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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.

Contents

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. This boils down to two requirements
  - Contain the fission products
  - Cool the reactor

- 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.
-

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. ¡insert flow-chart graphic¿. 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 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

Fission was discovered in December 1938. It's potential was immediately realized and the race to develop the ultimate bomb began. Uranium bombs require enrichment facilities, but plutonium bombs could be fueled by reprocessed fuel from a reactor. Thus the mission for the first reactors was anything that could produce plutonium. The key attributes were the use of natural uranium and quick production time. Safety was established by siting the reactor in an uninhabited area of Washington state and following good engineering practices. Graphite moderated, water cooled reactors were the clear choice because heavy water was too scarce.

Following the war plutonium production was still a key objective so further breeder reactors were built at Hanford. Heavy water reactors were constructed at the Savannah River Site in South Carolina. All of the energy produced from fission was simply dumped into rivers, rather than used for generating electricity.

In 1951 the EBR-I reactor demonstrated that nuclear reactors could be used to generate electricity. In 1954, Russia began operation of the first nuclear reactor that was connected to an electrical generator with a rating of 5MWe. Similarly, without sufficient enrichment capabilities, the United Kingdom used natural uranium metal, gas-cooled, graphite moderated reactors. The first of these came on line in 1956. France followed a similar path as the UK with graphite moderated, gas cooled reactors. Canada completely avoided the path to enrichment and utilized their heavy water capabilities to create reactors.

2.2 Naval Reactors

In the 1950s Admiral Hyman Rickover oversaw the development of pressurized water reactors. In order to fit a reactor into a submarine, highly enriched fuel and light water were used. In 1954 the USS Nautilus was launched. Zirconium purification was developed to support the naval reactors program—previously zirconium was unsuitable due to Hafnium impurities.

With the research and development covered by the naval reactors program, light water reactors were now feasible for use by electrical utilities. In 1957 the Shippingport 60 MWe reactor began operation as the first commercial nuclear reactor in the United States.

2.3 Design Evolution

From the starting point of light water reactors, technology steadily improved performance without any major design changes. Most of these developments involve enhancing fuel performance. Various alloying elements were added to zirconium to improve corrosion resistance. This was essential for increasing the amount of time the cladding could survive in the core. In 1977 when President Carter banned reprocessing of fuel, reaching higher burnup became the key goal for fuel management. Until that point it had been understood by the industry that fuel would be reprocessed by the Atomic Energy Commission.

Controlling the grain size of sintered UO_2 allows for mitigating swelling and better retention of fission products. Creating a dished shape allows the pellets to accommodate thermal expansion and reduce stress on the cladding.

2.4 Growth of Safety Requirements

From the very beginning, safety has been integral to the development of nuclear reactors. At the Chicago pile, Fermi stationed a Super-Critical Reactor Ax Man to drop boron into the reactor if anything should go wrong. The plutonium production reactors were sited at Hanford to minimize the impact of a catastrophic failure. Admiral Rickover demanded that those designing the submarines took as much care as if their sons were aboard the ships.

As an extra precaution, the Shippingport Reactor was constructed with a containment building in case of a reactor meltdown or malfunction. All of the subsequent reactors followed suit. Initial safety considerations followed the idea of the maximum credible accident. Initially this was a reactivity insertion. Commercial designs prevented withdrawing control rods too rapidly, so the next scenario to worry about was a Loss Of Coolant Accident (LOCA). After 1966, the Emergency Core Cooling System (ECCS) began to be viewed as necessary in order to prevent disastrous consequences of a LOCA. “it has certainly obtained the bulk of the resources expended in nuclear reactor safety research.”[1]

In 1975 the Nuclear Regulatory Commission (the successor of the Atomic Energy Commission) published the Reactor Safety Study (WASH-1400). This report used Probabilistic Risk Assessment to estimate the risk that nuclear reactors pose to public health. The report showed that human error and small-break LOCAs were larger concerns than the maximum credible accidents that had been previously fixated on.

The 1979 accident at Three Mile Island unit 2 served as a wake-up call to the nuclear industry that serious accidents could occur. The importance of a safety culture became apparent. Human error finally became a major focus of safety. On the engineering side, better instrumentation and presentation in the control room were now clearly necessary.

Construction costs had been escalating in the 1970s and increasing regulations from the nascent Nuclear Regulatory Commission added to the load. The accident at TMI turned public opinion against nuclear energy and many construction projects were stopped or canceled.After the Chernobyl disaster occurred in 1986, nuclear power was even more taboo.

In the 1990s passive hydrogen recombiners were recommended as a retrofit.

With rising oil prices and growing concerns about global warming in the 2000s, attention turned back to nuclear power. Several construction projects resumed. The capital and construction costs of multi-billion dollar nuclear plants have become the major impediment to new construction. Even though the risk is low, the return on investment is so long in coming, that capital is hard to obtain. Small modular reactors were considered the solution to this problem. Research and development along this line is ongoing. Commercial plants must be designed to minimize construction costs (including time) which account for 60% of the cost of electricity [2]. Fuel costs only make up 20% of the cost of electricity, which is significantly less than fossil fuel plants. Thus fuel efficiency and even thermal efficiency may be less than ideal in the minimum cost reactor.

2.5 Other Reactor Designs

Up to this point in the chapter only a few reactor types have been discussed. This is because nuclear technology has been inextricably linked to government research and development for military use. Graphite reactors cooled with either water or gas stemmed from plutonium production efforts as did heavy water reactors. Light water reactors grew out of naval propulsion programs.

Given that the goals of commercial power plants differ from the military goals that the reactor designs grew out of, it is unlikely that these designs are optimal for power production. Furthermore, the perspective taken on issues of safety has significantly changed in the 50 years since the reactors began operation.

To be fair, many reactor designs have been created and prototyped. Gas-cooled reactors, sodium-cooled fast reactors, organic-moderated reactors, molten-salt reactors, lead(-bismuth)-cooled reactors have all been operated. But they have all been discontinued because of various setbacks and challenges. Could it be that given a government R&D push like LWRs experienced, that these advanced reactor designs would out-perform the current standard?

