NUCLEAR POWER
OR A PROMISE LOST

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A Policy Maker's Guide for a Future of a Carbon Free, Sustainable Energy

EDWARD T. BURNS

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*This book is dedicated to my mother, Elizabeth, and my father, Edward,
and the values that they instilled in me.*

*For
Mackenzie, Parker, Edward, and Hudson*

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Preface

The intent of this non-fiction work is to describe the aspects of nuclear power as an energy source and how it may fit into 21st century electrical energy generation. This book captures the status of current electrical energy markets including the principal forces affecting decisions on selecting an energy source. It represents a seminal work that lays out an electrical energy decision tree for selecting an energy source in a world that is on the verge of catastrophic global warming because of the past choices that have been made in the name of cheap energy. The impetus for this book includes the dire need to mitigate continued anthropogenic causes of global warming by enlisting carbon free energy sources.

A discussion of the peaceful use of nuclear energy inevitably requires examination of its relationship to nuclear weapons and the potential for their proliferation. Nuclear power's evolution is described from the pure nuclear physics developments of the early 20th century to the vision of future exotic reactor designs. Along the way, it includes a short history highlighting some of the personalities that led to the development of both nuclear power and nuclear weapons. The detour taken to create the looming destructive power of nuclear weapons is explored because of its place in vaulting the technology forward and its intimate link in the popular press with things nuclear. This book does not include an in depth description of the nuclear physics involved nor does it derive every concept. Rather, it assumes some basic familiarity with the concepts and terminology.

This book is directed at a wide audience to define the critical decisions that are incumbent upon the governments and the peoples of the world related to choosing a future with both sufficient energy to support strong economies and energy sources that will not destroy the environment through toxic wastes and global warming. The emphasis of the book hinges on whether there are energy sources that are appropriate and equitable for both current and future generations. It provides a summary of the broad scope of issues for those interested in formulating energy solutions that are compatible with promoting strong economies and simultaneously ensuring Earth's survivability as a welcoming habitat to the human species.

Some scientific units and level of detail are included for those wishing to delve more deeply into the nuclear power accident investigations but the main purpose is to provide a narrative that describes the journey of scientists, engineers, corporations, and governments into the nuclear age and into the confrontation facing the world beyond 2020 regarding the threats that have brought civilization's survival to the brink.

Peaceful nuclear power arose out of the ashes of Hiroshima and Nagasaki. One of the pioneer engineers around whom a highly technical organization formed was H.G. Rickover, the "Father of the Nuclear Navy". He implemented a concept of a pressurized water reactor (PWR)—developed at Oak Ridge National Laboratory (ORNL)—suitable for use in submarine propulsion. His engineering discipline and drive for excellence was extraordinary as was his insistence on the same dedication from his team. The commercial nuclear program in the US and in many other countries grew out of his vision and his engineering concepts, but the commercial nuclear industry lacked a visionary that could command the same respect and recognition of a single minded objective. Companies like GE, Westinghouse, Combustion Engineering (CE), and Babcock and Wilcox (B&W) struggled with designs and building an infrastructure to support reactor development. Architect Engineers were not prepared for the quality assurance needs of the nuclear power industry. The building boom of the late 1960s and 1970s caused shortages of qualified people to design and construct nuclear plants. This shortage also extended to the early operation of plants where qualified and trained operators were in short supply.

While the industry settled on two fundamental reactor design concepts, a pressurized water reactor and a boiling water reactor, the details of the reactor system and the balance of plant (e.g., the turbine and auxiliaries) were never standardized to a level that made economic sense. The myriad of unusual reactor designs that included wave reactors, lead cooled fast reactors, molten salt reactors, etc. never materialized in the commercial nuclear industry. The basic PWR design concept that Rickover pioneered was adopted with slight variations among 3 of the 4 vendors. Then, GE developed commercial versions of a different variation known as the Boiling Water Reactor (BWR).

