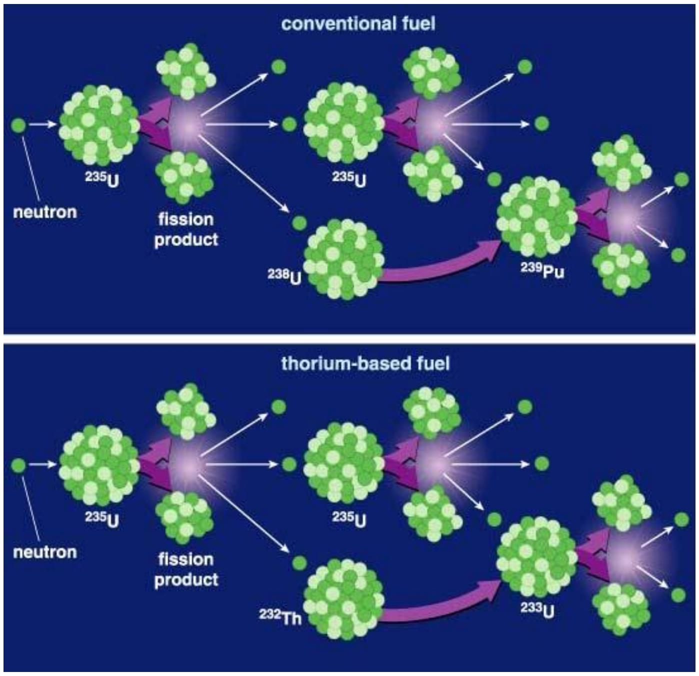

Figure 1: Conventional Uranium Fuel Cycle vs. Thorium Fuel Cycle in a RTR [Kazimi 2003].

In the first reaction, Th-232 absorbs a neutron, forming Th-233. The Th-233 then forms protactinium-233, or Pa-233, by emitting an electron. This reaction takes about four hours to reach completion. During the final reaction, Pa-233 transforms into U-233. This is a much slower reaction taking about ten months to occur [Juhasz 2009]. Pa-233 is also a neutron absorber, meaning that it can steal neutrons from other particles that could be used for further fission of U-233. There is therefore an inherent storage requirement for the Pa-233 produced [Penny 2010].

A deceptively negative issue with thorium is that the isotope U-232 is always found in conjunction with the U-233 produced because it is a side product of the reaction sequence. U-232 needs to be handled carefully, as it emits harmful gamma radiation. This apparent drawback also serves as an advantage of the thorium fuel cycle because it makes weapons proliferation using U-233 less attractive. Not only does U-232 present an immense danger to those handling it, but the process of removing U-232 from U-233 is extremely hazardous, [Penny 2010]. U-233 alone is actually a great fissile material and would perform well in nuclear weapons, but the inherent presence of U-232 makes weapons proliferation unappealing and tremendously dangerous [Lung 1998].

Fuel Fabrication

Speaking generally, the manufacturing of thorium-based nuclear fuels is similar to making uranium-based fuels. However, some thorium-based fuels contain uranium-233, which requires high-intensity shielding and remote or automated handling because of gamma emissions. Moreover, manufacturing fuel containing this harmful uranium isotope is often not feasible [Majumdar 1998] or cost-effective [Lung 1998]. In addition, any fabrication process that involves the production of fine radioactive dust or powder requires automation. The production area also needs to be well-ventilated and hermetically sealed [International Atomic Energy Agency 2005]. However, the operator may be in contact with the fuel material if it contains only naturally occurring U-235 and/or Th-232, which both emit low-level alpha radiation and are not overtly harmful if the operator is well-protected [International Atomic Energy Agency 2005].

Thorium-based nuclear fuels can either be fabricated in pellet or particulate (microsphere) form via numerous methods [International Atomic Energy Agency 2005]. The most straightforward process is the powder-pellet route, which involves cold pressing and high-temperature sintering [International Atomic Energy Agency 2005]. This method produces highly dense green pellets containing a mixture of ThO_2 and either PuO_2 or UO_2 [Majumdar

1998]. It also results in the production of fine radioactive dust that can easily settle on surfaces in the fuel fabrication facility [Majumdar 1998]. Thus, frequent decontamination of the facility would be needed to reduce employee exposure as much as possible [Majumdar 1998]. Automation of the process would be preferable; however, it is difficult to do so with this method [International Atomic Energy Agency 2005].

Other fuel fabrication methods can be easily automated. The vibro-sol method is used to manufacture fuel microspheres using uranium, plutonium, and thorium nitrate solutions as starting materials [International Atomic Energy Agency 2005]. Vacuum impregnation takes place in a shielded facility, so it can be automated [Majumdar 1998]. The sol-gel microsphere pelletization process produces no radioactive dust or aerosols and according to the IAEA in 2005 is "ideal for manufacturing {…} thorium-based and U-233 and Pu bearing fuel pellets for nuclear power reactors" [Majumdar 1998]. In any case, it is estimated that the production of thorium mixed oxide fuel is about twice as expensive as that of uranium oxide fuel, but the absence of the need for enrichment may offset the fabrication costs [Lung 1998].

Nuclear Reactors

Uranium

Light Water Reactors (LWR)

The two most widely used types of uranium reactors are the Pressurized Water Reactor and the Boiling Water Reactor. Both reactor types are classified as Light Water Reactors (LWR's) as they use "light water" (unmodified H_2O) as a moderator and a coolant for the reaction [Nave].

Pressurized Water Reactor (PWR)

In a pressurized water reactor (PWR), pressurized water is used to carry heat from the reactor core to a steam generation chamber. The generated steam is carried through a steam pipe to the turbine, which is connected to a generator. This generation process is what creates electricity from the nuclear reaction. The steam is then condensed into water and pumped back into the steam generation chamber. The fuel assemblies are cooled by water, which is pumped electrically using power from the electrical grid, though backup systems are implemented that use diesel power to run the cooling pumps [US Nuclear Regulatory Commission 2011b].

Boiling Water Reactor (BWR)

In a boiling water reactor, water is run through the core and is heated by the reaction process until it boils. The boiling water is channeled out of the core and into a moisture separation chamber, where excess moisture is removed from the steam. The steam is then channeled through the turbine which, in turn, powers the generator. The remaining steam is condensed and returned to the core. The reactor core is cooled in the same manner as in the PWR [US Nuclear Regulatory Commission 2011a].

Heavy Water Reactor (HWR)

Heavy Water Reactors (HWR's) differ from LWR's in their use of heavy water (deuterium oxide, or D_2O) rather than natural light water for reactor core moderation. They are also capable of using cheaper, less enriched fuel than LWRs. A good example of an HWR is the

Canadian-developed CANDU reactor, which is fueled by a combination of natural uranium and uranium oxide. Heavy water is pumped through the reactor core, where it is heated. The heavy water pipe runs through a steam generator, where light water boils. The steam is channeled through a turbine, and then condensed and returned to the steam generator [Gonyeau 2003].

Thorium

Modified Light Water Reactors: The Radkowsky Thorium Reactor (RTR)

With a few modifications, thorium fuel can be used in existing reactors. The most common and promising implementation of this methodology is the Radkowsky Thorium Reactor (RTR) design. This design is a new fuel management paradigm, as opposed to a reactor design; therefore minimal changes are required to enact the process in existing light water uranium reactors [Radkowsky].

In the RTR, a thorium ‘blanket’ is used as the primary fuel. A ‘seed’ of uranium is put in the center of the blanket and showers the blanket with neutrons to begin the fission reaction. A very small amount of U-235 is used to provide neutrons to the thorium blanket, which produces plutonium and uranium as it reacts [Radkowsky]. The reaction is inherently proliferation-proof, as all of the fissile material is burned during the reaction. It is also unusable if removed mid-cycle because the fuel is denatured as it is consumed [Radkowsky]. The thorium blanket lasts for about nine to ten years, producing about one hundred gigawatts of electricity over that time [Radkowsky].

There are numerous benefits of the RTR design. One of the highest touted consequences of using the design is that the reactor produces very little waste that could be used in a weapon. The plutonium isotopes produced are mostly Pu-238, Pu-240, and Pu-242, all of which are difficult to use for a nuclear weapon [Kazimi 2003]. They have very large heat emissions, greatly complicating weapon designs. The amount of physical plutonium waste is also reduced significantly. The waste is less in mass than a standard uranium reactor, and also reduced in toxicity, radioactivity, and heat emissions [Kazimi 2003]. A standard uranium light water reactor will produce about 250-300 kg of enriched plutonium during its fuel cycle, a large problem for proliferation concerns, as only 5-7 kg of enriched plutonium are required to make a nuclear weapon [Kazimi 2003]. The Radkowsky design, in contrast, produces eighty percent less plutonium (92 kg/GW-year instead of 232 kg/GW-year), with almost none of it able to be readily used in a weapon. In order to be suitable for weapons production, the plutonium used "must be rich in the isotope Pu-239 and should have little of the highly radioactive isotope Pu-238" [Kazimi 2003]. A typical uranium reactor produces virtually none of this radioactive isotope, so weapons proliferation using spent uranium fuel is relatively straightforward. Spent fuel from RTRs, on the other hand, is not at all suitable for weapons production because of the higher percentage of Pu-238 in the waste [Kazimi 2003].

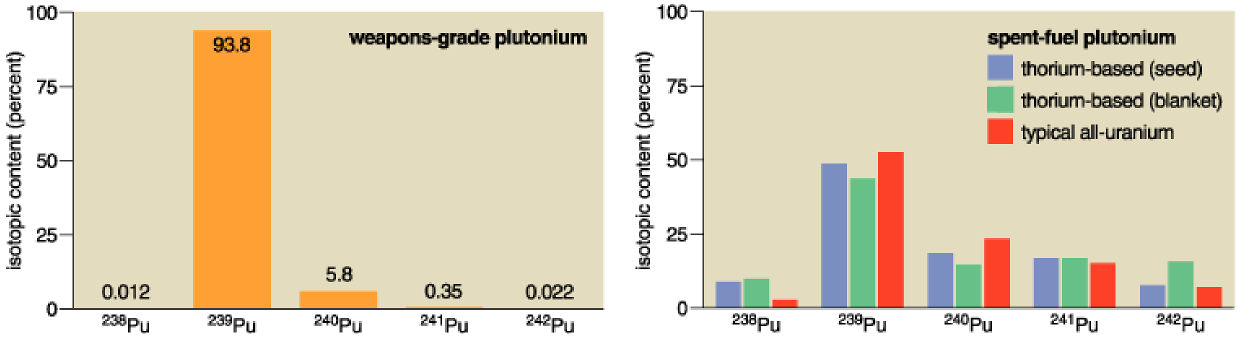

Figure 2: Production of Plutonium Isotopes from a conventional water-cooled uranium reactor (left) and an RTR (right) [Kazimi 2003].

There are also economic advantages to using the Radkowsky seed-blanket fuel design. As it is a fuel system design, it can be implemented in every light water reactor currently in service today with virtually no changes [Radkowsky]. Fuel costs will drop by about twenty percent due to the lack of waste, reduced amount of uranium used, and forgoing the fabrication expenses of enriching the uranium for use. There will be no need to change existing safety regulations or procedures in the plants themselves, further ensuring economic feasibility of the design. Only about eighty percent of the standard amount of uranium required needs to be used in order to power the fuel cycle [Radkowsky]. Spent fuel is also no longer reprocessed, as it is inherently innate and significantly safer than spent fuel from uranium reactors. Between the reduction in uranium required and limiting processing required for waste, the fuel cycle cost is reduced by about twenty to thirty percent from the standard uranium light water process [Kazimi 2003].

Reactors Using Liquid Fuel: The Molten Salt Reactor (MSR)

The Molten Salt Reactor (MSR) is a design originally proposed in the 1950s at Oak Ridge National Laboratory in Tennessee [Briant 1957]. It has never been implemented commercially but has garnered a significant amount of interest recently because of its impressive efficiency, safety, and prospects with the thorium fuel cycle [Hargraves 2010].

MSRs have a core and blanket structure. The blanket is composed of thorium tetrafluoride (ThF_4) mixed with fluoride salts containing lithium and beryllium. The heat of the core causes these salts to melt. The core consists of a graphite cylinder filled with U-233 in the form of uranium tetrafluoride (UF_4) and the same fluoride salts found in the blanket. The graphite has pores, which facilitate the mixing of UF_4 and the thorium contained in the blanket [Hargraves 2010].