Perhaps the additional impetus will come from shortages of U-235. SFRs have received considerable attention throughout the years because they can accomplish a mission that thermal reactors cannot: breeding their own fuel. But that goal has become less important as uranium ore deposits continue to be discovered.

2.6 Homework Problems

1. What materials were used for the first critical assembly? What limitations drove this selection? How did other reactors follow in these footsteps?

2. Pick a country and briefly describe its nuclear history. What factors influenced the evolution of their technology?

3. Imagine you are the leader of a non-nuclear state. What technologies and strategies would you pursue to obtain a) nuclear weapons b) nuclear power c) independent nuclear power technological capabilities.

4. Research a reactor design you don't know much about. Why is this type of reactor not more widely used?

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Chapter 3

How to Begin

This part might go in Chapter 1???

3.1 Design Progression

While it may be tempting to attack a design problem with all of the computational tools at your disposal, that may not be the best approach. Informed decisions at the beginning of the project reduce the amount of work that you and your computer will have to do. In general, low-fidelity methods or formulations are entirely satisfactory at the start. Simple calculations also tend to provide understanding and intuition that will be useful as the design process continues.

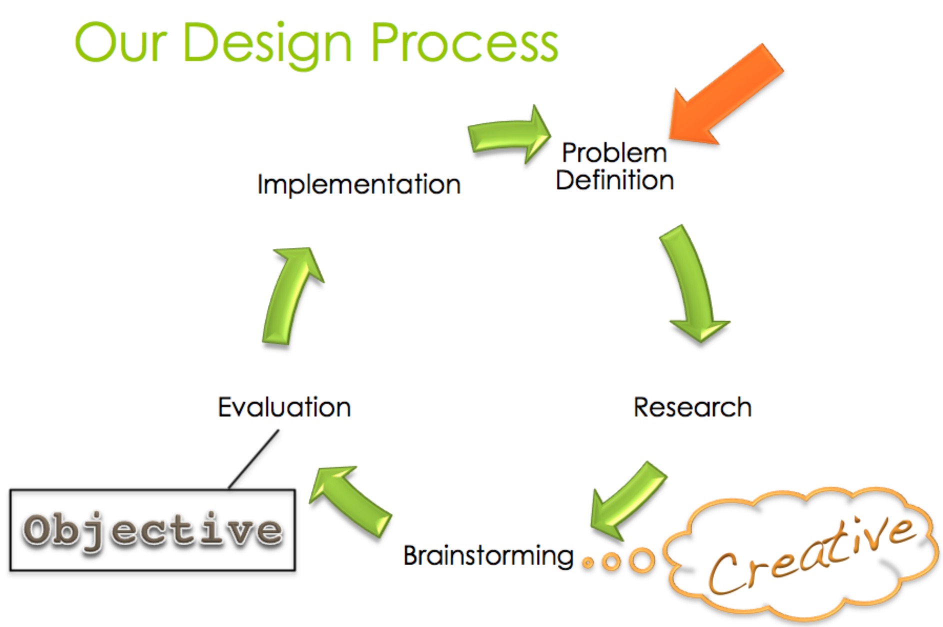

Figure 3.1: Simplified design process. (Graphic from http://ahmackenziedesign.com/faq/)

As the design matures, so should the tools being used. Think of computer codes as sieves. Low-fidelity codes will filter out designs that obviously won't work and more sophisticated tools may be needed to decide between closely competing design alternatives.

That being said, the ultimate goal is to reduce the time needed to generate a satisfactory design. There is no reason to spend more time on a less accurate method. For example, spending an hour to calculate the four-factor formula by hand with analytical methods is not as wise as waiting 15 minutes for the results from a Monte Carlo simulation. So the rough-cut tools you use should also be fast and easy to use.

While it is easier to describe a linear design process, that is usually not how it works in practice. Initially there will likely be several candidate designs which should be investigated in parallel. The number of competing designs will decrease as time goes on. Furthermore, design textbooks generally present the design process as a chronological journey through a serious of tasks (Figure 3.1). But this is not accurate, because design is an iterative process. So then the flow charts are given arrows for every point to every preceding point, as in Figure 3.1. With such a tangled picture in mind, we wish to emphasize from the outset that the design process will involve regular backtracking, especially since ideas are not generated only during brainstorming sessions. The important thing is keep moving and maintain a willingness to backtrack, modify, and change your design. Trying to design an optimal reactor from the outset will certainly lead to slow going. So do your best to stay out of rabbit holes at the beginning and leave the details for later.

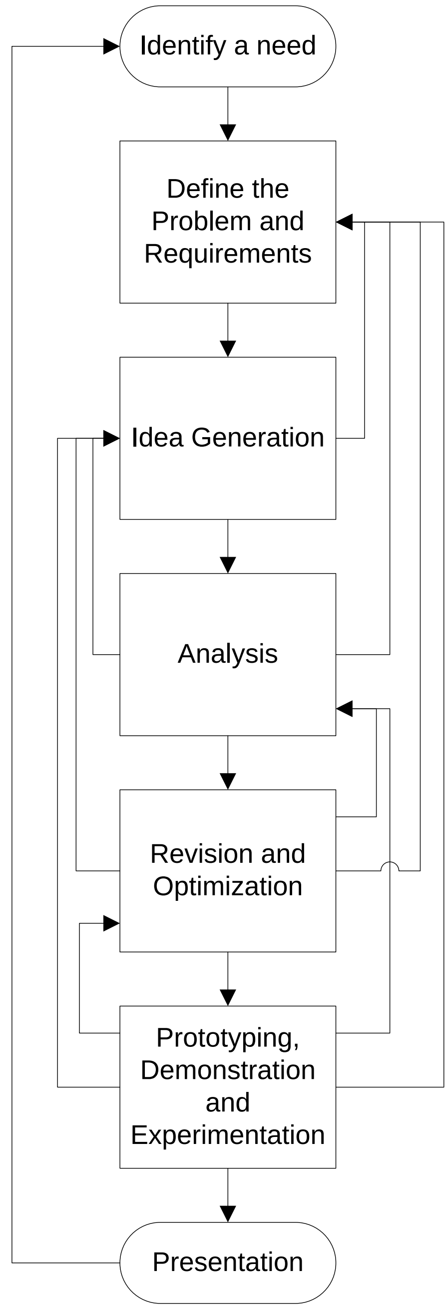

Figure 3.2: Realistic design process.