The early success at selling these units was due to a combination of:

- Projected high growth rate of electricity demand
- Bargain prices offered by vendors seeking a competitive advantage (including "turnkey" plants)
- Low interest rates
- Optimistic schedules for constructing the units
- Low estimates of the numbers and quality of the operating staff needed to safely operate these plants
- Prestige for a utility to own a nuclear plant
- A regulated utility industry that allowed costs to passed along to customers

During the 1970s, these facets of initial euphoria slowly began to evaporate because:

- The oil embargoes by OPEC slowed the growth rate of electric demand
- The vendors needed to raise their prices to remain in business
- Interest rates increased dramatically crippling financing of these highly capital intensive projects
- Schedules for construction and licensing were extended far beyond what had been projected because of interveners and inability to resolve controversial issues
- The number of personnel needed to safely operate a unit increased far above preconstruction estimates

Finally, as the decade of the '70s was about to close, the event that was not anticipated by the vendors or the utilities happened—a core melt accident occurred at TMI-2. This accident severely damaged the credibility of all those who had believed that man could conquer this complex and potentially dangerous technology without a superhuman effort in design and training. It revealed that the deterministic design basis concept that served the industry so well during the initial development needed to be expanded to consider cliff edge effects. Probabilistic Risk Assessment (PRA) and the consideration of severe accident phenomena in the design and procedure development of nuclear reactors was identified as a supplement to the design process.

The evolution of PRA as a tool for use in examining accidents beyond the design basis was slow to take hold but the NRC and industry gravitated to this methodology for difficult problems that ventured beyond the design basis and defied simple solutions based on the deterministic rules. In the 1990s, there was a flurry of activity as the NRC had mandated that a PRA like approach be applied to each nuclear plant. During this time, Dr. Bob Henry, Jeff Gabor, and Don Vanover (experts in the modeling of thermal hydraulic processes governing severe accidents) worked to provide critical severe accident analyses to satisfy the NRC requests. Their work pointed out many issues with plants and their procedures as qualitative and quantitative insights. Many of these procedural issues were resolved in the BWR Owner's Group (BWROG) Severe Accident Management

Guidelines (SAMGs) that were then developed by Taggart Rogers working within the Emergency Procedures Committee of the BWROG. Successes of the application of PRA techniques continued into the 21st century with effective on-line maintenance applications, design changes, extensions in allowed outage times (AOT), and other changes that improved the economics of the nuclear plants while maintaining a high level of safety. Similar SAMGs were also developed for PWRs.

Today, the need for an energy source that produces no carbon dioxide discharge to the atmosphere is cited as critical to the future survival of the Earth System as we know it. Protecting the Earth from a rapidly accelerating global warming that represents an existential threat to the world's growing population has become an important but controversial topic. The threat is encapsulated in the identified possibility of slow developing feedback mechanisms that may not fully reveal themselves until a so-called cliff edge is passed making the drawing back from the precipice impossible. The question is whether a safe nuclear power industry can act as the support network for renewable energy sources in an economic manner plus solve the other residual issues such as the secure and safe disposal of high level nuclear waste. The status of the world's climate and projections for the disruptive effects of global warming on future populations, migration, economics, and world strife are debated against the backdrop of an increasing world population and the drive by developing nations to achieve economic parity with the industrialized nations. Within a context of increased world strife, the quest by nations to obtain nuclear weapons is also discussed. Because the nuclear power discussion cannot be even-handedly done without acknowledging the relationship to nuclear weapons, a portion of this book addresses this relationship and the potential for nuclear weapons proliferation. The importance of this topic cannot be overestimated because the very existence of the human race is threatened by those nations that continue to flaunt their arsenals of nuclear weapons without a respect for the awesome responsibility entailed in their use and even their continued existence. The steps taken by the world to limit nuclear weapons proliferation are examined with emphasis on potential links between nuclear power generation and access to nuclear weapons.