The initial step in the process of U-233 production is the generation of neutrons in the uranium core. Th-232 absorbs these neutrons to form Th-233, which eventually produces U-233 in the blanket [Hargraves 2010]. The protactinium from the second reaction could be diverted to a separate chamber to undergo its slow transformation to U-233 without absorbing neutrons from the core [Mathieu 2006]. The U-233 produced is then extracted from the blanket salt and transferred to the core to undergo fission. Energy and neutrons are released, and the cycle repeats [Hargraves 2010]. The MSR process is therefore a continuous cycle. It follows that after the first cycle, an outside source of U-233 is not needed, as it is bred continuously in the blanket [International Atomic Energy Agency 2005].

Because Molten Salt Reactors use liquid fuel, they are inherently more efficient than traditional nuclear reactors. The fuel is not vulnerable to structural stresses, unlike solid fuel rods. These fuel rods must be periodically replaced, mandating a plant shutdown and a decrease in overall efficiency. The ionic bonds of the salt also make the fuel resistant to radiation [Hargraves 2010]. Because ionic bonds are extremely strong, they are unlikely to be broken in the presence of radioactive material. Thus, MSR fuel is also more chemically stable than fuel rods**.**

In addition, any heavy transuranic products that form can stay in the core and eventually undergo fission [Hargraves 2010]. These products may also be extracted and used in fast neutron reactors to produce electricity [Mathieu 2006]. It is also possible to remove lighter fission products from the core. This ensures that the fuel is viable for a longer period of time because these products can make fission less efficient. Another advantage is that refueling is possible without shutting down the reactor because the fuel can simply be pumped into the reactor [Hargraves 2010]. It may also be possible to use the heat from the reactor core to produce hydrogen gas [Juhasz 2009].

MSRs also have several unique safety features. The fuel is not under pressure, so pressure explosions cannot occur. Meltdowns are also impossible because the fluoride salts expand with increasing temperature, making the core less reactive. As a result, less U-233 is produced, and the temperature drops again because less heat is released from fission. A secondary line of defense is a frozen salt plug located at the bottom of the core. If the temperature in the core reaches a critical level, the plug will melt, safely releasing the fuel into a catch basin [Hargraves 2010]. Molten Salt Reactors using thorium fuel are therefore both safer and more efficient than traditional uranium reactors.

The major problem associated with MSR's is that there does not seem to be one widely accepted design. Engineers are still experimenting with ways to deal with many issues associated with the model. For example, the graphite core needs to be optimized in order to maximize performance for the longest amount of time [Nagy 2011]. The use of thorium fuel in

MSR's is conceptually a sensible idea, but more research needs to be done before it could be implemented commercially.

High-Temperature Gas-Cooled Reactors (HGTR)

The architecture of the HTGR is inherently novel, as the fuel is kept in the form of microspheres. These microspheres are tiny (about nine tenths of a millimeter in diameter), and about 11,000 microspheres are encased together in a graphite pebble. These pebbles are about 60mm in diameter, approximately the size of a billiard ball. Approximately 91,000 of these pebbles are used in the core, with a total of approximately one billion microspheres. Defects are very rare in the fuel, at a rate of about 1 microsphere per pebble. The use of these pebbles is tremendously advantageous both in the efficiency of the fission (approaching 45%-50% efficiency) and the fact that fuel can be fed continuously into the reactor, eliminating the requirement of shutting down the reactor to refuel [Kazimi 2003].

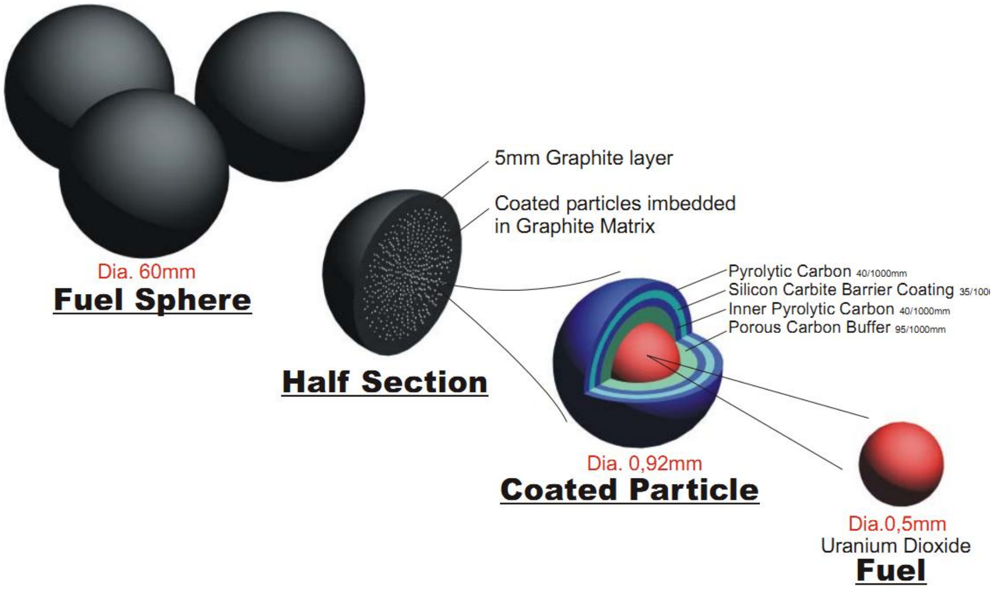

Figure 3: The Fuel "Pebble" [Kadak 2010].

HTGR’s are easily scaled to any size. It is one of the most promising designs for use in ‘personal’ reactors. Reactors can also be assembled in a modular manner, making construction cheaper and taking significantly less time than other models of reactors [Kadak 2010].

High-temperature gas-cooled reactors are also among the safest of possible designs. When constructed properly, the low power density of the reactor makes for much safer operation [Kazimi 2003]. The core is not susceptible to meltdowns like many other designs, and if there were to be a release of radiation of any kind, it would not be significant due to the fact that the fuel is encased in graphite, which slows neutrinos [Kadak 2010]. If there is any sort of emergency with the reactor, all actions are taken automatically with no user input required. Cooling is disabled, the control rods are withdrawn, and the fuel is dumped. These procedures are implemented very quickly, making this one of the safest reactor designs [Kadak 2010].

In comparison to standard light water uranium reactors, the most common reactor available on the market today, HTGR’s have a higher thermal efficiency, meaning that fuel burn-up is more efficient. HTGR’s also use significantly less water for cooling, as the reactor is cooled by helium, a non-corrosive inert gas. The design of the HTGR is also significantly simpler, reducing chances of manufacturer error and reducing cost of the plants [Kadak 2010].

World Thorium Reserves and Sources

Thorium is a solid radioactive element from the actinide series of the periodic table. In fact, it is the only element besides uranium that can be used in a nuclear reactor to generate electricity [Penny 2010]. There are twenty-seven known isotopes of thorium, but only one, Th-232, occurs naturally [Penny 2010]. It is three to four times more abundant than uranium, with an average concentration between 6 and 10 ppm in the earth's crust [International Atomic Energy Agency 2005]. Most estimates of world thorium reserves do not include sources that would be too costly (above $80/kg thorium) to recover in today's market, so the total is often less than the total recoverable uranium reserves, which is usually around 5 million metric tons (tonnes) [Penny 2010].

The primary source of thorium is the mineral monazite, which contains 3-10% thorium oxide (ThO_2) [Argonne National Laboratory]. Thorium can also be found in the minerals thorite (thorium silicate) and thorianite, which contains a mixture of uranium and thorium oxides [Argonne National Laboratory]. The element usually occurs along with uranium and other rare earth elements [International Atomic Energy Agency 2005]. In fact, most thorium produced today is a by-product of rare-earth extraction from monazite [International Atomic Energy Agency 2005]. Monazite is found in particularly high concentrations in Brazil, India, Australia, South Africa, and in the United States, most notably in North and South Carolina, Idaho, Colorado, Montana, and Florida [Argonne National Laboratory]. There are also known deposits in India, Malaysia, and Sri Lanka [Herring 2004].

Tables A4 and A5 quantify the total world reserves of both thorium and uranium, and table A6 gives the composition of monazite by country.

Radiological Risk Assessment and Perception

Background

Classes of Ionizing Radiation

There are three types of ionizing radiation: alpha, beta, and gamma. Alpha radiation is the least harmful of the three types, as it is unable to penetrate deep into human skin. An alpha particle is essentially a helium nucleus, making it the heaviest radiation particle with a mass of 6.64×10^{-27} kg [McQuarrie 1997]. This gives alpha particles a very short range, meaning that they cannot travel for more than a few inches through air. It follows that alpha particles cannot penetrate clothing; however, alpha radiation can become harmful if the particles are inhaled, ingested, or absorbed through wounds. Examples of alpha-emitters include radium, radon, uranium, and thorium [Health Physics Society 2011].

Beta radiation is slightly more harmful than alpha radiation. Beta particles, which are electrons, can travel up to several feet because of their extremely low mass (9.109×10^{-31} kg) [McQuarrie 1997]. Unlike alpha particles, beta particles can penetrate human skin to the germinal layer, which is the bottom layer of the epidermis [Marks 2006]. This can cause radiation burns to the skin. Beta particles are also detrimental if deposited within the body. Clothing provides moderate protection from absorption. The pure beta-emitters include strontium-90, carbon-14, tritium (an isotope of hydrogen), and sulfur-35 [Health Physics Society 2011].

The most harmful type of radiation is gamma radiation, or x-rays. X-rays are a type of electromagnetic radiation, meaning that a gamma particle is a matter wave and has essentially no mass. Gamma radiation is therefore highly penetrating. It is able to travel many feet in air and several inches through human tissue. Moreover, it can penetrate most materials. Clothing provides scant protection from gamma radiation; however, it will prevent skin contamination by gamma-emitting materials. Iodine-131, cesium-137, cobalt-60, radium-226, and uranium-232 all emit gamma particles [Health Physics Society 2011].

Definition of Units

Several units have been defined to measure different aspects of radiation contamination, and they are summarized in Table 3.

Unit	Standard	Measurement	Equivalency
rad (radiation equivalent dose)	English	Absorption of radiation	1 rad = 0.01 Gy
Gray (Gy)	SI	Absorption of radiation	1 Gy = 100 rad
rem (rad equivalent man)	English	Biological risk of exposure to radiation (Dosage of radiation that is harmful to one cell)	1 rem = 0.01 Sv
Sievert (Sv)	SI	Biological risk of exposure to radiation	1 Sv = 100 rem
roentgen (R)	English	Exposure to radiation in disintegrations per minute	
Curie (Ci)	English	Amount of radiation emitted by a particle over time	1 Ci = 37 billion disintegrations/second = 37 billion Bq
Becquerel (Bq)	SI	Amount of radiation emitted by a particle over time	1 Bq = 1 disintegration/second

Table 3: Radiation Units (Sources: CDC 2004; Health Physics Society 2011; Gopinath 2007)

Radiation Dose Limits, Risk Coefficients, and the Effects of Low Dose Radiation Exposure

Although many do not realize it, human beings, as well as all other earthly species, are constantly exposed to ionizing radiation from both natural and man-made sources. Exposure can result from three major routes, comprising of the presence of radiation particles on clothing or skin, the inhalation or absorption of radiation through wounds, and the steady concentration of radiation in the atmosphere [Health Physics Society 2011]. Body tissues that constantly need to regenerate cells, such as blood, hair, and the reproductive organs, are more vulnerable to radiation than muscle or nerve tissue, which do not often need to reproduce [Hanson 2000].

The average yearly dose of radiation for a human ranges between 2 and 3 mSv or about 170 mSv in a lifetime [World Nuclear Association 2005; Gopinath 2007]. This represents the exposure resulting from natural background radiation as well as that from human activities, including electricity generation from nuclear power plants and medical procedures like x-rays. This number can vary among individuals because background radiation differs depending on geographic location. It is for this reason that the radiation dose limits established by the International Commission on Radiation Protection (ICRP) do not take this background radiation into account [World Nuclear Association 2005].