3.2 Initial Decisions

Decisions made at the beginning of the design process have a bigger effect on life cycle costs than decisions made toward the end as shown in Figure 3.2. As time goes on, certain design commitments have been made and retroactive actions are more costly than designing it right the first time. Clearly, proper engineering design which takes full account of all foreseeable problems will greatly reduce the cost of the project. Furthermore, the front end of the design phase is also important. So it is worthwhile to carefully examine all of the options available at the beginning of the project.

Some decisions can be made immediately based on engineering knowledge and an understanding of the design goals. Two of the most generic questions are What enrichment is acceptable? and What energy spectrum should the reactor have? The constraint of using natural uranium will quickly suggest a thermal reactor with only a few options for moderators. The desire to breed plutonium will dictate a high-neutron energy spectrum.

After the obvious choices have been made, but without accidentally eliminating any viable choices, there are a few fundamental decisions to make. The choice of moderator (if needed), coolant, fuel isotope, and chemical fuel form are the fundamental features around which the reactor will be designed. These decisions do not require any computer simulations if the correct figures of merit are identified and used.

Often selection is not straightforward because the materials are better at some things and worse in other respects. In cases like these, the decision is which set of issues you want to deal with. The way each issue is weighted will influence the decision. For example, if low R&D requirements is a priority, UO_2 will be selected and the poor thermal conductivity will have to be dealt with. Dichotomies like this help explain why there remains such a diversity of opinions and research efforts. In other words, there may be more than one acceptable answer, but it is important to explain why the selection was made.

3.2.1 Coolant Selection

Nuclear engineers often think of neutronic design as the critical (pun intended) part of the reactor system. However, neutron transport is actually a smaller part of the design than one would think. In any reactor that produces power, cooling is essential. When the goal is producing electricity, managing the working fluid is the key to reliability and efficiency. Thus we begin with a discussion of coolants.

The first question is, Is this a thermal spectrum reactor? If the answer is no, many low-Z coolants are automatically eliminated from consideration. Next, the desired operating temperatures need to be assigned ballpark numbers. This is determined by estimating the capabilities of heat exchangers, turbo-machinery, and structural and piping materials. You can prescribe these limits later if necessary, remember design is an iterative process.

The following coolant properties are desirable for any reactor. *High heat capacity.* This allows the coolant to absorb more energy per change in temperature. *Non-corrosive.* Whatever the coolant contacts, or has the potential to contact, it should be compatible with. If the coolant corrodes the cladding, it will limit the fuel cycle length and sabotage the fuel utilization. *Radiation stability* The coolant in the core will experience high radiation fields and radiolysis and neutron activation will occur. The coolant should be selected so that these phenomena are minimized. *Low cross section* Neutrons absorbed in the coolant or coolant impurities will diminish the performance of the reactor [1].

Comparison of Liquid and Gaseous Coolants

The phase of the coolant is an important consideration. Both liquid and gaseous coolants have their advantages and disadvantages. If gaseous coolant is chosen, the chemically inert noble gases become attractive options.

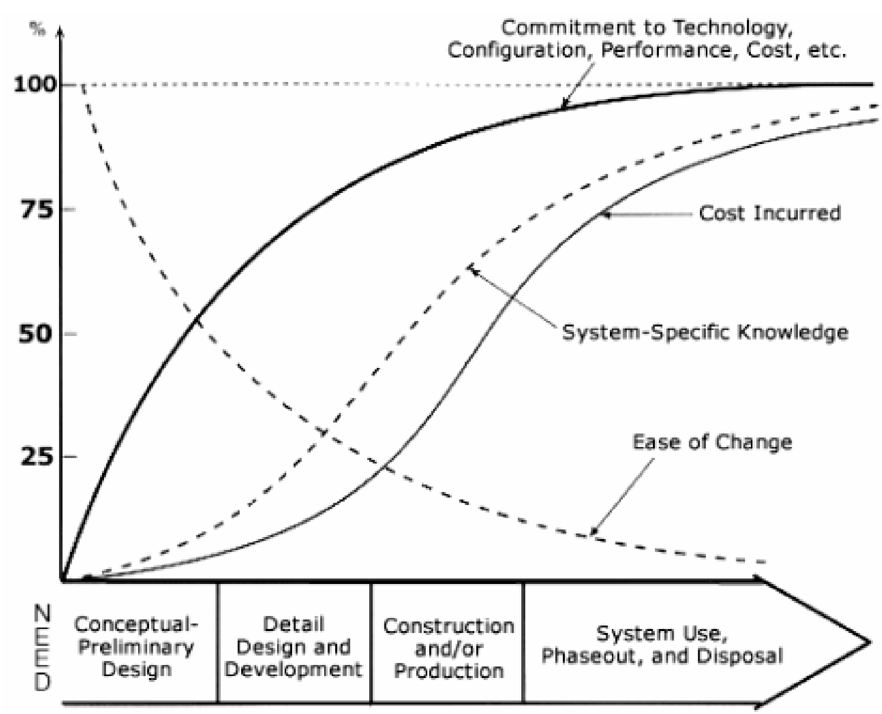

Figure 3.3: Commitment, system-specific knowledge, and cost (source: B.S. Blanchard & W.J. Fabrycky, Systems Engineering and Analysis, 3rd Ed., Prentice Hall, 1998, Figure 2.11).