This book lays out an electrical energy decision tree that characterizes the advantages and disadvantages of different energy sources to frame the problem of the electrical energy supply decisions that need to be answered. Each energy source has its own disadvantages and it is necessary to make objective and sometimes subjective judgments regarding the efficacy of using each energy source in the support of electrical grids. By understanding these advantages and disadvantages of energy sources, informed decisions can be made in a way that respects the needs of current generations and the expectations of future generations.

Doomsday prognosticators have long existed citing imminent threats causing the end of the world. Many times these predictions come in the form of a messianic cult-like figure. Even if we may not like the messenger or his method of delivery, it can still be relevant to heed the message or the call to action before the threat takes an unwanted toll on humankind.

The human species has shown a remarkable ability to overcome challenges from nature and technology—to cope with, and adapt to, imminent threats. Sometimes this coping mechanism is not elicited until the threat becomes strikingly apparent. While this human trait will undoubtedly continue, it should not prevent humankind from attempting to anticipate threats and challenges and seek to avoid them by using prudent risk averse approaches.

Chapter 1
Introduction

OVERVIEW

The wise use of natural resources to ensure a hospitable environment for the human race has become a source of widespread discussion, protests, and calls to action. This revolves around the fact that the world faces a climate crisis that has been brought on by the actions of humans releasing sequestered carbon into the atmosphere potentially creating a "hot house" environment on Earth. This is manifested in an increasing global average temperature and the accelerated melting of both Arctic and Antarctic glaciers and sea ice.

A potential path to preventing or substantially mitigating this crisis is through the use of energy sources that do not emit greenhouse gases (GHG) in the generation of electrical energy for homes, industry, and transportation. One of these potential energy sources is the use of nuclear energy, however, this energy source has encountered significant issues that create uncertainty with regard to its overall safety and cost. This book examines the dilemma of a global climate crisis and the efficacy of using nuclear energy to prevent and mitigate such a crisis. As part of this examination, a logical and systematic approach to decision making is presented to assist in the formulation of informed choices regarding future electrical energy generation sources.

The historical origins of nuclear power are outlined. Then, the continued impetus to include nuclear power as part of the electric energy grid mix is assessed exposing the obstacles and roadblocks to the continued use of nuclear power. Specific attention is paid to revealing the causes and lessons learned from the three severe accidents in commercial nuclear plants: TMI-2, Chernobyl, and Fukushima. An extensive discussion of nuclear waste disposal is also provided as part of the decisions required for energy selection. A second critical focus of the book is a plea for the elimination of nuclear weapons, another existential threat to humanity. Considerations to address steps toward nuclear non-proliferation are examined as a key aspect of the world's future.

THE DILEMMA

The world is on the verge of catastrophic global warming as a direct result of choices made in the name of cheap energy. In both the developed and developing world, populations have thrust massive amounts of sequestered carbon in the form of GHG into the atmosphere. This increase in GHG emissions has resulted in trapping ever increasing fractions of the sun's infrared rays within the atmosphere prompting a "hot house" effect that manifests in a rising global average temperature. Therefore, these human activities have created: (1) the potential for substantial transformation of the global climate; (2) increasing ocean temperatures with accelerated melting of both Arctic and Antarctic glaciers and sea ice; (3) continued sea level rise with consequential challenges to the integrity of coastal mega-cities; and, (4) a threat to our ability to maintain sufficient water and adequate food for the growing world population.

Chapter 4 and Appendix A lay out the case for the correlation of increasing global temperature linked to the increases in atmospheric GHG. They also identify the ways this condition manifests itself in increased frequency and magnitude of high precipitation events, rising sea levels, increased storm intensity, and increased periods of extended droughts. Most frightening, it identifies possible cliff edge effects that can result in feedback that can reinforce and accentuate these adverse impacts on the Earth's ecosphere.