The annual limit for the general public is 1 mSv, but the dosage can be higher as long as the average dose over 65 years is less than 1 mSv. The annual occupational limit is 20 mSv averaged over a five-year period, provided that the dose for a particular year is no greater than 50 mSv [Gopinath 2007]. To compare, the average dose for employees in the nuclear industry is 2-8 mSv/year, and this figure is steadily decreasing due to improvements in nuclear technology [Gopinath 2007]. Also, nuclear activities represent less than “a few tenths” of a person’s annual dose [World Nuclear Association 2005]. These two facts are evidence that nuclear power is an extremely safe source of electricity.

In addition to dose limits, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has published risk coefficients for exposure to ionizing radiation. These risk coefficients quantify the probability that an individual will develop cancer or a genetic disorder after absorbing a certain amount of radiation. Several factors affect the impact of radiation, including the time exposed, the amount of radiation absorbed, and the ability of the radiation to penetrate human skin or organs [Hanson 2000]. The risk coefficient for cancer is 0.05/Sv, and that for genetic disorders is 0.01/Sv. Both of these values have been derived from high exposure data [Gopinath 2007]. However, some scientists and health care professionals believe that this is a conservative way to quantify risk for low-dose exposure to radiation and that “backward interpolation of high exposure data tends to overestimate the effects at low doses” [Gopinath 2007].

On the other hand, it is known that high doses of radiation cause detrimental health effects. Cancer, infertility, anemia, genetic defects, birth defects, and a shortened life span are all established results of exposure to high doses [Hanson 2000]. A dose of 0.5-2 Sv will lead to cancer, and any dose above 5 Sv will kill half of those exposed within thirty days [Hanson 2000].

Although it is easy to quantify lethal doses, it is more difficult to analyze the effects of low doses. There are other factors, such as the body’s repair mechanisms and adaptive response, which affect the likelihood of an individual to develop a radiation-induced disorder [Gopinath 2007]. In fact, several studies have shown evidence that there might be biological benefits to being exposed to low doses of radiation. These benefits could include amplified protection against DNA damage and lessening of the effects of higher doses [Gopinath 2007]. About 30% of chemical elements have radioactive isotopes, and the concentration of certain isotopes varies by region. People living in areas with high background radiation are generally healthier and more able to handle higher doses without suffering from radiation-induced illness [Cuttler 2009].

This hypothesis is similar to the fact that physical and mental exercises encourage body and brain development and that small exposure to disease-causing pathogens increases the body's natural immunity. Once radiation is absorbed, an individual's homeostasis, or equilibrium, is disturbed. This stimulates a positive defensive response in the person's cells, which increases that person's resistance to the adverse effects of radiation. Obviously, the effectiveness of the defensive response depends on the dose absorbed. If too much radiation is taken up at one time, it overwhelms the body's defenses, and the individual cannot respond quickly enough. It is at these doses that cancer and genetic defects can develop. In addition, those with compromised immune systems are not able to adapt as quickly, which means that young children, the elderly, and those with immunosuppressive disorders are more susceptible to the harmful effects of radiation [Cuttler 2009].

There is another theory that low-dose radiation exposure is more dangerous than high-dose exposure. Some scientists argue that the cancers induced by low doses differ from those induced by high doses and are more difficult to treat [Hanson 2000]. It is clear when considering these contrasting explanations that quantifying the risk associated with low-dose absorption is difficult, and no one model is universally accepted.

Perception of Risk Associated with Nuclear Energy

There is a certain amount of risk associated with any method of electricity generation. For example, the adoption of hydropower involves the construction of dams, which have several disadvantages. In India, dams have resulted in the loss of ecologically significant forests, the relocation of several local populations, and soil erosion [Gopinath 2007]. There is also always the possibility that a dam will overflow or even burst, presenting a major risk to the surrounding population [Gopinath 2007].

The use of fossil fuels involves an even greater hazard to both the environment and to industry employees. Coal mining often destroys ecosystems, and releases from coal power plants will have dire long-term effects on the environment. In one gigawatt per year operation, a coal power station will release multiple millions of tonnes of carbon dioxide, sulfur dioxide, nitrogen oxides, and ash into the atmosphere. An increased concentration of carbon dioxide can effectively lock heat in the earth's atmosphere; this phenomenon is commonly referred to as the greenhouse effect. The other chemicals can cause acid rain and smog, both of which are harmful to plant life and can cause lung disease in humans. Additionally, mining and transporting fossil fuels is perilous for those employees involved. Between 1980 and 2000, more than one hundred fatalities have resulted from coal accidents [Gopinath 2007].

On the other hand, nuclear power is considered to be one of the safest ways to produce electricity based on risk coefficients that have been calculated for different energy options [Gopinath 2007]. The nuclear industry is very aware of its responsibility to protect nuclear employees, the public, and the environment from exposure to radiation, especially since the health effects of radiation are not wholly known. Thus, nuclear power plants have an intricate network of safety features that is designed to withstand multiple system failures. There are numerous containment mechanisms that prevent the uncontrolled release of radioactivity in the case of any malfunction, and there are several different shutdown procedures. An alternate power supply is required, as is a coolant system that has multiple pathways. Altogether, these features ensure that everyone and everything is shielded from any release of radioactivity from a nuclear power plant [Gopinath 2007].

In addition to safety systems, there are limiting conditions for the operation of nuclear power plants. These include a maximum fuel load, and they are set well below the reactor's safety limits as an extra precaution [Gopinath 2007]. The nuclear industry is strongly safety-conscious, and as a result the normal release of radioactivity from nuclear power plants is less than one percent of the allowable dose [Cuttler 2009]. Furthermore, any measures taken to protect humans from radioactivity will benefit all other plant and animal species because studies have shown that humans are the most sensitive to radiation [Gopinath 2007]. Unless workers lack a strong safety culture, nuclear accidents are extremely unlikely, and humans will not be affected by their proximity to nuclear plants [Cuttler 2009].

Unfortunately, the uncertainty regarding the long-term effects of low-dose radiation exposure makes nuclear power seem unrealistically dangerous to most of the populace. Major nuclear accidents such as those at Three Mile Island, Chernobyl, and Fukushima have also heightened the dangers of nuclear power in the minds of the general population. The perception of risk associated with nuclear power is therefore different among experts than among the public, even though "the risks due to severe accidents form only a small part of the overall risk" [Gopinath 2007]. For example, experts predicted 0.7 radiation-induced cancer deaths for the two million people living within thirty miles of the Three Mile Island facility after the 1979 accident [Gopinath 2007]. As for Chernobyl, there have been less than fifty accident-related deaths as of 2005 rather than the ten thousand total cancer deaths predicted. The survival rate for the four thousand instances of thyroid cancer in the region is 99% [Gopinath 2007].

Disappointingly, the media tends to sensationalize any nuclear accident and ignore the very low probability of nuclear accidents, putting nuclear power at a distinct disadvantage for public acceptance. If the public was more aware of the real dangers connected with each of the major means of electricity generation, nuclear power would not have the negative stigma from which it currently suffers, and policy would be more inclined toward its adoption and expansion.

Environmental Impacts

Thorium Mining

Today, thorium is largely produced as a by-product of rare earth mining from monazite [Kamei]. Although the metal may be used to make tungsten welding rods and magnesium-based alloys, most nations have little or no use for it [International Atomic Energy Agency 2005]. As a result, the thorium produced from rare earth mining is often disposed of as radioactive waste, creating a worldwide oversupply as well as environmental and regulatory concerns about radioactive waste disposal [Kamei]. These concerns are valid for public health reasons; however, monazite and thorium mining is very safe as long as it is highly regulated.

If handled improperly, thorium waste can be a dangerous and costly burden on the public. For example, Brazil had a large rare earth mining and processing industry from 1949 to 1992. The waste obtained from monazite extraction, which included thorium and uranium hydroxides, was stored improperly and without regard for public safety because the nation had poor regulatory laws. This led to contamination of soil, groundwater, and the atmosphere and raised serious environmental and health concerns. In fact, two processing sites in Sao Paulo had to be decommissioned, which was an extremely expensive process. The site remediation also increased public fears about the dangers of radiation, necessitating the development of a new monazite processing method that produces less radioactive waste [da Costa 2005].

Arguably the simplest solution to this problem is to use this excess thorium to fuel nuclear reactors or export it to nations that have the means to use it for this purpose. Not only would this be an economical way to deal with the current worldwide excess of thorium, but it would also alleviate concerns about the environmental impact of thorium waste disposal from the classical monazite cycle.

Thorium mining is also easier and less dangerous than uranium mining, providing an impetus for the transition to thorium nuclear power. Radioactive waste production from thorium mining is about two orders of magnitude lower than that from uranium mining, largely because thorium needs no enrichment or isotopic separation after extraction [International Atomic Energy Agency 2005]. It is also possible to extract other useful products, like rare earth compounds, from the monazite that is mined [Penny 2010]. Therefore, less waste has to be stored and less radiation is released to the environment. The radiation from thorium tailings is also easier to manage [Penny 2010]. Instead of having to deal with the radon-222 (commonly known as radon) produced from uranium mining, thorium mining produces radon-220, or thoron. The half-life of thoron, 55.6 seconds, is much shorter than that of radon (3.8 days); thus, thoron radiation simply does not travel as far in air as radon radiation. In other words, the concentration of thoron sharply decreases with increasing distance from the source, unlike radon, which is said to be uniformly distributed in the atmosphere [Tommasino 2003]. As a result, public exposure to high thoron concentrations can be easily and cheaply prevented; a ten centimeter layer of sand or soil can inhibit thoron emission from thorium tailings [Cothern 1987]. In addition, the occupational risk for thorium miners is lower than that for uranium miners. There is no need to control ventilation in thorium mines because it is mined in an open pit, as opposed to underground uranium mines, where the concentration of radon can reach potentially harmful levels [Penny 2010].

There is a surprising lack of information on the occupational and public health effects of thorium mining. One study points out that “thorium and its daughter products can be considered as potential health hazards by analogy with known health effects precipitated by other alpha emitting isotopes” [Argonne National Laboratory 1979], but there is not much data on the subject. A study of 112 New Jersey households in the vicinity of a waste disposal site containing thorium waste revealed a slightly higher prevalence of birth defects and liver diseases than a control group, but no definitive conclusions could be drawn because of the small number of families studied and the wide confidence intervals used during analysis. However, the authors claim that “industrial and mining exposure to thorium have resulted in an increased incidence of lung cancer, pancreatic cancer, colorectal cancers, chronic respiratory diseases, liver damage, and other serious illnesses.” [Najem 1990].

Three professors at the University of Salzburg seem to believe something similar. They argue that “several health effects have been associated with elevated exposure among workers in thoron-related industries and residents in high thoron background areas.” These effects include increased chromosomal aberrations, Down’s syndrome, pancreatic cancer, and respiratory disease [Steinhausler 1994].

Another study tested the speed of immune response in workers in a thorium refinery and found a decrease in the responsiveness of lymphocytes, a type of white blood cell. However, this slower response could be due to other factors like nutrition, medication, and smoking habits. Indeed, a study of eight American thorium workers showed no significant increase of chromosome aberrations [Argonne National Laboratory 1979].

Even the US government's toxicological profile on thorium has gaps and inconsistencies. Studies are cited in which thorium workers showed an increased risk for lung disease, pancreatic and bone cancer, and somatic cell mutations as well as studies that showed that the mortality of thorium workers was not significantly higher than that of US males ["Toxicological Profile for Thorium" 2011]. They also assert that thorium is not known to cause birth defects or sterility ["Toxicological Profile for Thorium" 2011], which contradicts the results of the New Jersey study. The effects of low doses of thorium on many body systems are largely unknown, partly because other factors may play a role in disease development ["Toxicological Profile for Thorium" 2011].

However, it is clear that thorium has carcinogenic potential when it is highly concentrated in the body. From about 1930 to 1950, some medical patients were injected with colloidal thorium, or Thorotrast, for x-ray analysis. These patients showed increased cancer rates compared to the rest of the United States. This existing data suggests that "thorium may pose a potential health threat to an exposed population," but the amount of thorium required to cause adverse health effects is unknown ["Toxicological Profile for Thorium" 2011]. It is very possible that the amount of radiation released from thorium mining processes is below this threshold, but so far no definitive conclusions can be drawn.