Qualtiy	Liquid	Two-Phase	Gaseous
Heat Capacity	High	High	Low
Phase Change	Limiting condition	Desirable	Not an issue
Heat Transfer Coefficient	High	Very high	Low
Natural Circulation	Good	Very good	Poor
Pumping Power	Low/good	Low/good	High/bad
Neutron Absorption	High	Less	Low
Direct Cycle	No	Yes, Rankine	Yes, Brayton
Low Pressure	Maybe	No	No

Table 3.1: Phase of coolant

Comparison of Liquid Coolants

Water is the first liquid coolant that comes to mind because of its vast experience. Water is an effective moderator, and it can be used directly in a steam turbine. But aqueous systems can be very corrosive, and the low boiling point mandates high system pressure. Heavy water is similar to light water except it is much more expensive and absorbs many fewer neutrons.

Other coolants of interest boil at higher temperatures and therefore do not require high pressure containment. Thus in a loss of coolant accident, there is no dryout of the core.

Molten salts have good heat transfer properties (high heat capacity, large thermal expansion for natural circulation), but have very little operating experience. Usually they will have light atoms which will moderate neutrons too much for fast reactors, but not enough for thermal reactors. Elements like Lithium and Potassium will also absorb significantly, which can lead to a positive void coefficient of reactivity. Molten salts can be transparent (good for fuel handling) and they are not toxic. However they melt at high temperatures which introduces complex freezing problems.

Liquid metals are suitable for fast reactors because they have low moderating powers. They allow high temperature and low pressure operation. They also allow for power densities greater than for water and gas reactors. Disadvantages include high melting points and neutron activation. Elements of interest are Sodium, Potassium, Lithium, Lead, Bismuth, and Mercury. Second tier metals include Tin, Gallium, Rubidium, and Phosphorus. A helpful summary of their properties (which may be out of date) is given in Table 4.1 of [2].

Sodium has attained much experience, and it is generally viewed as the best choice for fast reactors. But other metals have some definite advantages. Sodium burns in water and air and it produces gamma rays when it is activated. On the other hand, it is a very good coolant that allows for high power density and tight fuel lattices.

3.2.2 Moderator Selection

For thermal reactors, a low-Z element is needed to slow down the fission neutrons to low energy levels where fission is more likely to occur. It must also do this without absorbing too many neutrons. Hydrogen is an obvious choice because of its ability to stop a neutron completely with only one scattering interaction and its low mean free path. Deuterium comes to mind next because it absorbs neutrons 1000 times less. Graphite is a desirable moderator because it can withstand extremely high temperatures.

Recall from Duderstadt and Hamilton[3] that discussing moderators is easier to do in terms of lethargy $u \equiv \ln \frac{E_0}{E}$. The average lethargy gain is

$$\xi \equiv 1 + \frac{\alpha}{1-\alpha} = 1 - \frac{(A-1)^2}{2A} \ln\left(\frac{A+1}{A-1}\right) . \tag{3.1}$$

The average number of collisions required to slow down from 2MeV to 1eV is given by

$$< \# >= \frac{\ln \frac{2\times 10^6}{1.0}}{\xi} = \frac{14.5}{\xi} \tag{3.2}$$

Moderator	A	α	ξ	$<\#>$	$\xi\Sigma_s$ cm^{-1}	$\xi\Sigma_s/\Sigma_a$
H	1	0	1	14		
H_20	-	-	0.920	16	1.35	71
D_20	-	-	0.509	29	0.176	5670
Be	9	0.640	0.209	69	0.158	143
C	12	0.716	0.158	91	0.060	192

The *moderating power*, $\xi\Sigma_s$, is a figure of merit that takes into account the probability that a scattering interaction will occur. Σ_s is much lower for graphite than it is for water and thus more of the moderator material is needed.

But a high moderating power is not useful if most of the neutrons are absorbed in the moderator. The *moderating ratio* takes into account the absorptions in the moderator.

$$Moderatingratio \equiv \frac{\xi\Sigma_s}{\Sigma_a} \tag{3.3}$$

Common moderators are listed in Table 3.2.2, which was reproduced in part from Duderstadt and Hamilton[3].

3.2.3 Fuel Selection

The requirements of nuclear fuel are very demanding due to the environment it must withstand. Hausner [1] lists the following requirements for nuclear fuel

1. It must be able to tolerant radiation damage
2. It must not corrode upon contact with the cladding or coolant
3. It or its impurities must not absorb too many neutrons

4a. It must be able to withstand the temperature gradient caused by the heat it generates

4b. It should have high thermal conductivity (or appropriate dimensions) in order to transmit its heat to the coolant

5. It must be able to withstand the thermal cycles that it will experience during operation
6. It must be able to withstand the mechanical loads placed upon it
7. It must be inexpensive
8. It should lend itself to the fuel cycle in which it will be used, e.g. easy to reprocess

Also it is generally preferable to have a high density in order to ease requirements for enrichment.

Uranium dioxide is always the first fuel material to be considered. It is chemically stable in air and water, it can tolerate extreme temperatures, and most of all it is widely used and studied. UO_2 essentially has an extreme R&D inertia behind it, that makes the use of other fuel compositions an uphill task. The primary reasons to move away from UO_2 are its wretched thermal conductivity and its incompatibility with fast reactor coolants.

Uranium metal was originally used in the Hanford B reactor because it was easy to extract Plutonium from. The high density of metal makes it attractive, especially for fast reactors. Uranium metal is made much more usable by alloying it with Molybdenum or Zirconium, which increase the melting temperature and avoid phase/density changes. Metal fuels were used to achieve and demonstrate passive safety in EBR-II. They have also successfully reached very high burnups. Metal fuel has a relatively low melting point and suffers from swelling issues.

Uranium Carbide and Uranium Nitride are quite similar. Both have melting points similar to the ceramic UO_2, but thermal conductivities similar to metal fuel. Their density is larger than UO_2 and they are compatible with sodium as a coolant. They are both harder to work with because they will oxidize in air. When UN is irradiated it creates C-14, so it may be necessary to enrich the nitrogen in N-15. *Say something about Uranium Silicide...*

Fluid fuels can be gases (UF_6), molten salts (UF_4), or molten metals (e.g. Bismuth with dissolved Uranium). Fluid fuels have several benefits[4]: continuous removal of fission products, simplified core layout, no radiation damage to the fuel, and simplified heat transfer. However, fluid fuels also have disadvantages: delayed neutrons leave the core, corrosion issues, and difficulty accounting for the exact location of fissile materials.