Under these conditions, energy technologies that promote continued prosperity without contributing to global warming need to be urgently adopted, both to maintain economic vitality for developed countries and to establish a positive economic trend for developing nations. One such energy technology is nuclear power, which has the potential to provide the electricity needed for industrial activities, residential use, and a burgeoning electric transportation complex. However, there remain multiple obstacles to the use of nuclear energy including cost, risk of accidents, and waste disposal. Have we now reached a tipping point, where these obstacles to nuclear power can be resolved and nuclear energy can be accepted as necessary to preserve the environment, civilized society, and economic growth?

THE ORIGIN OF NUCLEAR POWER

The historical perspective on the origins of nuclear energy development from its beginnings as novel physics research into the nature of the nucleus to its manifestation in nuclear weapons is presented in Chapter 2.

RADIATION

Chapter 3 discusses radiation as it influences the health and safety of the public. Particular attention is given to the sources of radiation from nuclear power installations. The ubiquitous nature of radiation sources throughout the human experience is emphasized. This includes the radiation that encroaches on the world's population due to all forms of electromagnetic radiation. Insights into what is known about radiation and its health impacts are provided for a spectrum of exposures based upon observed effects from accidents and nuclear weapons. The theory that conservatively tries to link the radiation dose to human health effects, the Linear No Threshold (LNT) theory, is discussed. Inadequacies in the LNT theory are identified especially in the low dose regime by emphasizing the body's ability to cope with radiation. The LNT theory and its use in specific applications are examined.

ELECTRICAL ENERGY DECISION TREE

In order to responsibly establish an equitable, reliable energy mix as part of a nation's electrical grid, a discussion of a wide range of economic, social, and political factors that influence the selection of these energy sources is necessary. In Chapter 4, a primary focus of this book is set forth: the decisions that need to be made by the public, politicians, scientists, engineers, and industry executives to determine if nuclear power is worth saving as an alternative energy source in view of the current and future challenges facing humanity due to the on-going global warming associated with the continued use of fossil fuels.

A primary motivation that necessitates rethinking electrical energy generation sources of the 19th and 20th centuries is a series of scientific studies that have identified an existential threat to the Earth as we know it. This threat is linked directly to human actions in burning previously sequestered carbon and discharging vast quantities of carbon dioxide to the atmosphere. This GHG atmospheric accumulation has caused the Earth's temperature to rise by trapping long wavelength infrared electromagnetic waves radiated by Earth and leading to adverse effects on the global climate.

In this examination, it is important to be aware that each country has a unique set of needs and restrictions affecting their decisions about which energy sources can viably meet their demands. The Electrical Energy Decision Tree (EEDT) found in Chapter 4 of this book highlights the critical decisions citizens and countries must make in optimizing its energy sources. The decision tree approach examines the attributes of viable energy sources to provide a framework that can lead to logical conclusions in selecting among these sources. The decision tree involves multiple considerations to examine the rationale for selecting electrical generation energy sources. These considerations include the following:

- Availability of energy resources
- Costs, health effects, and long term adverse global warming effects
- Subsidies and portfolio mandates for renewable energy sources
- Reliability and diversity of energy sources
- Energy independence
- Waste
- Risk considerations

Particular attention is focused on whether or not nuclear energy can fulfill a critical need for energy yet maintain a safe and economic energy source. The context for the future of nuclear power as a viable energy source is illuminated by the current confrontation between economic growth and the harm created by burning fossil fuels. The projections for the disruptive effects of global warming on the uprooting of entire populations leading to mass migration, the adverse effects on national economies, and the ensuing world strife are debated against the backdrop of an increasing world population and the drive by developing nations to achieve economic parity with the industrialized nations. Responsible energy decisions must be guided by a knowledgeable public and national government so that the energy sources selected meet that country's consensus goals. Without such input, deregulated utilities will always choose the lowest perceived cost energy source, regardless of the attendant damage to the country's ecosystem, environment, and public health. Risk averse actions to forestall or prevent catastrophic global warming must acknowledge the reality that there are strong, short-term incentives to produce electrical energy at the lowest possible direct costs. To provide a proper counterweight to such short-term incentives, a means to expose the full accounting of all the costs associated with an energy source is required. These indirect or hidden costs include both increased health care and environmental costs. Chapter 4 compares the advantages, disadvantages, and biases applicable to each energy source. As will become apparent, the battle for the environment and public health includes a moral struggle between the immediate good for current generations versus the long-term benefit for future generations. Appendix A provides an expansion on this discussion. The ability to engage populations and central governments in this conversation is critical to optimizing the choices they make.

