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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.
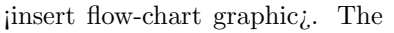
Several key attributes are desirable for almost every nuclear reactor

- 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.

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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. ¡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 60MWe 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.

Bibliography

[1] "The history of nuclear power safety." Available online, 2002.

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.

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. 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. 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.

Insert a figure: flow chart or reactor categorization.

3.2   Initial Decisions

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.

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.

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.

3.2.3 Fuel Selection

The requirements of nuclear fuel are very demanding due to the environment it must withstand. Hausner 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.

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.

3.3   Geometric Specification

After these have been determined, the basic core geometry comes next. Fuel pins increase centerline temperatures, but minimize the amount of cladding required, thus the neutronics expert prefers this option. The heat transfer expert prefers a design that tends towards a plate with more surface area per volume. At this point an optimized design is unlikely and even unneeded. More likely each analysis will provide the limits of a feasible design space.

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 short-comings 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.

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.
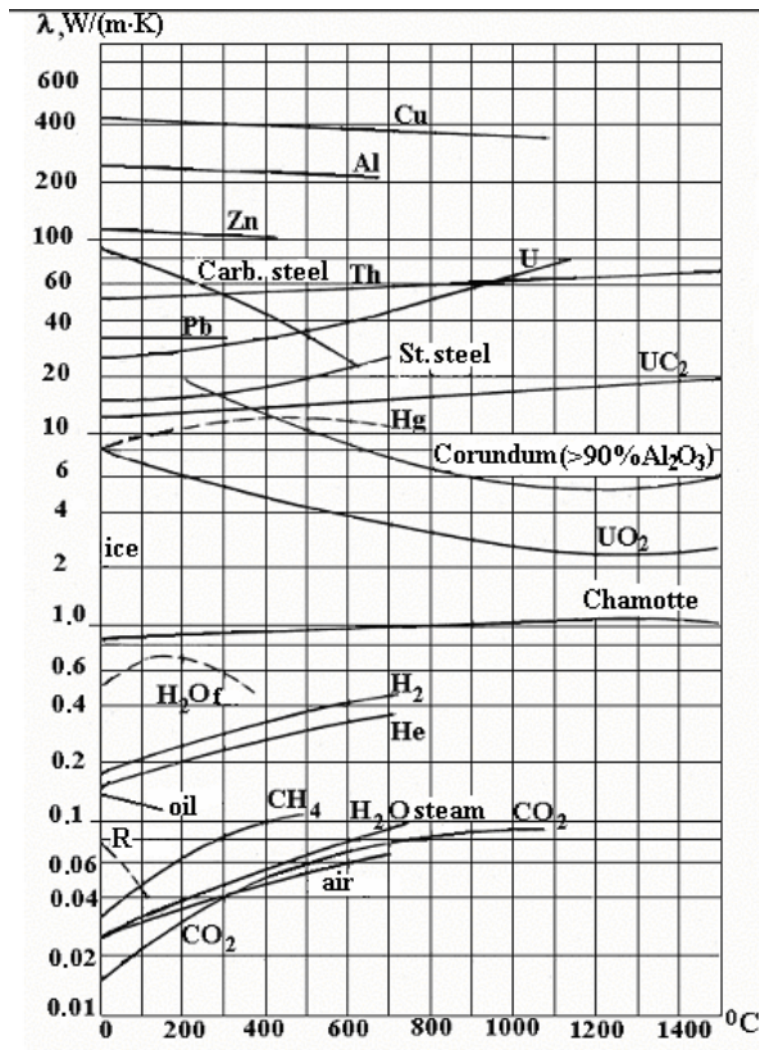

FIG. 1.2. Thermal conductivity of various materials at 0.1 Mpa.

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

Table 4.2: Basic Thermal Properties[1]

Material	Conductivity W/cmK	Heat Capacity K/W/g	Melting Point °C	Boiling Point °C
UO$_2$				
UN				
U metal				

Bibliography

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