3.2.4 Cladding Selection

Material selection for cladding is important because it is the first line of defense for retaining radioactive material. Even for reactor designs with no cladding, e.g. a molten salt-fueled reactor, it is necessary to select compatible and durable materials to contain the nuclear material and working fluid. Selecting reliable cladding and piping materials allows the reactor to run smoothly with fewer interruptions. The primary requirement is for the cladding to be chemically compatible with both the fuel and the coolant. Superior corrosion performance is the foremost concern.

The cladding material must also be capable of enduring an extreme environment of neutron, gamma, and fission product irradiation and high temperatures. It must also maintain its strength and ductility while absorbing as few as possible neutrons. After all this, it would be preferable if the material was cheap and easy to manufacture.

3.2.5 Secondary Circuit Working Fluid Selection

For power reactors that do not use a direct cycle, a working fluid in the secondary system must be selected. Generally the working fluid for energy conversion can be selected after the primary coolant has been determined. However, the potential secondary fluids may weigh on the decision of the primary fluid. For example, sodium coolant may be disfavored because of its incompatibility with water. But for most other coolants the choice is not as important.

Water is by far the most used working fluid for nuclear reactors. Even sodium-cooled reactors have converted energy with a steam system (making the complexity of intermediate loops and pipe-in-pipe heat exchangers necessary). The widespread use of steam turbines has made that power conversion system quite familiar.

Several advanced reactor concepts call for the use of the Brayton cycle with Helium or super-critical CO_2 as the working fluid. These systems can (must) work at higher temperatures and they achieve higher efficiency.

3.3 Fuel Geometric Specification

After these have been determined, the basic core geometry comes next. At this point an optimized design is unlikely and even unneeded. More likely each analysis will provide the limits of a feasible design space.

There are several options for fuel layout: blocks, pins, plates, pebbles, and fluid. Blocks have the smallest surface area for heat transfer, whereas plates and small pebbles/particles have more surface area per volume, see Figure 3.3. For optimal neutronics performance, the percentage of cladding material must be reduced. Thus large fuel pins are favored. From the heat transfer perspective the surface area of the fuel per volume should be maximized. This pushes the design towards plate fuel. In the extreme case, the fuel is the working fluid and the reactor core does not need a heat transfer surface. These competing requirements will lead to trade-offs and constraints.

Within these fuel types, the fuel meat can be composed of either uniform fuel (e.g. a pellet of UN) or some type of composite (e.g. TRISO fuel in a graphite matrix). Solid fuels allow for smaller reactors cores or lower enrichment. Dispersion fuels such as TRISO particles in a graphite matrix can combine favorable material properties. Fissile material with a low thermal conductivity (such as UO_2) can be embedded in a matrix with a high thermal conductivity. This enables efficient heat transfer to the working fluid and

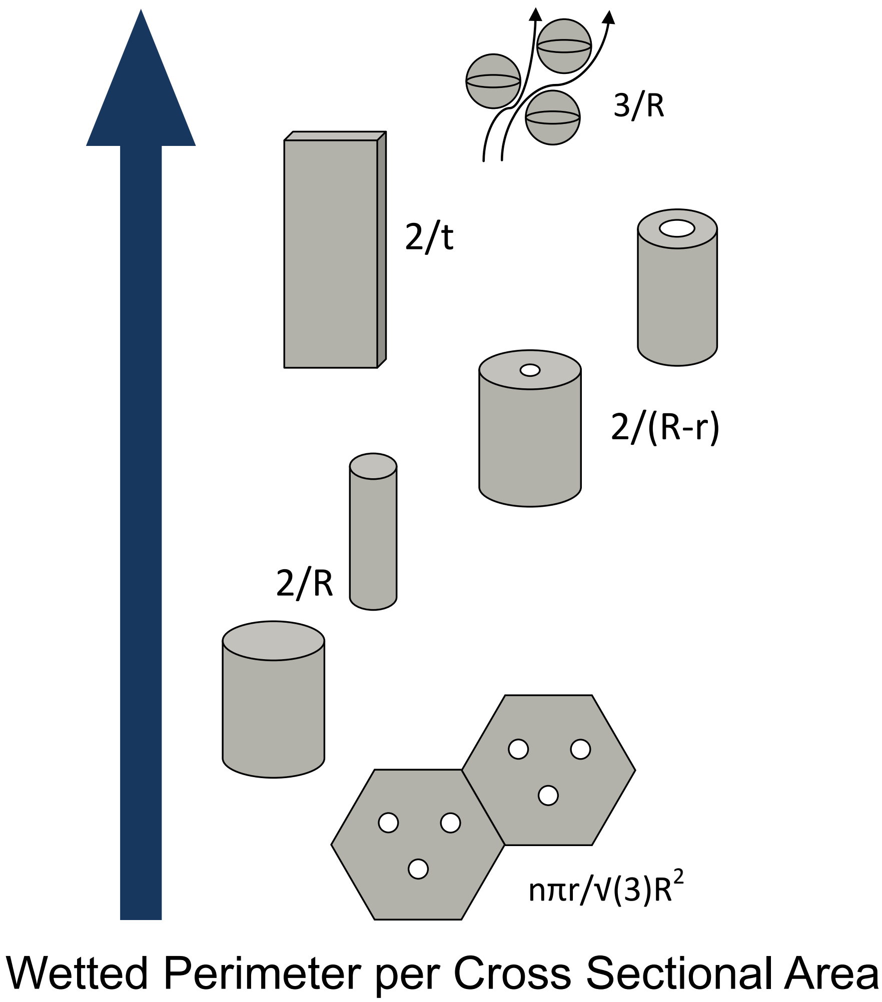

Figure 3.4: Surface area per volume is a function of fuel layout.

avoids excessive temperatures in the fissile material. The primary drawback of composite fuels is that the fuel volume fraction in the reactor core is reduced. For graphite reactors this is not a problem because the moderator to fuel ratio is so large anyway.