To summarize, there is currently a worldwide oversupply of thorium obtained from rare earth monazite mining. This extra thorium can easily be utilized in nuclear reactors, thus alleviating concerns about the disposal of this radioactive by-product. Thorium mining from monazite produces less waste than uranium mining, and other useful materials can be obtained from the process, like rare earth compounds. It is also easier to control radiation emissions from thorium tailings than from uranium tailings. Therefore, thorium mining is gentler on the environment than uranium mining; however, the health effects of thorium are largely unknown and speculative.

Uranium Mining, Processing, and Waste Disposal

The environmental aspect of uranium can be separated into the three phases of mining, processing, and waste disposal. Each of these three phases has the potential to pollute the environment. It is important to note that human beings will be considered a part of the environment.

Mining

Uranium mining is much the same as the mining of any other ore from the earth. The radioactivity of uranium ore can vary in the range of 500 thousand to 25 million Bq/kg [World Nuclear Association 2011g]. Uranium ore actually gives off less gamma radiation than granite. The uranium is mined from either open pits or mineshafts. The mineshafts present more of a danger to miners, as the enclosed space allows for radon build-up. The ore is handled with gloves, as it is of similar toxicity to lead, but no additional precautions are taken in open pit uranium mining [World Nuclear Association 2011b].

There is also waste associated with uranium mining. There is about twice as much waste (by weight) as there is raw usable product [World Nuclear Association 2011b]. A study was done on the area around the Vale de Abrutiga open pit uranium mine in Portugal in the 1990’s. The mine had produced about 90 tons of Uranium oxide from 1982 until 1989, when it was shut down. The 1.4 million tons of waste from the mine, consisting of low-grade ore and waste rock, were placed on permeable ground that was never re-vegetated. By the time of the study, a lake had formed in the open pit left by the mine, and water from this lake had seeped into the groundwater. The pH of the pit lake was found to be about 2.5. Researchers tested a reservoir located 500 meters from the pit and found that the water was neither potable nor suited for agriculture [Pinto 2004]. Figure A1 and tables A2 and A3 further summarize the findings.

The concentrations of iron, manganese, radium, and lead found in the reservoir all exceeded the maximum permitted values for human consumption according to Portuguese law and Canadian norms. The reservoir was also found to be much too acidic for human consumption. In this instance, the presence of waste from uranium mining polluted an ecosystem and presented a health risk to any and all residents of the area.

An even more direct and dangerous health risk was discovered in Saskatchewan, Canada when tailings from a uranium mine were swept away by wind. The air-born particulates settled on lichens, which are the main food source for the local caribou population, which in turn is the main food source for the local aboriginal population. Tissue from the caribou was tested and found to contain the radionuclides uranium, radium-226, lead-210, polonium-210, and cesium-137. Further tests were conducted, and it was found that adults consuming 100 g of caribou meat per day could expect doses of 0.85mSv per year of the radioactive material, while those who consumed meat, liver, and kidneys could expect 1.68 mSv per year. The study concludes with the statement that “the risk of fatal cancer from a dose of 1.7 mSv is 8.5×10^{-5} per year, and 6×10^{-3} over a 70-year lifetime if caribou meat, liver, and kidney are consumed at the rate postulated” [Thomas 1999].

Processing

The processing of uranium requires human input and contact, so it presents a hazard to the environment. In a 1999 study, present and former workers at Fernald Feed Materials Production Center in Ohio, a uranium processing site, were studied with respect to cancer and mortality rates. Rates of malignant neoplasms, as well as prostate, brain, bladder, hematopoietic, lymphopoietic, and digestive cancers were slightly increased. Deaths from these cancers were shown to be increased from external radiation exposure above 100 mSv. Exposure above the age of 40 increased cancer mortality by "two to threefold per 100 mSv" for all cancers. Mortality rates from lung cancer were doubled by internal exposures of at least 200 mSv. Perhaps the most interesting piece of information from this study is that overall mortality rates in the study group were found to be "lower…than among US white males" [Ritz 1999].

A 1995 study assessed somatic gene mutations in residents of the area surrounding a uranium processing facility. Overall, 112 residents were studied. Fifty-six were from within a five-mile radius of the plant, and fifty-six were from a "control" region with no source of unusual radiation exposure. The study found that proximity to a processing facility has almost no statistically significant effect on gene mutation. Furthermore, the article shows that smoking is actually more dangerous in this respect than proximity to a processing facility [Wones 1995].

Waste

One of the most relevant examples of environmental contamination can be found at the Hanford site in southeastern Washington. The site was a national center of plutonium production from 1943 until 1987. In all, 110,000 tons of nuclear fuel were processed at the site, which created millions of gallons of high-level waste. Radioactivity at the site totals approximately 437 million Ci, 215 million of which can be found underground in storage tanks. The first leaks in the underground tanks were confirmed in 1961, and since then, 450 billion gallons of liquid and one to two Ci of radiation have leaked from the tanks [Hanson 2000].

There is an estimated 150 square-mile area of contaminated groundwater below the site. The contamination includes radiation as well as toxic levels of numerous metals. The metal concentration causes the affected groundwater to be very basic. As it stands, organisms that live in the soil and groundwater are the subset that is affected most by the contamination. The groundwater from beneath the site is expected to eventually contaminate the Columbia River, and there is radioactive spring water already flowing into the river. The presence of this water has hindered the growth and survival of fathead minnows and *Hyalella azteca* (an amphipod crustacean) along the riverbank. The population growth of daphnids, a swamp organism commonly used to measure environmental contamination, was also stunted [Hanson 2000].

Radiation concentration in the river equals approximately 1.16×10^{-20} Bq per gallon of water. This is a very low concentration. Moreover, the concentrations of radiation in the river's fish are declining more rapidly than expected, and the water can be used for irrigation with no harmful effects. Although the cleanup will not be finished until about 2030, the risk to humans is expected to be very low [Hanson 2000].

Waste from uranium processing is also prevalent in the United States' military's use of depleted uranium (DU) in ammunition. When a DU round strikes a target, 10% to 35% (but no more than 70%) of the DU breaks into fine particles. Most of these particles are smaller than 5µm in diameter, and together, they form a black dust that can travel for up to 40 km [Bleise 2003].

Over 30,000 of these DU rounds were fired from aircraft to the ground in Kosovo in the 1990's. This amounts to about 10 tons of DU at 112 sites throughout the country. A study by the UN Environment Programme took urine samples from 32 Red Cross and Red Crescent workers in Kosovo in May of 2000. Troops serving in the Balkans were also tested by their countries of origin. Uranium levels in the urine were found to be normal in all cases [Bleise 2003].

In a 2001 study by McClain, Gulf War veterans with embedded DU shrapnel were tested for uranium content in the blood. The study showed that DU "slowly solubilizes" in the blood, and that a decade after the war, "blood and urine levels of uranium are elevated by up to two orders of magnitude" [Bleise 2003]. Furthermore, in US soldiers with "a high load of DU shrapnel, no indications of kidney dysfunction [sic] were seen in tests made several years after the Gulf War" [Bleise 2003]. The soldiers tested in the latter study had blood uranium content of 100-times the normal level. The source goes on to report that "…additional risk of a lethal cancer associated with a dose of 1 mSv is about 1 in 20,000" [Bleise 2003]. This can be compared to the calculated 'normal' chances of any single European citizen contracting cancer, which is 1 in 5 [Bleise 2003].

Environmental Effects of RTR and HTGR Utilization

Radkowsky Thorium Reactor (RTR)

Many of the environmental aspects of the Radkowsky design are very similar to standard uranium light-water plants, as the same technology is used. However, there are several key differences in the composition of the waste due to the inclusion of thorium to the process and reduction of the amount of uranium involved.

Plutonium waste is reduced by roughly 80% compared to a standard uranium-fueled light water reactor [Radkowsky]. The plutonium waste is largely Pu-238, a relatively safe isotope. It only emits alpha radiation and has a half-life of less than ninety years. Pu-238 is commonly used in radioactive imaging and fuel for space exploration, so the fuel could viably be reprocessed for other purposes [Idaho National Laboratory 2005]. The physical mass of plutonium produced in an RTR is reduced significantly. A standard light water reactor will produce about 250-300 kg of plutonium per standard reactor cycle, whereas a LWR retrofitted with an RTR fuel system will produce about 15-20 kg [Radkowsky].

The majority of waste produced by the RTR is from the uranium seeds used to maintain the reaction [Radkowsky]. U-235, the isotope commonly found in nature, is produced as the primary uranium byproduct. As the thorium “blanket” will last for about ten years, the only significant thorium waste is produced when the blanket is replaced.

High-Temperature Gas-Cooled Reactor (HTGR)

HTGRs, in contrast to RTRs, produce a constant stream of waste due to the persistent refueling model in use. None of the waste produced by a standard HTGR is particularly dangerous, however. The waste is produced in the form of graphite pebbles, so many dangerous elements are already shielded by the graphite [Kazimi 2003]. As HTGR’s are inherently efficient, much more of the mass of fuel is burned completely (up to 90%) in the reaction, producing less physical waste [Kazimi 2003].

One of the biggest issues with HTGR’s is that the design uses helium as a coolant. Helium is a finite resource on Earth, and reserves are rapidly running out. This will inevitably lead to an increase in cost, which would be a significant barrier to entry for HTGR’s [Kazimi 2003].

Economic Sustainability

Uranium

Uranium has monetary as well as environmental costs in every phase of its fuel cycle, including mining, enrichment and fabrication, energy production, and waste disposal.

The most pertinent costs of uranium mining are those projected for the near future. Namibia is planning to implement a large scale open-pit uranium mining operation starting in 2014. The plant may produce up to 15 million pounds of U_3O_8 per year, with an initial development cost of $1.6 billion. Excluding transport, royalty, and marketing costs, the U_3O_8 should cost about $28.50/lb to produce. To support the mine, the outside infrastructure cost is expected to total about $210 million [Swanepoel 2011].

Current data presents more conservative figures. An online mining cost calculator uses a total production cost of $52.209 per pound of U_3O_8 to make its calculations. This total cost combines costs of $15.882/lb for mining, $24.67/lb for milling, and $11.66/lb for miscellaneous costs, including administration. Considering the conversion from uranium ore to U_3O_8, the calculator estimates a cost of $135.188 per kg of uranium ["Uranium Mine Feasibility Calculator"].

In March of 2011, the cost of uranium fuel fabrication was calculated using current price data. Table 4 outlines the costs of the conversion, enrichment, and fabrication in order to "get 1 kg of uranium as UO_2 reactor fuel" [World Nuclear Association 2011a].

Uranium:	8.9 kg U_3O_8 x $146	US$ 1299
Conversion:	7.5 kg U x $13	US$ 98
Enrichment:	7.3 SWU x $155	US$ 1132
Fuel fabrication:	per kg	US$ 240
Total, approx:		US$ 2769

Table 4: Cost of uranium conversion, enrichment, and fuel fabrication [World Nuclear Association 2011a]

At 45,000 MWd/t burn-up this gives 360,000 kWh electrical per kg, hence fuel cost: 0.77 c/kWh.

Another source has the 2004 production cost per kWh as 1.68 cents [Sevior et. al. 2011]. Confusion notwithstanding, the World Nuclear Association estimates that the cost of nuclear waste disposal equals about 5% of the cost of the generated energy [World Nuclear Association 2011h].

Thorium

It is no secret that thorium is currently expensive, at a cost of about $5000/kg. However, if one were to consider that thorium in an LFTR can produce upwards of 1GW/year-tonne, the total production cost becomes $0.0004/kWh. Furthermore, it is estimated that if thorium is mined as aggressively as uranium, the price could drop to $10/kg [Penny 2010].

It becomes clear when attempted to corroborate the above $5000/kg figure that Penny must be referring to the price of thorium fuel for an LFTR. The price of 99.99%-pure ThO_2 at the end of 2010 was $252/kg [Cordier 2011]. If we assume that the mining company makes 100% profit, the cost to mine one kg of ThO_2 is approximately $126. If the liquid fluoride fuel fabrication firm buys the thorium at the market price and makes 50% profit, then the cost of LFTR fuel fabrication can be found to be about $3200/kg.

Consider now that RTR fuel is approximately 20% cheaper than LWR fuel [Kazimi 2003]. If we take uranium reactor fuel costs to be about $2800/kg [World Nuclear Association 2011a], then completed RTR fuel costs approximately $2240/kg. If the RTR fuel fabrication firm buys thorium at the market price and makes 50% profit, then the cost of RTR fuel fabrication can be found to be about $1325/kg.