A primary positive effect of the use of nuclear energy includes benefits associated with preserving the Earth's environment by reducing GHG emissions. As nuclear units supplant coal fired and combined cycle natural gas plants, the large reduction in CO_2 discharges to the atmosphere represents a positive method of environmental preservation while simultaneously supporting continued advancement in economies. In addition, the use of nuclear energy represents a diverse energy source that can make the world much less dependent on the oil and gas producing countries (e.g., the Middle East, Venezuela, Africa, and Russia) particularly in the future where transportation vehicles become increasingly electrified with the attendant reliance on the electrical grid. This has the potential to drastically reduce a major source of the GHG and atmospheric pollution that have been tied to humankind's love affair with burning fossil fuels.

THE RISE OF NUCLEAR POWER

Chapter 5 discusses the development of nuclear energy as a technological marvel of science and engineering. Beginning with the birth of nuclear power that was intimately tied to the development of the atomic bomb, this perceived relationship has been firmly embedded in the minds of the public and political figures. This association of nuclear energy power plants with nuclear weapons has contributed to the reluctance by many countries to accept nuclear power as a legitimate, peaceful source of energy.

The nuclear story is laden with unique personalities, people who have demonstrated both admirable human traits and those frailties of the kind found in intriguing novels. These personalities are discussed throughout this book as they have influenced different aspects of the development and use of nuclear energy. They include the following:

- Robert Oppenheimer
- Edward Teller
- Joseph Stalin
- Albert Einstein
- Hyman G. Rickover
- Franklin D. Roosevelt

The evolution of nuclear power is built on the accumulated efforts of giants in the fields of physics, chemistry, and engineering. The great scientists and engineers from all walks of life conversed in a common language, seeking to uncover the mysteries of the atom and apply its potential for the benefit of humanity.

Nuclear power as a US commercial energy source was born out of the Atoms for Peace initiative put forward by President Dwight D. Eisenhower in the 1950s based on several key beliefs. The first was that the world's oil reserves were finite and would eventually be exhausted, making oil prices prohibitive. On the other hand, nuclear energy, appeared to be limitless, especially if fast breeder reactor technology could be made safe and economical. In addition, a synergistic relationship apparently existed between the national security need for a nuclear deterrent and the development of nuclear power—they both involved similar resources, the same enrichment path, and similar technologies, and both depended on the availability of highly educated and trained scientists and engineers.

Caught up in the initial euphoria over this exotic and advanced energy source, utilities viewed having a nuclear plant as a sign of great prestige. In addition, in the regulated electric utility environment of the 1960s and 1970s, the Public Utility Commissions (PUCs) allowed legitimate progress costs to be passed along to the consumer. This resulted in a rapid growth of the nuclear power infrastructure as a means to achieve energy diversification. During the rise of nuclear power as an important component of the US electric energy supply, there were many stumbling blocks along the way. These took the form of high interest rates for construction loans, the severe accidents at TMI-2 and Chernobyl, and the failure of utility management to efficiently operate nuclear plants to maximize their availability and capacity factor. Nevertheless, in most of the 20th and in the early 21st century, the possibility of using this energy source to diversify their energy portfolios was attractive for utilities. After a pause in new US nuclear power plant orders following the TMI-2 accident in 1979 and the subsequent birth of the Institute of Nuclear Power Operations (INPO), nuclear power plants in the US achieved very high capacity factors making them an attractive and cost effective means of electric power generation especially compared with the high cost of natural gas at the time. It appeared that a nuclear renaissance was on the horizon. Today, the impetus for energy diversity has shifted from concern over finite oil and gas reserves to a concern over an existential threat to the global environment. The continued development of nuclear power plants represents a risk averse hedge against the exclusive use of fossil fuels (coal, gas, and oil) that contribute such a large fraction of GHG emissions by providing the electrical grid with the needed baseload electrical generation capacity while the grid adapts to the expansion of intermittent and renewable electrical generation sources.

