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Preface

Teaching college students how to solve equations is easy to do. But teaching students how to design systems is more complex, mostly because it is less regimented. From our experience as graduate students in nuclear engineering we feel that the process of designing reactors has not been adequately covered by the existing curriculum. Perhaps this is due to the fact that reactor designs seem limited to PWRs and new construction is quite rare. Our hope is that this book will help prepare young engineers to design the reactors of tomorrow. (Our hope is that we are among those engineers). Furthermore, all existing nuclear reactors were designed about fifty years ago, so our goal is to learn from those who were there when it happened. Perhaps this book can be used as the basis for a course in reactor design.

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Chapter 1

Starting from a Clean Slate

1.1 Initial Design

It all starts with a mission, a set of goals that must be accomplished. There are five types of missions: Commercial power, propulsion, science/medical, military, and political.

- **Commercial power.** Missions typically state requirements on power rating, fuel loading cycle, and operability. Constraints are usually to satisfy regulatory requirements for safety. Design goals include anything from small modular reactors to breed and burn reactors to the familiar behemoth LWR. The idea is usually to maximize profits to the owner/operator.
- **Propulsion.** Nuclear fission provides a large supply of power in a very compact space. At various times the ability to continue almost indefinitely without refueling has been desired for marine, aeronautical, locomotive, and space propulsion. Thus the requirement is to minimize size and weight and provide power on demand.
- **Science/medical.** Small test reactors are desirable for producing irradiating targets. The goal may be to produce isotopes through neutron activation or fission or to test materials under neutron bombardment. Thus the goal is to provide neutron flux to a target. The product of these reactors is either data or isotopes.
- **Military.** The power density of nuclear is desirable to the military because it eliminates the need for supply chains. (Sub)marine propulsion is the primary application, but there is also interest in land-based power. Cost becomes less of an issue for these applications and where power may be needed at a moment's notice.
- **Political.** Nuclear reactors may be commissioned as a demonstration of a country's technological capabilities. Due to the cost of R&D and manufacturing, government leaders are often involved in the nuclear industry. Political missions may fulfill long term needs that could not be supported by commercial entities.

Given the mission, a list of requirements must be generated. There will be constraints and quantities to be optimized. For example, the customer desires maximum thermal flux, but also expects a safe reactor. This list of requirements and reactor attributes will guide the reactor design process.


Several key attributes are desirable for almost every nuclear reactor

- **Safety.** Nuclear engineers are ethically responsible for designing reactors that will not harm the public.
- **Economics.** Saving money is always good.
- **Efficient fuel utilization.**
- **Non-proliferation.** This reactor should not be an avenue for your enemies to acquire materials for nuclear weapons or dirty bombs.

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There are many attributes that may be desirable or required for a reactor. The mission will dictate which features are necessary, desirable, or unneeded.

- Minimizes enrichment requirements
- Breeds fissile material from fertile isotopes
- Destroys stockpiled fissile materials
- Destroys transuranic waste
- Minimizes total fissile material in-core inventory
- Longer intervals between refueling
- On-line refueling
- Provides high temperature process heat
- Capable of changing power rapidly to follow load demands
- Low weight to enable mobility or efficient propulsion
- High flux (fast or thermal) on target

Nuclear reactor design is multi-disciplinary by nature. Neutronics design affects thermal-hydraulic design and vice versa. Structural and material analysis must also be included. . The coupled effects between disciplines confound the design process, thus design iteration is necessary.

First the design parameters must be selected for each discipline. Pitch and diameter of the fuel pins affects thermal-hydraulics, whereas enrichment is a parameter of the neutronics design. It is necessary to obtain an understanding of how these parameters effect the metrics of interest.

1.2 Homework Problems

1. (a) For each of the following reactor missions list several requirements and/or desirable attributes that the reactor should have. (b) List a type of reactor that would and one that would not be suitable for this mission.

A reactor for utilizing limited fuel resources. A reactor that can transmute actinides. A reactor that is proliferation resistant.

1.3 Cold Fusion

Some things are too good to be true. Often when people design a new paper reactor they describe it as the savior of the industry. The truth is, every reactor has a downside. Even a reactor that is optimized for one mission will be inadequate for other missions. It is important to keep an open mind when designing new reactors. But it is also important to make decisions based on analysis of *all* the pertinent considerations. By all means be a proponent of your reactor design, but understand that it will have limitations.

Chapter 2

How Did We Get Here? The History of Nuclear Energy

In the field of nuclear technology, change is difficult. Developing materials that can withstand high temperatures and intense radiation is a timely, laborious process. Proving new technologies and demonstrating extreme reliability of parts in any foreseeable environment is costly. Imagining and protecting against extremely low-probability events is even more difficult for new ideas with unknown failure modes.

All of these hurdles and more must be overcome in order to implement new reactor designs. At the time of this writing, it seems that these hurdles are so large in the United States that the LWRs will be the only design ever built here. Indeed, looking back on the history of nuclear power, no reactor design has ever successfully reached market that was not driven primarily by the government. In other words, the benefits of advanced reactor designs are not enough to warrant the monumental investment from industry that would be needed to develop new technology. This is greatly exacerbated by the decades-long research and development time frame.

2.1 World War II

2.2 Naval Reactors

2.3 Design Evolution

2.4 Growth of Safety Requirements