Fluid fuel has only been used in the Molten Salt Reactor Experiment. Fluid fuels are not used primarily because of the high temperatures required (which is very taxing for materials) and the potential mobility of fuel. In an accident, the worst case is that the nuclear fuel and radioactive material can not be accounted for. Containing radioactivity is the primary safety mandate for nuclear reactors and fluid fuels make this more difficult.

At this stage of the design, the unit cell is typically the geometry of interest. The representative fuel pin with its surrounding coolant channel is taken to be part of an infinite lattice. This is modeled by using reflected boundary conditions.

3.4 Assembly Design

Where does this section go?

Fuel pins are arranged into assemblies in order to resist buckling and simplify fuel handling. To be compatible with existing reactors, the size of the assembly must be constant. So an 11-pin-by-11-pin assembly can replace a 10x10 assembly if it has the same size.

Table 3.2: Geometric Buckling Factors. $\nu_0 = 2.405$. Tildes denote extrapolated lengths. Geometric buckling is additive whereas the peaking factors and flux profiles are multiplicative. (Adapted from Duderstadt.)

Geometry	Geometric Buckling B_g^2	Flux Profile	Peak/Average
Slab	$\left(\frac{\pi}{\tilde{a}}\right)^2$	$\cos\frac{\pi x}{\tilde{a}}$	1.571
Infinite Cylinder	$\left(\frac{\nu_0}{\tilde{R}}\right)^2$	$J_0\frac{\nu_0 r}{\tilde{R}}$	2.316
Sphere	$\left(\frac{\pi}{\tilde{R}}\right)^2$	$r^{-1}\sin\frac{\pi r}{\tilde{R}}$	3.2899
Finite Cylinder	$\left(\frac{\pi}{\tilde{H}}\right)^2 + \left(\frac{\nu_0}{\tilde{R}}\right)^2$	$J_0\frac{\nu_0 r}{\tilde{R}}\cos\frac{\pi z}{\tilde{H}}$	3.638

3.5 Core Geometry

Neutron leakage from the reactor core can have a significant reactivity effect. This penalty is minimized by making the core as large as possible—this is one economy of scale. For a fixed power rating, creating a reactor core in the shape of a sphere is optimal for reducing neutron leakage. Such a geometry is often impractical because it precludes (or greatly complicates) fuel shuffling. It is also difficult to construct. For this reason, reactor cores are generally assembled in the shape of cylinder.

Sodium cooled reactors rely on increased leakage to mitigate the positive sodium void coefficient of reactivity that comes from reduced absorptions in the coolant. This is accomplished with a "pancake core" design with a radius larger than the height.

Annular cores can be used to mitigate power peaking...

The height of the core is usually limited by thermal hydraulic considerations. In order to limit the pressure drop and temperature change across the core the height should not be too large.

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Chapter 4

Learning from Other Designs

In the process of learning about nuclear engineering one undoubtedly learns a great deal about existing reactor designs. On one hand the designer should start a project with a clean slate, but on the other hand knowledge in memory can greatly accelerate the design process. Trends, heuristics, and limitations are useful as long as the designer does not prematurely eliminate design possibilities.

In this chapter we will discuss types of nuclear reactors that have been built. The strengths and shortcomings will be listed, although not exhaustively. The purpose of this chapter is not to promote one design over another, because different constraints, priorities, and goals will favor different designs.

4.1 Light Water Reactors

Light water reactors are by far the most common reactor in the world.

Advantages	Disadvantages
Widely used technology	
Inexpensive coolant	Corrosion issues
	Requires enriched fuel

4.1.1 Pressurized Water Reactors

Pressurized water reactors are the more common type of light water reactor. The water must be kept high pressure to preclude boiling inside the primary coolant loop.

4.1.2 Boiling Water Reactors

Boiling Water Reactors aim for improved efficiency by using a direct power conversion cycle. However, boiling in the reactor core leads to a variety of challenges.

Advantages	Disadvantages
Improved Efficiency	Two-phase flow
Load following	Unstable at low power
	Radioactivity in the steam turbine

4.2 Heavy Water Reactors

This type of reactor was developed in Canada and has since been exported around the world. The use of heavy water allows the use of un-enriched uranium. This appears to be a good feature for proliferation resistance, but the combination of on-line refueling and natural uranium leads to optimal conditions for breeding plutonium for weapons. The excellent neutron economy of this design may lead to extended uses in the future. For example used LWR fuel could be used as fuel in a heavy water reactor.

Advantages	Disadvantages
Natural uranium fuel	Expensive Moderator
On-line refueling	Proliferation Risk
High burnup per ore	Low burnup per fuel element
No pressure vessel	Many pressure tubes

4.3 Graphite-Moderated Water-Cooled Reactors

These reactors are traditionally associated with weapons production. Graphite moderation allows for natural uranium fuel and efficient breeding of plutonium. The RBMK reactor in Chernobyl was not carefully designed to achieve a negative boiling reactivity coefficient, which was part of the cause of that disaster.

Advantages	Disadvantages
Natural uranium fuel	Large size
On-line refueling	Proliferation Risk
	Potential for positive reactivity coefficients

4.4 Gas Cooled Reactors

4.4.1 MAGNOX Reactors

4.4.2 Prismatic Block Reactors

The fuel for these reactors is composed of millimeter-scale TRISO particles. A kernel of UO_2 is surrounded by several layers of graphite and silicon carbide which act as containers for fission products. The TRISO particles are interspersed in a graphite matrix. This fuel block has various holes for coolant flow and fuel handling. Fuel blocks are stacked to compose the reactor core. The large mass of graphite has a very large heat capacity which can absorb the energy of almost any transient.

Graphite reactors do have some safety issues, however. First, dislocations to the graphite atomic matrix build up with neutron fluence. The reactor must be taken to higher temperatures periodically in order to anneal the graphite and release the energy stored in these imperfections. Also, there is still some debate about the flammability of graphite.