Nuclear power technology has been forced to address the following throughout its history and evolution:

- Misgivings about its intertwined military origin and commercial application
- Fear of the proliferation and use of nuclear weapons

- A legacy of radioactive waste
- Accidents affecting local and world populations
- High capital costs

Principal among these is the fact that politicians and the military have co-opted the beneficial and peaceful aspects of nuclear energy and created massive stores of nuclear weapons. As a result, the narrative regarding nuclear power has become conflated with the issue of nuclear weapons proliferation. These same politicians of the nuclear weapons states (NWS) have been ineffective in ridding the planet of the nuclear weapons threat despite the commitment in the nuclear Non-Proliferation Treaty (NPT).

The promise of an energy source that allows increased independence from Middle East and Russian oil and natural gas reserves, while also offering the possibility of controlling the massive discharges of CO_2 emissions into the Earth's fragile ecosystem, now seems to be fading. This is occurring despite the fact that the uses of nuclear technology extend far beyond military weapons and even electricity generation to applications such as power for space exploration and life-saving medical treatments.

RISKS OF NUCLEAR ENERGY: ACCIDENTS AND RADIATION

The history of nuclear energy is fraught with overblown promises and rhetoric that exaggerates the benefits and minimizes the risks. Advocates such as Lewis Strauss (Atomic Energy Commission (AEC) Chairman during the 1950s) promised electric power that was "too cheap to meter." He was also the 'tone deaf' AEC Chairman who hid the adverse health consequences of nuclear weapons testing from the public. Nuclear energy has been shown to be both a reliable source of electrical baseload generation but if not strictly regulated it can lead to catastrophic accidents. The promise of nuclear power as a source of energy for generations to come must be understood in the context of the costs and risks it presents to achieve these benefits. To provide this perspective, a detailed review of the three commercial nuclear reactor accidents is provided in Chapter 6.

NUCLEAR FUEL CYCLE AND NUCLEAR WASTE

Next, the issues with the nuclear fuel cycle and eventual storage of high level nuclear waste are discussed in Chapter 7 and Appendix C. Chapter 7 also reviews the task of minimizing proliferation risk in the advanced fuel cycle research. Chapter 7 summarizes the investigations into high level nuclear waste disposal including the consensus solution—the deep geologic repository (DGR) as being constructed in Sweden and Finland in 2020. In this regard, most nations have not definitively engaged in near term implementation of a repository and as a result, there is a scramble by utilities to find interim storage locations for used nuclear fuel, which presents its own low level of risk.

NON-PROLIFERATION

In Chapter 8, within the context of increased world strife, the quest by nations to obtain nuclear weapons is discussed. To counter this pursuit of new weapons, the steps taken by the world to limit nuclear weapons proliferation are examined with emphasis on potential links between nuclear power generation and access to nuclear weapons. Successes of the world community in preventing the spread of nuclear weapons are offered as proof of the efficacy of the steps being taken. In addition, the complicit failure of the nuclear weapons states (NWS) (including the US) to fulfill their pledge to eliminate nuclear weapons is underscored.

LICENSING AND REGULATION

The use of nuclear power requires a strict regulatory environment to ensure the safety of nuclear plants and the nuclear fuel cycle. Therefore, in

Chapter 9 key aspects of the current US regulatory framework are outlined. As part of this regulatory environment, the licensing process requires an assessment of plant response to accidents using strict deterministic rules. However, the severity of accidents in the deterministic coping assessment for Generation II reactors (i.e., operating reactors) was limited to what is generally called the 'maximum credible accident' including design basis accidents (DBAs). However, in the US, future reactors (i.e., Generations III and IV) are being subjected to additional requirements to further enhance safety as discussed in Chapter 10.