An LFTR may be less expensive than a conventional LWR [Hargraves 2010]. This hypothesis is based on several factors. First, LFTR's operate at atmospheric pressure and do not rely on pressurized water. Therefore, the plant's containment structure can be constructed more cheaply. The coolant injection systems for a conventional plant must operate at high pressure and at great cost, but an LFTR does not require these. LFTR's operate at temperatures near 800°C, which places the efficiency of the thermal-to electrical energy conversion in the 45% range. This can be compared to efficiencies closer to 33% for coal and some other nuclear plants. Some of the benefits of the LFTR conversion can be found in the offset of the costs of the developing world [Hargraves 2010]. If the use of fossil fuels is reduced, money can be saved on environmental cleanup. Finally, it is estimated that a 100 megawatt LFTR can be mass-produced at $200 million per unit. As a point of comparison, Boeing produces approximately one airplane per day at this cost [Hargraves 2010].

The costs for outfitting an existing LWR to use the Radkowsky Thorium Reactor (RTR) model are negligible, as there are no inherent costs for retrofitting. The only modifications required are in the fuel that is used in the reactor [Radkowsky].

We can only assume that the cost of waste disposal for thorium plants is lower than for uranium plants. Thorium plants produce less waste overall, and the waste has fewer long-lived actinides. Therefore, the waste containment structures for thorium-reactor waste can be less secure and therefore less expensive.

Conclusion

This paper assessed the most relevant facets of nuclear energy generation as applied to thorium and uranium fuels and reactors: environmental impact, energy efficiency, economic sustainability, and proliferation risk. It was found that thorium is in many respects superior to uranium as a nuclear fuel.

Thorium power theoretically generates less waste than uranium power during its fuel cycle. The caveat “theoretically” is important because no thorium reactor has been implemented long enough to be refueled, and there is essentially no waste from the power cycle currently in existence. It is known that there is exactly as much mining waste from thorium as from uranium because the mining process is identical. Thorium requires virtually no processing to be usable for energy generation, so thorium creates less waste than uranium in this respect. Furthermore, the waste from the thorium fuel cycle is less dangerous overall than uranium fuel cycle waste.

The deceptively negative issue regarding the thorium fuel cycle is that U-232, a harmful gamma-emitter, is always formed in the fission reaction sequence. Since it needs to be handled with extreme care and virtually cannot be separated from U-233, it makes weapons proliferation using U-233 less attractive. U-233 alone would perform well in nuclear weapons, but the inherent presence of U-232 renders proliferation unappealing and tremendously dangerous.

Pound for pound, thorium is considerably more energy dense than uranium. In other words, a lesser mass of thorium fuel is required to produce the same amount of energy as a greater mass of uranium fuel. The world’s thorium reserves are also several times larger than uranium reserves, so the supply of thorium will last significantly longer than that of uranium. There is a sizeable quantity of thorium already being stored as a byproduct of rare earth mining; this waste material could be easily utilized in new thorium reactors.

Thorium power's greatest shortcoming is its lack of existing infrastructure. Regardless of the reactor type being constructed, there will be some initial investment required. Beyond this, however, operating and maintenance costs for thorium reactors are drastically lower than those for uranium reactors, leading to an overall savings over time. In addition, fabrication costs for thorium fuel are less than or equal to those for uranium fuel, but thorium does not need to be enriched before use. Uranium enrichment is the most costly element of the uranium fuel cycle; lacking this expense, thorium fuel is both more cost-effective than uranium fuel and simpler to produce.

With a substantial monetary investment into research and development, thorium could successfully be used to supplement or replace uranium as a nuclear fuel given its inherent advantageous characteristics. Although thorium research has been ongoing as long as uranium research there has never been enough of an impetus for widespread commercial adoption of thorium power to date. Due to the early implementation of a uranium infrastructure, politicians and researchers largely put thorium on the back burner. The demands and concerns of today's world, however, make thorium a more desirable option than uranium. Threats of nuclear weapons proliferation have become more serious, and natural disasters have proven to be a menace to the current uranium infrastructure. Thorium power will solve these problems as well as other dilemmas caused by use of uranium. The adoption of thorium power by industrializing nations like India suggests that these nations already see thorium as a means of satisfying their long term energy needs.

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Appendix

Illustrative Examples Of Interpretive Packages In Post-Fukushima News Media Coverage	
Interpretive Packages/Frames	**Example Extracts From News Media Coverage**
Progress	“Why Fukushima made me stop worrying and love nuclear power … A crappy old plant with inadequate safety features was hit by a monster earthquake and a vast tsunami. The electricity supply failed, knocking out the cooling system. The reactors began to explode and melt down. The disaster exposed a familiar legacy of poor design and corner-cutting. Yet, as far as we know, no one has yet received a lethal dose of radiation.”[55]
Energy Independence	“The recent disaster in Fukushima has set public confidence in nuclear power back to levels not seen since the aftermath of the Chernobyl or Three Mile Island disasters. This really is a shame, because I believe that nuclear power, if the proper precautions are taken, could greatly lessen the current dependency for fossil fuels, something which is direly needed.”[56] “The Germans topped that by switching off several nuclear power stations unnecessarily and importing millions more tonnes of coal (the biggest killer of all energy sources by some margin) from the United States to keep the lights on.”[57]
Soft Paths	“100% renewables (and geothermal) is where we need to get to eventually—so why not seek to get there just as soon as possible without yet another disastrous foray into today's nuclear cul-de-sac?”[58]
Public Accountability	“Investigators may take months or years to decide to what extent safety problems or weak regulation contributed to the disaster at Daiichi, the worst of its kind since Chernobyl. But as troubles at the plant and fears over radiation continue to rattle the nation, the Japanese are increasingly raising the possibility that a culture of complicity made the plant especially vulnerable to the natural disaster that struck the country on March 11. … The mild punishment meted out for past safety infractionshas reinforced the belief that nuclear power's main players are more interested in protecting their interests than increasing safety.”[59]
Not Cost-Effective	“Fukushima shows us the real cost of nuclear power…The economics of nuclear power don't add up—which is even more reason to invest in renewable energy.”[60]
Runaway	“The twin natural disasters have also turned the Fukushima Daiichi nuclear power plant into Frankenstein's monster, a man-made object threatening man.”[61]
Devil's Bargain	“There is no doubt that the explosions and radioactive releases at the stricken Fukushima Daiichi plant represent the worst nuclear disaster since the explosion at the Chernobyl power plant in Ukraine in 1986. However … if we abandon nuclear, prepare for a future of catastrophic global warming, imperilling the survival of civilisation and much of the earth's biosphere.”[62]

Table A4 [Butler 2011]

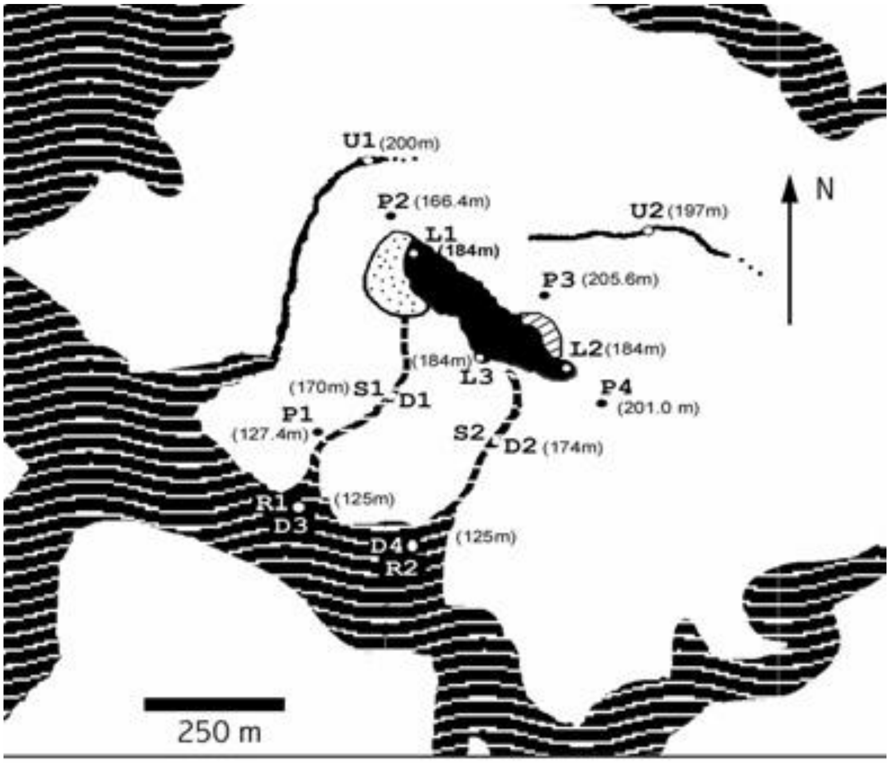

Figure A1: Map of the area around the Vale de Abrutiga uranium mine [Pinto 2004].

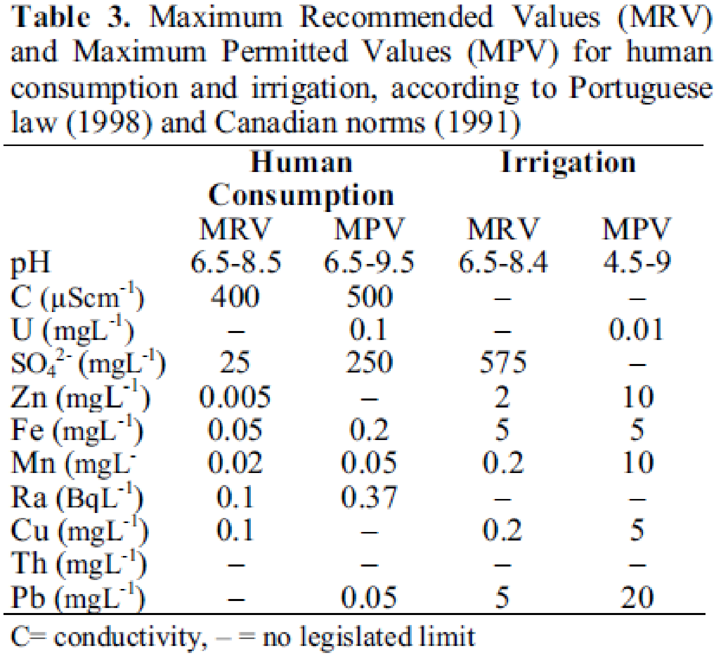

Table 3. Maximum Recommended Values (MRV) and Maximum Permitted Values (MPV) for human consumption and irrigation, according to Portuguese law (1998) and Canadian norms (1991)

	Human Consumption		**Irrigation**	
	MRV	MPV	MRV	MPV
pH	6.5-8.5	6.5-9.5	6.5-8.4	4.5-9
C (μScm^{-1})	400	500	–	–
U (mgL^{-1})	–	0.1	–	0.01
SO_4^{2-} (mgL^{-1})	25	250	575	–
Zn (mgL^{-1})	0.005	–	2	10
Fe (mgL^{-1})	0.05	0.2	5	5
Mn (mgL^{-}	0.02	0.05	0.2	10
Ra (BqL^{-1})	0.1	0.37	–	–
Cu (mgL^{-1})	0.1	–	0.2	5
Th (mgL^{-1})	–	–	–	–
Pb (mgL^{-1})	–	0.05	5	20

C= conductivity, – = no legislated limit

Table 5 [Pinto 2004].