Advantages	Disadvantages
High heat capacity	Requires annealing
High temperature ceramic	Flammable?
Low absorption moderator	Large core
Multiple layers around fuel	Complex manufacturing
Allows high output temperature	High pumping power
	Complex/large spent fuel waste

4.4.3 Pebble Bed Reactors

Pebble bed reactors share many features with prismatic block reactors. However, by using many fuel pebbles, better fuel economy can be achieved. Construction of the reactor core is greatly simplified: it is essentially a can with guide tubes and a bottom nozzle.

Advantages	Disadvantages
Increased burnup	Complex fuel manufacturing
Replaceable fuel elements	Greater likelihood of individual failure
	Complex, indeterminate geometry

Table 4.1: See Table 4.4.2 for the pros and cons common to graphite reactors.

4.4.4 Gas-Cooled Fast Reactors

Gas cooled fast reactors share several features with gas-cooled thermal reactors, but the lack of a large mass of graphite moderator greatly reduces the heat capacity of the reactor core. Without out this sink for energy during accidents, passive safety is much harder to attain.

The original motivation for gas cooled-fast reactors was improved neutron economy due to decreased absorption in the coolant.

Advantages	Disadvantages
Single-phase coolant	High pumping power
Direct cycle energy conversion	High pressure
	Coolant leakage
High temperature	Risk of corrosion
Little absorption in coolant	Low heat capacity
High breeding ratio	Low heat transfer coefficient

4.5 Liquid Metal Cooled Reactors

Liquid metal coolants have been considered for fast spectrum reactors since the earliest days of nuclear energy. It was the NaK-cooled Experimental Breeder Reactor (EBR-I) that first produced electricity from nuclear energy. Liquid metals are excellent heat transfer media and also allow for the benefits of a fast-spectrum.

4.5.1 Sodium(-Potassium) Cooled Fast Reactors

Sodium is an excellent heat transfer medium, but its melting temperature is 98°C. Either the coolant loops must be heated continually during shutdown, or potassium must be added to lower the melting temperature. Both metals are highly flammable. Potassium absorbs more neutrons.

Advantages	Disadvantages
Good heat transfer	Incompatible with air and water
Fast neutron spectrum	shorter neutron lifetime
Passive safety demonstrated	Sodium activated by neutrons
Electronic pumping	opaque coolant
	Sodium: solid at room temperature
High temperature	Intermediate coolant loop

4.5.2 Lead(-Bismuth) Fast Reactors

Bismuth is added to lead to decrease the melting point. Lead does not react with water, air, or CO_2, which means intermediate cooling loops are unnecessary. There is less experience with lead-cooled reactors. Some Russian submarines had lead-cooled reactors, but there were eventually decommissioned. Corrosion issues can be managed by controlling the oxygen content of the coolant. The protective oxide layer will remain intact if the coolant flow rate does not exceed about 2m/s.

Advantages	Disadvantages
Good heat transfer	Melting point 327°C
Insignificant moderation	Inelastic scattering
Lead: does not absorb	Bismuth: creates Polonium
Inexpensive material	very heavy
	opaque coolant
High boiling point	Erosion limit on flow rate

4.6 Molten Salt Reactors

Molten salt reactors have received much attention in recent years, but have little operating experience.

Chapter 5

Design for Safety and Operations

After the initial design has brought the reactor concept to a feasible design space it is time to begin a more thorough analysis. At this point computational speed is not as essential because modifications to the design are smaller than at the initial stages.

5.1 Burnup Calculations and Fuel Life

In order to maximize capacity factors and profits, longer fuel cycles are desirable. The initial design activities delineated a feasible design space where the configuration would be critical. In this phase of analysis, depletion calculations must be run to estimate the life of the fuel. The fuel composition will be adjusted to attain the required fuel life.

5.2 Burnable Poisons, Reactivity Control, and Power Peaking Factors

The pin generating the most power will be the first to fail. Thus safety considerations usually focus on this limiting region of the core. For a cylindrical core, the power at the center of the core will be 3.64 times larger than the average power. Ideally, all of the fuel elements would operate at the average value so that the reactor could operate at a power that is 3.64 times higher.

To flatten the power distribution, a variety of methods are available. The most obvious method being control rods. However, that is not the most desirable because it distorts the axial power profile. Burnable poisons are widely used, varied enrichments are also common. Batch refueling adds the extra freedom of arranging fuel assemblies with different burnups. Removable absorbers (e.g. WABA) can be varied from batch to batch.

5.3 Control Rod Layout

Analytical calculations of control rod worth simplify the control rods into one central element. This may be a useful method for making estimates, but it is certainly not the appropriate way to design the control rods. Ever since the SL-1 accident, it has been accepted that no single control rod/device should have enough reactivity to bring the reactor critical. Thus if one rod fails, the others can still shut down the reactor.

5.4 Safety Analysis

Safety analysis for nuclear reactors is a strange combination of quantitative logic and whimsical imagination. On one hand systems and components are designed (and thoroughly tested in zealous quality assurance programs) to perform as intended over a wide range of conditions. On the other hand, accidents are postulated and analyzed where those systems fail. In the nuclear industry it is not satisfactory to design a reactor that will never melt down; designers must also show that if it did, the danger to the environment is minimal.

At first blush this seems absurd because it flies in the face of physics. But it is actually an effective approach for obtaining high levels of safety. There is no way to foresee every possible initiating event or mode of failure, so simply assuming a component failure helps mitigate the unforeseeable. For example, the failure of a Reactor Pressure Vessel is thought of as extremely unlikely due to the sound engineering principles codified in the ASME Boiler and Pressure Vessel Code. However, at the Davis-Besse plant in 2002 severe corrosion of the vessel head was discovered. If it had not been noticed, there could have been a severe loss of coolant accident. Incidents like this show how certain postulated accidents can be more likely than expected and they do in fact merit analysis.

Distrust of individual systems and components leads to redundancy referred to as Defense in Depth. DID provides multiple layers of protection to maintain safety even when one layer (or several) fail. Redundant safety measures are complimented by diverse systems. Diversity allows the intended function to be fulfilled in all cases because no initiating event disables all of the safety systems. Defense in Depth typically proceeds along these lines: fission products are contained in the fuel pellet, the fuel pellet is encased in cladding, the fuel assemblies are enclosed in the RPV, the RPV is inside a containment building, and if all of these rupture there is a large distance between the reactor and any populated area.