PROBABILISTIC RISK ASSESSMENT

Chapter 10 describes a supplemental examination of nuclear reactor safety to offer a different perspective than achieved with the purely deterministic DBA approach. This additional examination expands the boundaries of the original deterministic licensing process by using a probabilistic risk assessment (PRA) methodology. This expansion includes increasing both the types and severity of accidents evaluated. This approach is dictated as part of the US licensing process for new reactors including Generation III and IV reactors. PRA broadens the examination to include severe accidents in a risk assessment supplemented with deterministic requirements as a method to focus attention on severe accident mitigation and the benefits of the containment. PRA also has the potential to identify cliff edge threats that could be remedied early in the design stage by proper design or procedures.

MORAL RESPONSIBILITY

Chapter 11 discusses the moral responsibility that current generations have toward future generations. Specifically, the applicability of the concept of "intergenerational equity" in political and social decision making is laid out. However, while aspects of intergenerational equity have become part of court cases in the US and in Europe, the commitment to it particularly as it applies to the use of fossil fuels is found to be sorely wanting.

CONCLUSION

The final chapter presents a consolidation of the conclusions from this review of energy sources and the place nuclear power holds in the future of the world energy economy.

Can the public and their politicians, with an imminent climate crisis developing and in the face of the calls to halt nuclear proliferation, come to grips with the promise of nuclear energy?

Chapter 2

Historical Perspective on the Discovery of Nuclear Reactions and Radioactivity

The evolution of nuclear technology is built upon the accumulated efforts of the giants in physics, chemistry, and engineering. These great scientists from all walks of life conversed in a common language of science seeking to uncover the mysteries of the nucleus.

This chapter includes a brief historical perspective on the following:

- Discovery of Radiation and its Effects
- Theory of Relativity and The Evolution in Understanding Atomic Structure
- Nuclear Fission
- The Atomic Bomb
- The Cold War and the Hydrogen Bomb

The following discussions trace the origins of key scientific discoveries, engineering accomplishments, and political machinations that formed the basis for the eventual discoveries of the fission process and its implementation in nuclear power plants and nuclear weapons.

DISCOVERY OF RADIATION AND ITS EFFECTS

The early years of productive scientific research into the atomic structure of matter and the march toward understanding the nature of the atomic nucleus was dominated by European scientists. For example, Wilhelm Conrad Röentgen, a professor at Würzburg University in Germany discovered X-rays in 1895. Röentgen received the first Nobel Prize in physics in 1901 for his discovery of the electromagnetic waves that he referred to as X-rays. As in many cases in experimental science, the discovery was made not as the result of a targeted investigation, but rather as a result of ancillary observations made during his use of a high voltage cathode ray tube. Crystalline structures that "happened" to be nearby began to glow when the cathode ray tube was operating. [551] The X-rays are generated from unstable atoms that can be created if a high energy beam of electrons displace electrons from the inner shell of an atom. The unstable atoms then attempt to reach a stable configuration by replacing the missing electron. This return to stability releases energy in the form of electromagnetic waves, X-rays. Within several weeks of investigating this new phenomenon, Röentgen observed that these electromagnetic waves could penetrate soft tissue but not bone, and could be recorded on photographic plates. [551]

Then, in 1898, Henri Becquerel and his Ph.D. student, Marie Curie, discovered that rays emanating from certain naturally occurring elements were similar to the X-rays discovered by William Roentgen in 1895 and produced similar reactions. Marie Curie [3, 15] named the phenomenon of elements emanating these rays as radioactivity. The initial elements that were studied as having this property were:

- Uranium
- Thorium
- Polonium
- Radium