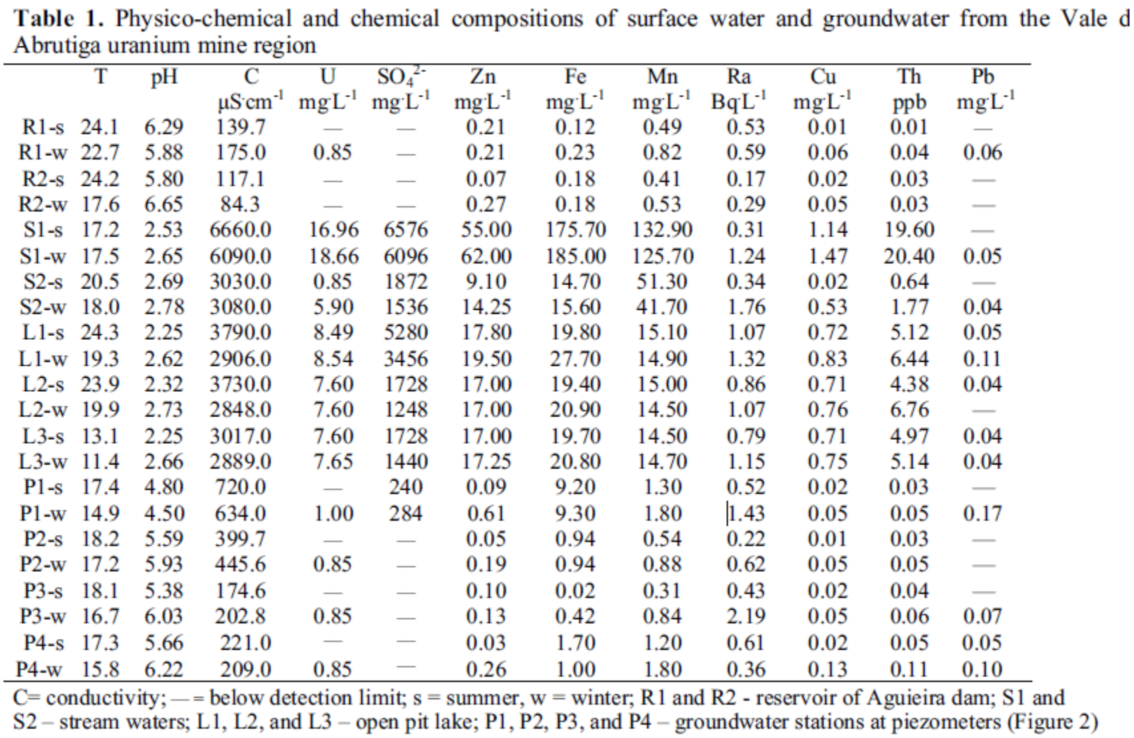

Table 1. Physico-chemical and chemical compositions of surface water and groundwater from the Vale d Abrutiga uranium mine region

	T	pH	C μS·cm^{-1}	U mg·L^{-1}	SO_4^{2-} mg·L^{-1}	Zn mg·L^{-1}	Fe mg·L^{-1}	Mn mg·L^{-1}	Ra Bq·L^{-1}	Cu mg·L^{-1}	Th ppb	Pb mg·L^{-1}
R1-s	24.1	6.29	139.7	—	—	0.21	0.12	0.49	0.53	0.01	0.01	—
R1-w	22.7	5.88	175.0	0.85	—	0.21	0.23	0.82	0.59	0.06	0.04	0.06
R2-s	24.2	5.80	117.1	—	—	0.07	0.18	0.41	0.17	0.02	0.03	—
R2-w	17.6	6.65	84.3	—	—	0.27	0.18	0.53	0.29	0.05	0.03	—
S1-s	17.2	2.53	6660.0	16.96	6576	55.00	175.70	132.90	0.31	1.14	19.60	—
S1-w	17.5	2.65	6090.0	18.66	6096	62.00	185.00	125.70	1.24	1.47	20.40	0.05
S2-s	20.5	2.69	3030.0	0.85	1872	9.10	14.70	51.30	0.34	0.02	0.64	—
S2-w	18.0	2.78	3080.0	5.90	1536	14.25	15.60	41.70	1.76	0.53	1.77	0.04
L1-s	24.3	2.25	3790.0	8.49	5280	17.80	19.80	15.10	1.07	0.72	5.12	0.05
L1-w	19.3	2.62	2906.0	8.54	3456	19.50	27.70	14.90	1.32	0.83	6.44	0.11
L2-s	23.9	2.32	3730.0	7.60	1728	17.00	19.40	15.00	0.86	0.71	4.38	0.04
L2-w	19.9	2.73	2848.0	7.60	1248	17.00	20.90	14.50	1.07	0.76	6.76	—
L3-s	13.1	2.25	3017.0	7.60	1728	17.00	19.70	14.50	0.79	0.71	4.97	0.04
L3-w	11.4	2.66	2889.0	7.65	1440	17.25	20.80	14.70	1.15	0.75	5.14	0.04
P1-s	17.4	4.80	720.0	—	240	0.09	9.20	1.30	0.52	0.02	0.03	—
P1-w	14.9	4.50	634.0	1.00	284	0.61	9.30	1.80	1.43	0.05	0.05	0.17
P2-s	18.2	5.59	399.7	—	—	0.05	0.94	0.54	0.22	0.01	0.03	—
P2-w	17.2	5.93	445.6	0.85	—	0.19	0.94	0.88	0.62	0.05	0.05	—
P3-s	18.1	5.38	174.6	—	—	0.10	0.02	0.31	0.43	0.02	0.04	—
P3-w	16.7	6.03	202.8	0.85	—	0.13	0.42	0.84	2.19	0.05	0.06	0.07
P4-s	17.3	5.66	221.0	—	—	0.03	1.70	1.20	0.61	0.02	0.05	0.05
P4-w	15.8	6.22	209.0	0.85	—	0.26	1.00	1.80	0.36	0.13	0.11	0.10

C= conductivity; — = below detection limit; s = summer, w = winter; R1 and R2 - reservoir of Aguieira dam; S1 and S2 – stream waters; L1, L2, and L3 – open pit lake; P1, P2, P3, and P4 – groundwater stations at piezometers (Figure 2)

Table A3 [Pinto 2004].

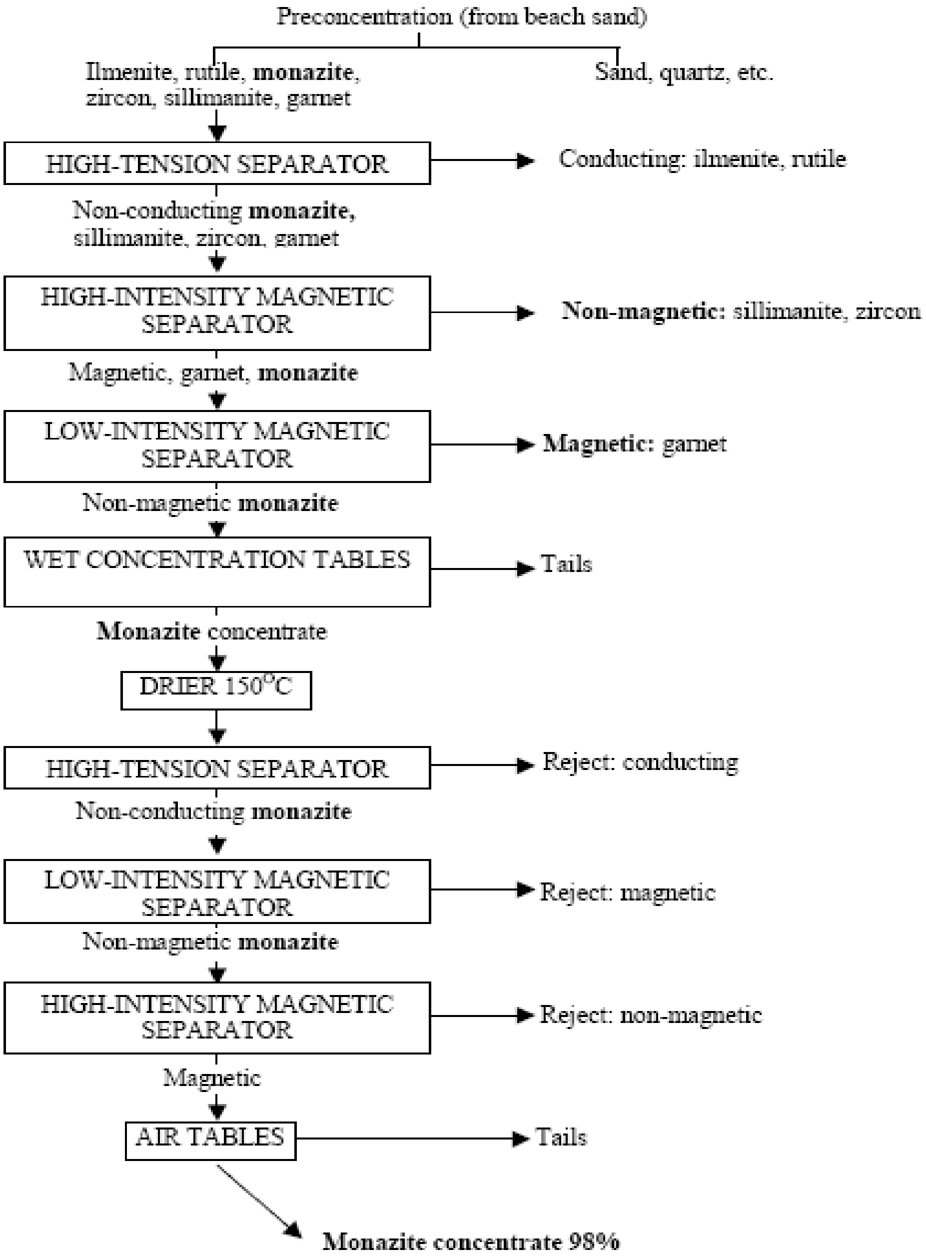

Figure A2: Monazite Extraction Process [Penny 2010]

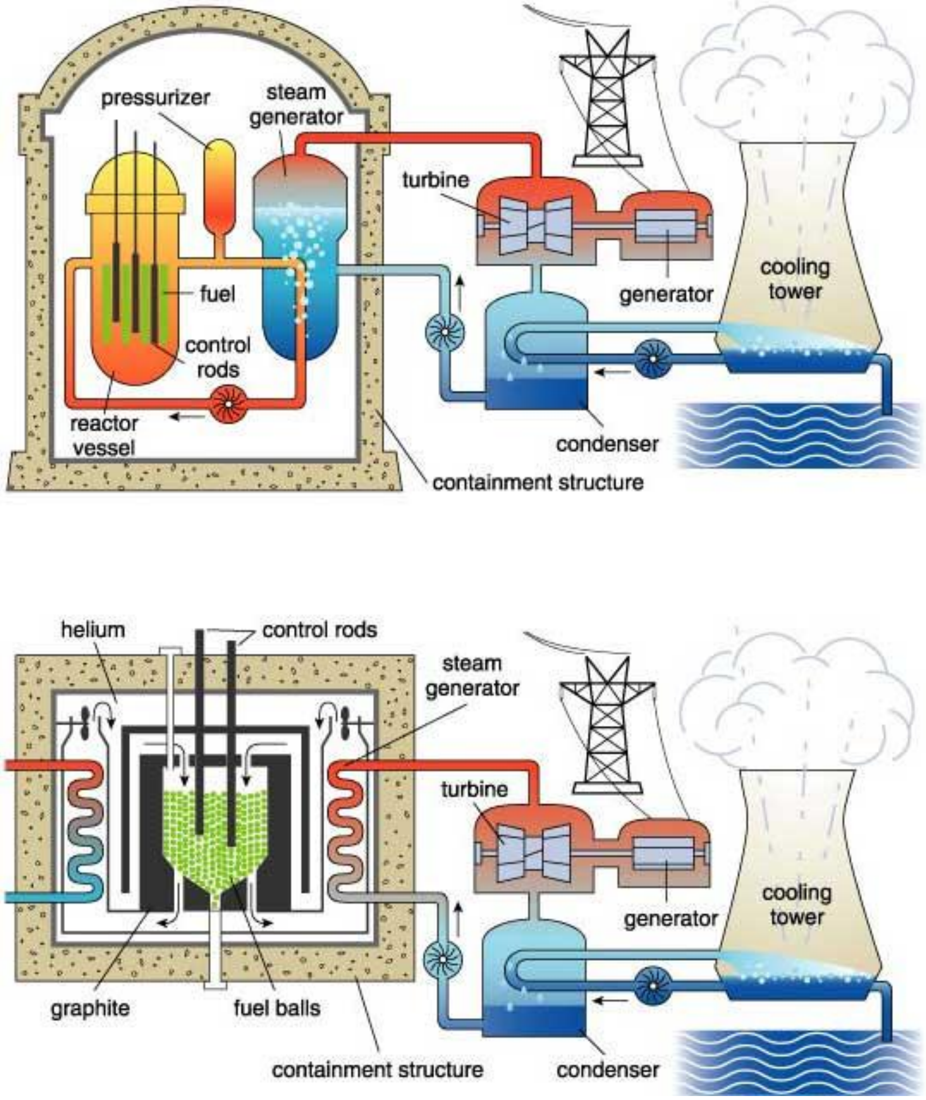

Figure A3: A standard Pressurized Water Reactor (top) and a HTGR (bottom) [Kazimi 2003].

	tonnes U	percentage of world
Australia	1,673,000	31%
Kazakhstan	651,000	12%
Canada	485,000	9%
Russia	480,000	9%
South Africa	295,000	5%
Namibia	284,000	5%
Brazil	279,000	5%
Niger	272,000	5%
USA	207,000	4%
China	171,000	3%
Jordan	112,000	2%
Uzbekistan	111,000	2%
Ukraine	105,000	2%
India	80,000	1.5%
Mongolia	49,000	1%
other	150,000	3%
World total	**5,404,000**	

Table A4: Known Recoverable Uranium Resources in 2009 [“Supply of Uranium”].

