

Chapter 1

How to Begin

This part might go in Chapter 1???

1.1 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.

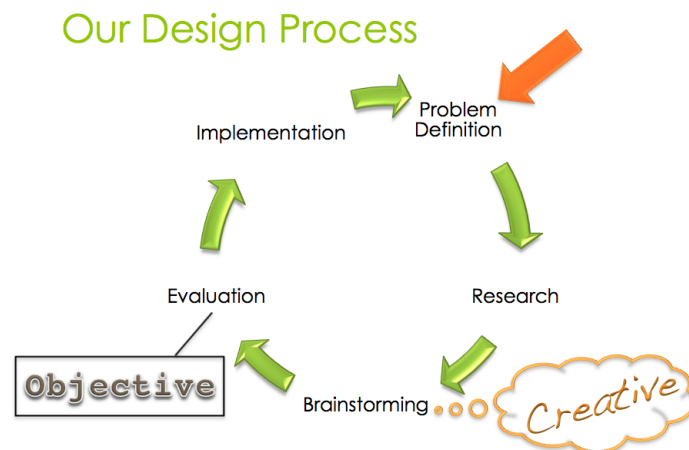


Figure 1.1: Simplified design process. (Graphic from <http://ahmackenziedesign.com/faq/>)

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 series 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.

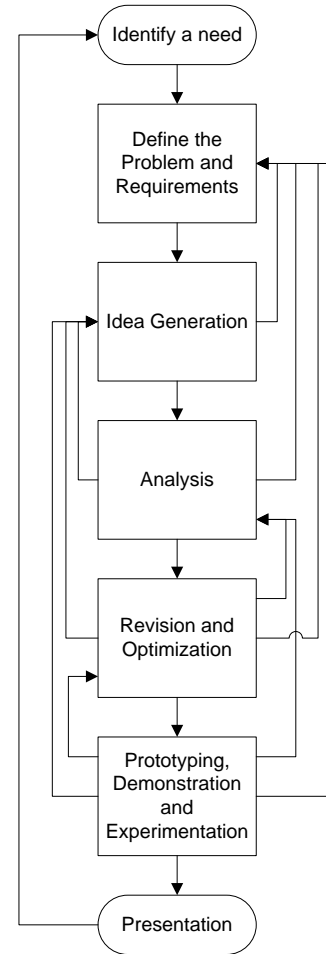


Figure 1.2: Realistic design process.

1.2 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.

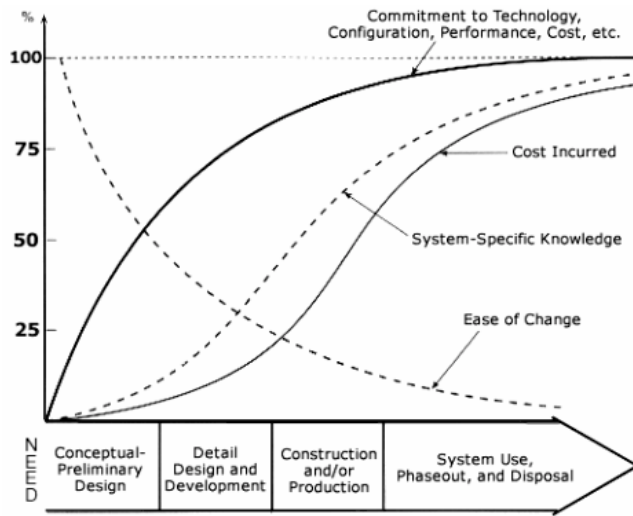


Figure 1.3: Commitment, system-specific knowledge, and cost (source: B.S. Blanchard & W.J. Fabrycky, *Systems Engineering and Analysis*, 3rd Ed., Prentice Hall, 1998, Figure 2.11).

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.

1.2.1 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.

Quality	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 1.1: 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.

1.2.2 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

$$\xi \equiv 1 + \frac{\alpha}{1 - \alpha} = 1 - \frac{(A - 1)^2}{2A} \ln \left(\frac{A + 1}{A - 1} \right). \quad (1.1)$$

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

$$\langle \# \rangle = \frac{\ln \frac{2 \times 10^6}{1.0}}{\xi} = \frac{14.5}{\xi} \quad (1.2)$$

Moderator	A	α	ξ	$< \# >$	$\xi \Sigma_s \text{ cm}^{-1}$	$\xi \Sigma_s / \Sigma_a$
H	1	0	1	14		
H ₂ O	-	-	0.920	16	1.35	71
D ₂ O	-	-	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.

$$\text{Moderating ratio} \equiv \frac{\xi \Sigma_s}{\Sigma_a} \quad (1.3)$$

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

1.2.3 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.

1.2.4 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.

1.2.5 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.

1.3 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 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

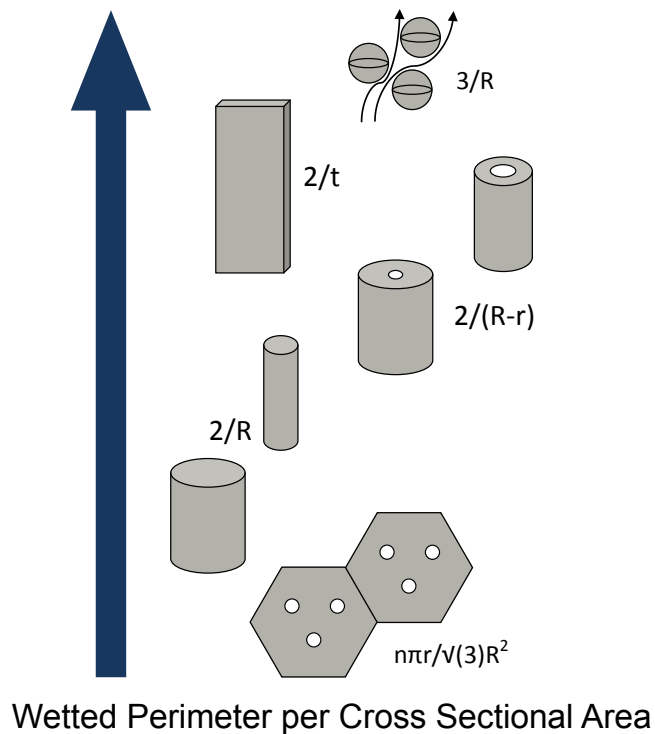


Figure 1.4: Surface area per volume is a function of fuel layout.

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.

1.4 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 1.2: 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

1.5 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.

Bibliography

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