A nuclear reactor operating at steady state is very safe. Failures due to creep and corrosion are easy to design for. The situations that really tax the nuclear reactor are when it deviates from steady state. Initially, the idea behind nuclear reactor safety was to survive the maximum credible accident. Since then, probabilistic risk analysis has expanded the view of safety to include smaller events that are more likely to occur.

The standard accident scenarios include: loss of coolant accidents (large break or small break), reactivity insertion accidents (control rod ejection, boron dilution accident, moderator overcooling, etc.), loss of heat exchanger, station blackout, loss of flow accident (blockages, pump failures).

Traditionally, the most analyzed accident scenarios are the Reactivity Insertion Accident (RIA) and the large break Loss of Coolant Accident (LOCA). For a water-cooled reactor, the LOCA scenario is particularly troubling because the loss of pressure in the primary circuit leads to the water flashing to steam and the core being uncovered.

New reactor designs will be susceptible to different accidents and failures. For this reason, it is imperative to be as imaginative as possible at this stage. (Try thinking of ways to compromise your reactor design if you were a nefarious person.) The earlier a path to failure is identified, the easier it will be to deal with. Good designs are simple and inherently avoid as many mechanisms for failures/accidents as possible.

5.4.1 Loss of Coolant Accident

This severe accident looks different in different reactor types. For a Light Water Reactor, a sudden loss in pressure may uncover the core when the water flashes to steam. For a gas cooled reactor, the heat transfer is much less effective with a loss of pressure. For a liquid metal cooled reactor, the coolant is not pressurized so it will not boil vaporize like water. But voiding in the core can be a positive reactivity, which merits investigation.

5.4.2 Reactivity Insertion Accident

Usually the hypothetical scenario for an RIA is a Rod Ejection Accident. Hypothetically, the high pressure inside a reactor vessel could eject a control rod if there was a seal breach. This clearly makes no sense in the case of a low pressure metal or salt cooled reactor, but it is good to know how a reactor responds to a step insertion of reactivity. There are other causes of reactivity insertions (e.g. excess heat removal from the coolant) so this is a class of accident that cannot be neglected.

5.4.3 Loss of Flow Accident

The nuclear reactor continues to generate power after a pump stops working. Even if a scram is initiated immediately, the decay heat is unavoidable. To ameliorate this problem, flywheels or other arrangements let the coolant wind down over a longer period of time in order to maintain cooling.

5.5 Homework Problems

1. Give an example of a) redundant and b) diverse safety systems.

Material Properties

This appendix of material properties should be useful for initial comparison studies. For precise values several resources are recommend in a later section.

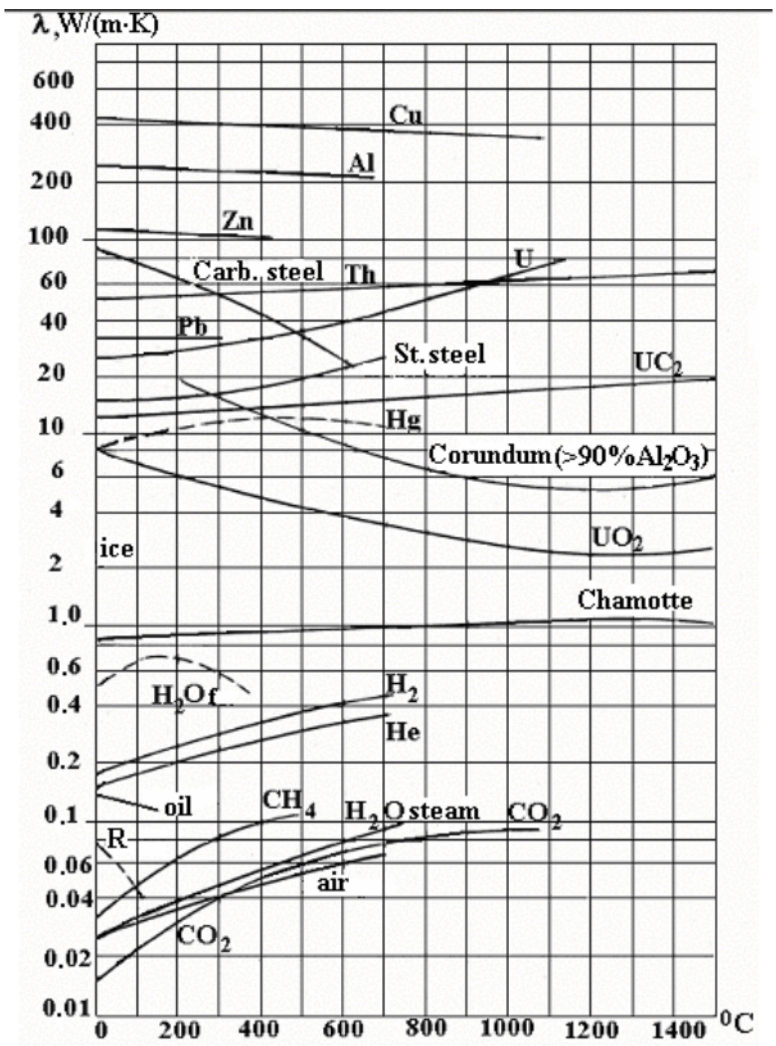

FIG. 1.2. Thermal conductivity of various materials at 0.1 Mpa.

A good resource has been provided by the IAEA[1].

Table 5.1: Basic Thermal Properties[1]

Material	Conductivity W/mK	Density g/cm^3	Melting Point °C	Thermal Expansion 1E6/°C
UO_2	2.79	10.963	2800	9.8
UN	20.9	14.42	2850	7.5
UC	23	13.63	2365	10.5
U metal	31.2	19.1	1130	13.9
U-20Pu-10Zr	16	15.67	1155	17
U_3Si_2	22	12.2	1700	16.1

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[1] IAEA, "Thermophysical properties of materials for nuclear engineering: a tutorial and collection of data." Available online, 2008.