Country	Tonnes	% of total
Australia	489,000	19
USA	400,000	15
Turkey	344,000	13
India	319,000	12
Venezuela	300,000	12
Brazil	302,000	12
Norway	132,000	5
Egypt	100,000	4
Russia	75,000	3
Greenland	54,000	2
Canada	44,000	2
South Africa	18,000	1
Other countries	33,000	1
World total	**2,610,000**	

Table A5: Estimated World Thorium Resources in 2011 ["Thorium" (*World Nuclear Association*)]

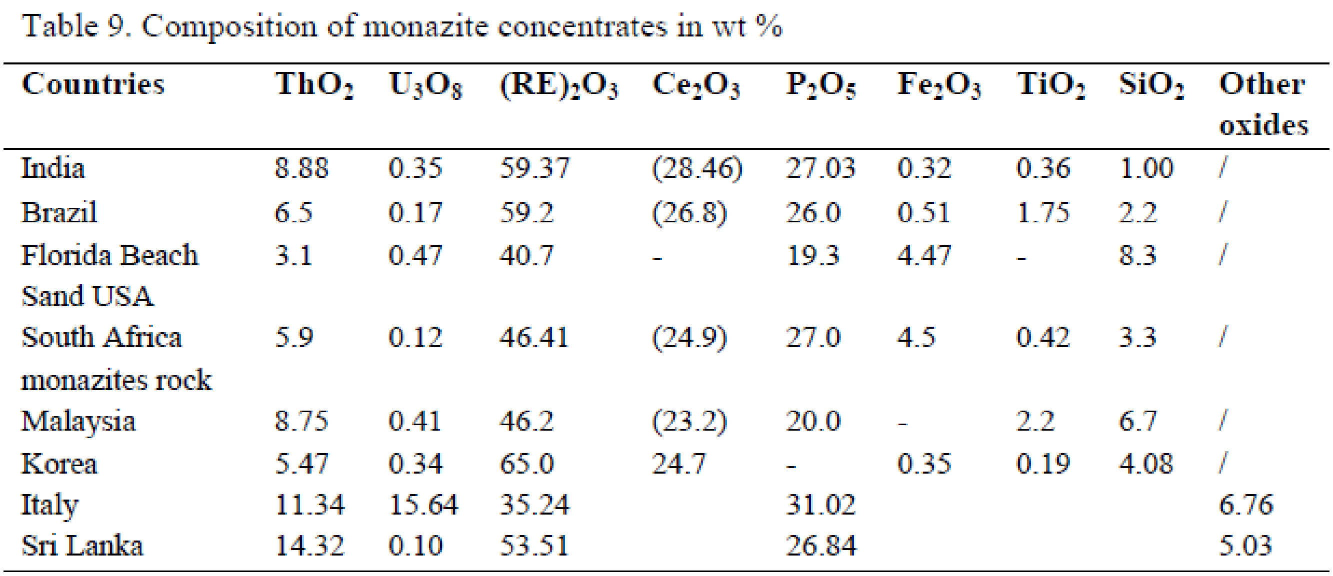

Table 9. Composition of monazite concentrates in wt %

Countries	ThO_2	U_3O_8	$(RE)_2O_3$	Ce_2O_3	P_2O_5	Fe_2O_3	TiO_2	SiO_2	Other oxides
India	8.88	0.35	59.37	(28.46)	27.03	0.32	0.36	1.00	/
Brazil	6.5	0.17	59.2	(26.8)	26.0	0.51	1.75	2.2	/
Florida Beach Sand USA	3.1	0.47	40.7	-	19.3	4.47	-	8.3	/
South Africa monazites rock	5.9	0.12	46.41	(24.9)	27.0	4.5	0.42	3.3	/
Malaysia	8.75	0.41	46.2	(23.2)	20.0	-	2.2	6.7	/
Korea	5.47	0.34	65.0	24.7	-	0.35	0.19	4.08	/
Italy	11.34	15.64	35.24		31.02				6.76
Sri Lanka	14.32	0.10	53.51		26.84				5.03

Table A6: Composition of Monazite by Country [IAEA: Thorium Fuel Cycle… 2005]

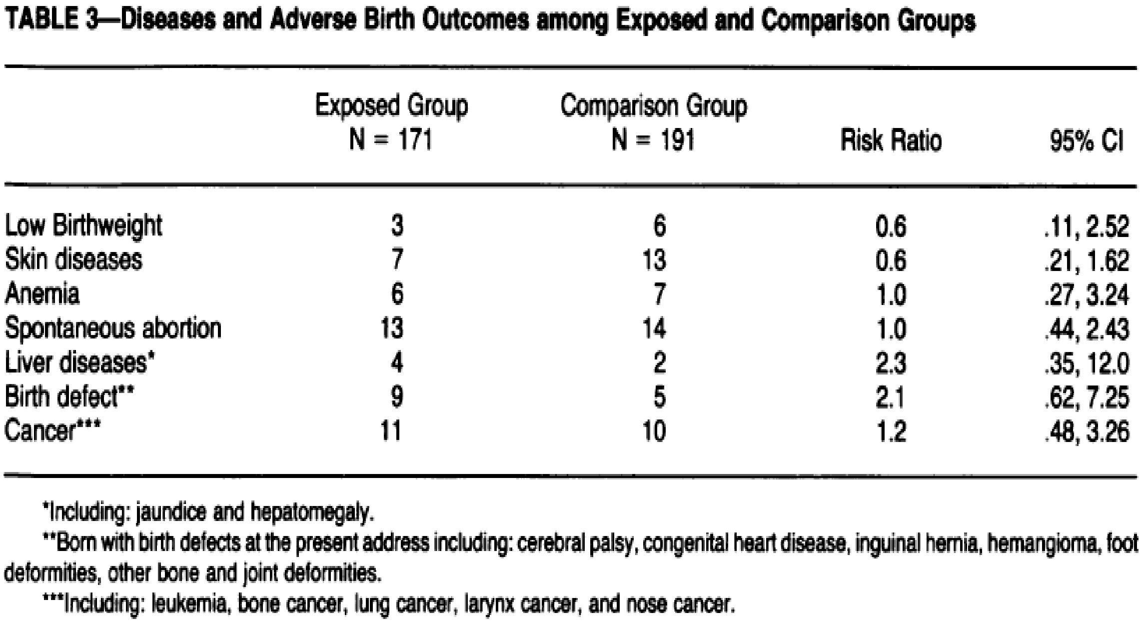

TABLE 3—Diseases and Adverse Birth Outcomes among Exposed and Comparison Groups

	Exposed Group N = 171	Comparison Group N = 191	Risk Ratio	95% CI
Low Birthweight	3	6	0.6	.11, 2.52
Skin diseases	7	13	0.6	.21, 1.62
Anemia	6	7	1.0	.27, 3.24
Spontaneous abortion	13	14	1.0	.44, 2.43
Liver diseases*	4	2	2.3	.35, 12.0
Birth defect**	9	5	2.1	.62, 7.25
Cancer***	11	10	1.2	.48, 3.26

*Including: jaundice and hepatomegaly.

**Born with birth defects at the present address including: cerebral palsy, congenital heart disease, inguinal hernia, hemangioma, foot deformities, other bone and joint deformities.

***Including: leukemia, bone cancer, lung cancer, larynx cancer, and nose cancer.

Table A7: Health Effects of a Thoron Waste Disposal Site [Najem 1990].

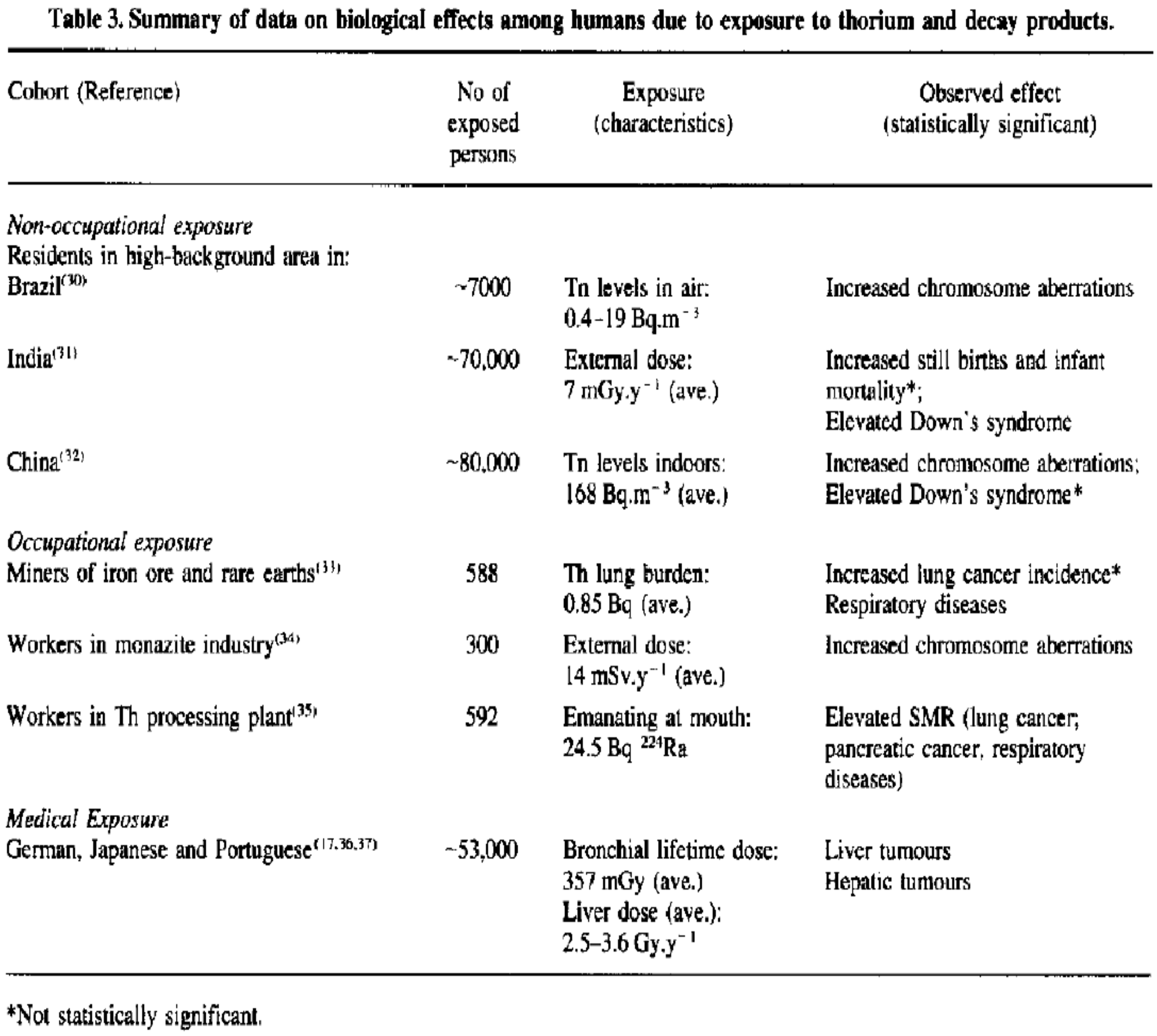

Table 3. Summary of data on biological effects among humans due to exposure to thorium and decay products.

Cohort (Reference)	No of exposed persons	Exposure (characteristics)	Observed effect (statistically significant)
Non-occupational exposure			
Residents in high-background area in:			
Brazil(30)	~7000	Tn levels in air: 0.4–19 Bq.m^{-3}	Increased chromosome aberrations
India(31)	~70,000	External dose: 7 mGy.y^{-1} (ave.)	Increased still births and infant mortality*; Elevated Down's syndrome
China(32)	~80,000	Tn levels indoors: 168 Bq.m^{-3} (ave.)	Increased chromosome aberrations; Elevated Down's syndrome*
Occupational exposure			
Miners of iron ore and rare earths(33)	588	Th lung burden: 0.85 Bq (ave.)	Increased lung cancer incidence* Respiratory diseases
Workers in monazite industry(34)	300	External dose: 14 mSv.y^{-1} (ave.)	Increased chromosome aberrations
Workers in Th processing plant(35)	592	Emanating at mouth: 24.5 Bq ^{224}Ra	Elevated SMR (lung cancer, pancreatic cancer, respiratory diseases)
Medical Exposure			
German, Japanese and Portuguese(17,36,37)	~53,000	Bronchial lifetime dose: 357 mGy (ave.) Liver dose (ave.): 2.5–3.6 Gy.y^{-1}	Liver tumours Hepatic tumours

*Not statistically significant.

Table A8: Biological effects among humans due to exposure to thorium and decay products [Steinhausler 1994].

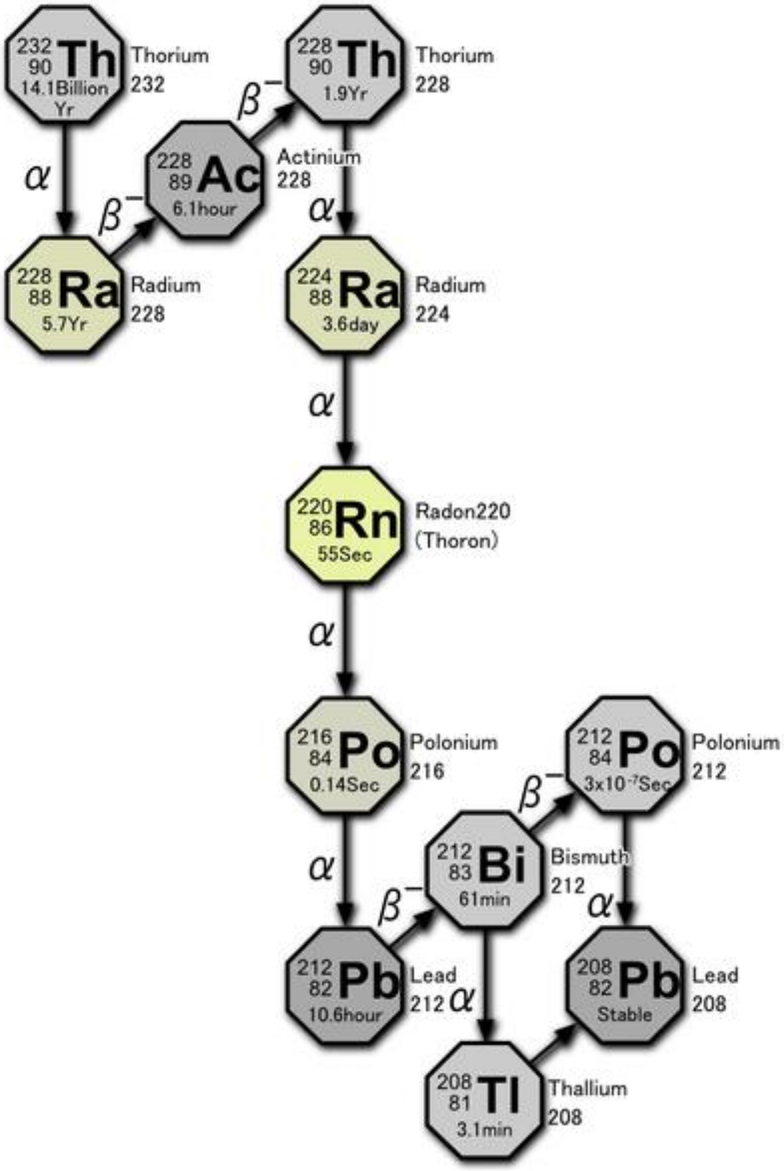

Figure A4: Thorium Decay Sequence [Penny 2010]

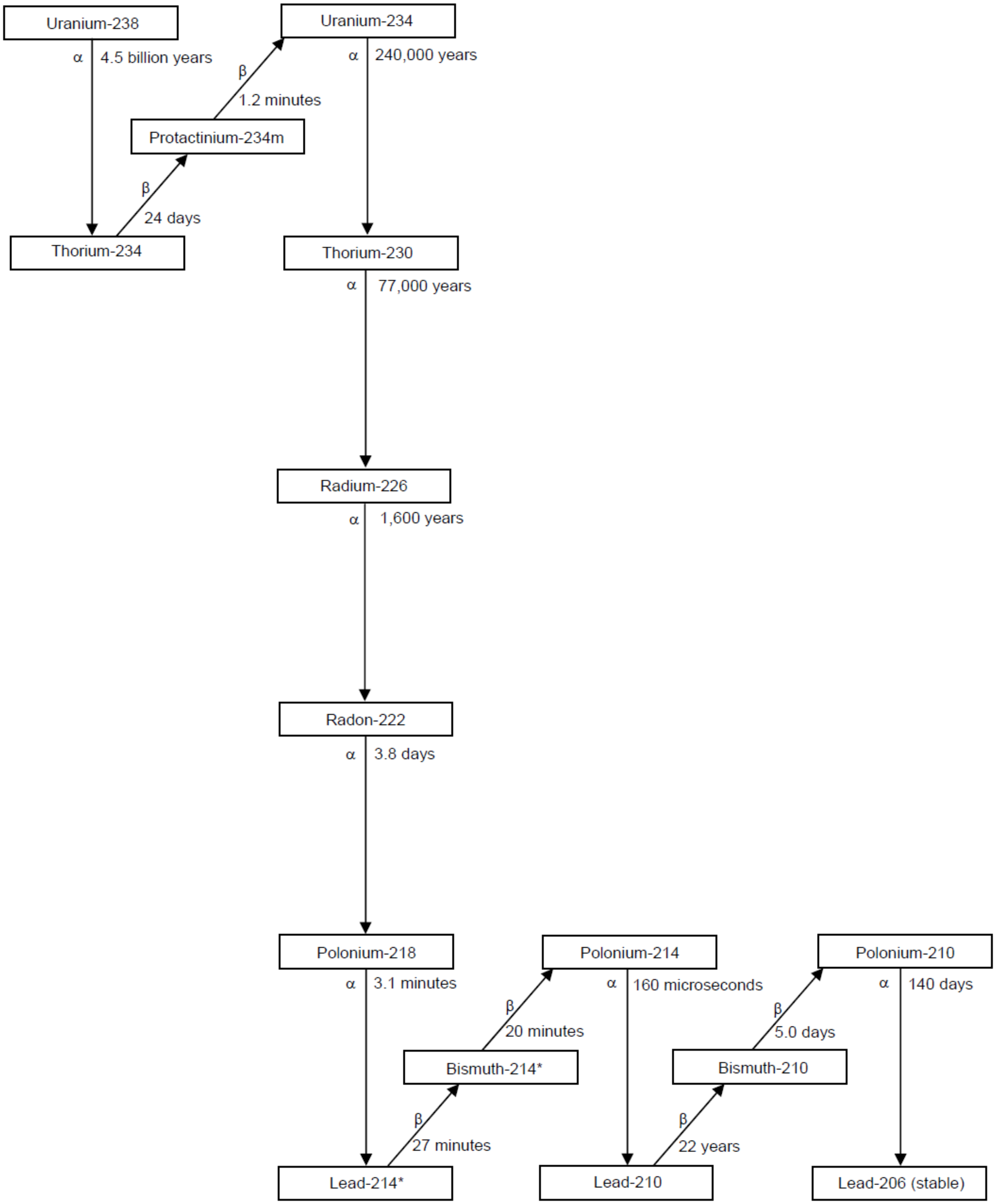

Figure A5: Decay Sequence of U-238 [“Natural Decay Series” 2005]

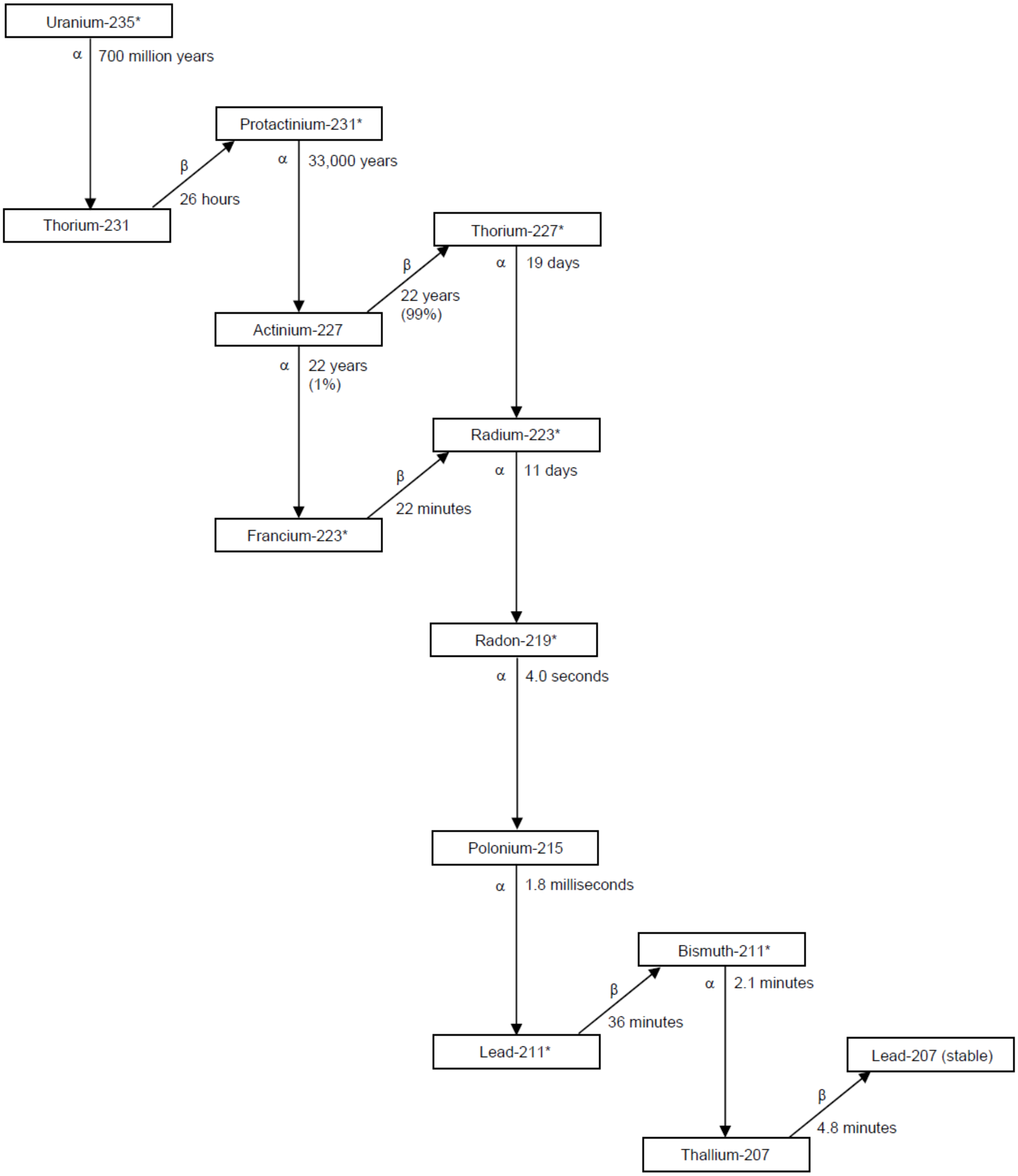

Figure A6: Decay Sequence of U-235 [“Natural Decay Series” 2005]