How and Why is CANDU designed the way it is

Introduction

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Summary:

Herein, we introduce the CANDU reactor by first looking at the broad social context to see why we need nuclear power. Then we take a look at the Nuclear Reactor in a nutshell, giving a quick overview to provide some context for the details found on the CANTEACH website in particular and in the technical literature in general. The engineering approach is discussed to provide some appreciation of the fact that CANDUs are engineered systems, typified by functional decomposition and piecewise refinement, which leads to functional requirements. The design process is exclude and rank, and is typically an evolutionary process. The various types of reactors are briefly shown via a quick overview of CANDU vs PWR vs BWR vs …

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1 Introduction - a reality check

Let's step back to take a glimpse of the context into which CANDU must be placed. The simple fact is that we are here. And there are a lot of us - some 6 billion in the year 2000 and our population is destined to hit 10 billion in a few generations. On the premise that life is worth living (and most of us think that way, otherwise our population wouldn't be growing), it follows that we should make the best of the situation. Quality of life is, thus, a worthy and meaningful pursuit. To achieve and maintain a reasonable quality of life requires energy. Access to energy is an enabling force, empowering society and individuals. In short, it is fundamental to our existence. Energy is not a panacea for the strife of life, to be sure; but without it, there would be no life at all.

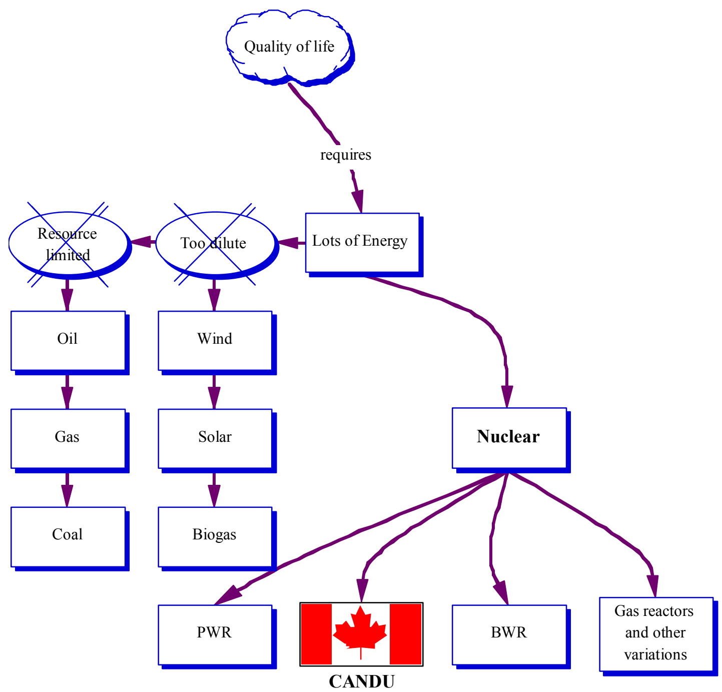

Figure 1 Nuclear power in context.

There is a very thought-provoking speech entitled "Who speaks for the poor?" (http://www.nuc.umr.edu/~ans/poor.html), also found at the "Nuclear Facts and Opinions" page (http://nuceng.mcmaster.ca/refer/facts.htm) along with other similar links. This is a **must read** for everyone. The speech makes it painfully clear that we must provide energy for the world masses in the interests of world stability and in the interests of simple humanity. Nuclear power is the only existing option for large scale power production that transcends the limitations of nonrenewable alternatives (such as coal, oil and gas) and renewable alternatives (wind, solar and biomass). To be sure, there are many local, national and international issues that flavour the ultimate choice of energy source, but nuclear should not be dismissed. The consequences would be dire.

We conclude, then, that nuclear should be part of the energy mix now and in the future, that is, we have a functional requirement for nuclear energy.

2 First some basics

2.1 Fission

To make sense of nuclear reactor design in general, and CANDU design in particular, the reader needs to have some familiarity with a few key nuclear concepts and phenomena. In a nutshell, slow neutrons (called thermal neutrons) can initiate a fission of uranium 235 (U-235), an isotope of uranium that occurs in nature. Natural uranium that is mined from the ground is 0.7% U-235 and 99.3% U-238. The result of fission is fission products that are radioactive, radiation, fast (or energetic) neutrons and heat. The fast neutrons have a low probability of inducing further fissions, and hence have a low probability of generating more neutrons and thus sustaining a chain reaction. So we need to slow down the neutrons (i.e., thermalize or moderate them), which we do by using a moderator such as water. We also need to remove the heat generated. We control the process by controlling the number of neutrons since the number of fissions per second (and hence the heat produced) is proportional to the number of neutrons present to induce the fissions.

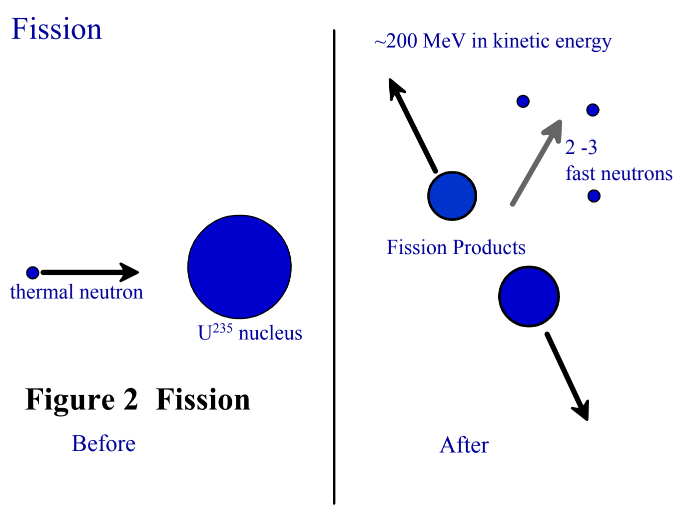

Figure 2 Fission

From this we can directly derive the basic functional requirements of a reactor. We need:

- a fuel such as U-235
- a moderator to thermalize (i.e., slow down) the fast neutrons
- a coolant to remove the heat
- a control system to control the number of neutrons
- a shielding system to protect equipment and people from radiation
- a system that pulls all this together into a workable device.

In the following, we look at these requirements in turn to gain some insight on how and why CANDUs are built the way they are.

2.2 The fuel: the source of energy by the fission process

The probability of neutron capture leading to fission is larger for slow neutrons than for fast neutrons. Hence, most practical reactors are "thermal" reactors, that is, they utilize the higher thermal cross sections. Possible fuels include some of the various isotopes of uranium (U) and plutonium (Pu). The only naturally occurring fuel with suitable properties of significant quantities is U-235, hence most reactors use this fuel.

Naturally occurring uranium is composed of 0.7% U-235. The rest is U-238. This percentage is too low to sustain a chain reaction when combined with most practical moderators. Hence either, the probability of fission must be enhanced or the moderator effectiveness must be enhanced. One group of reactor types (PWR, BWR, HTGR) enrich the fuel (a costly task) and use a cheap moderator (ordinary water or graphite).

Alternatively, natural uranium (relatively cheap) is used with an excellent but expensive moderator (heavy water). This is the CANDU approach. Which is better? There is no simple answer. Both work. In engineered systems, there are always tradeoffs and the final design has to be viewed in the overall context of the end-use environment.

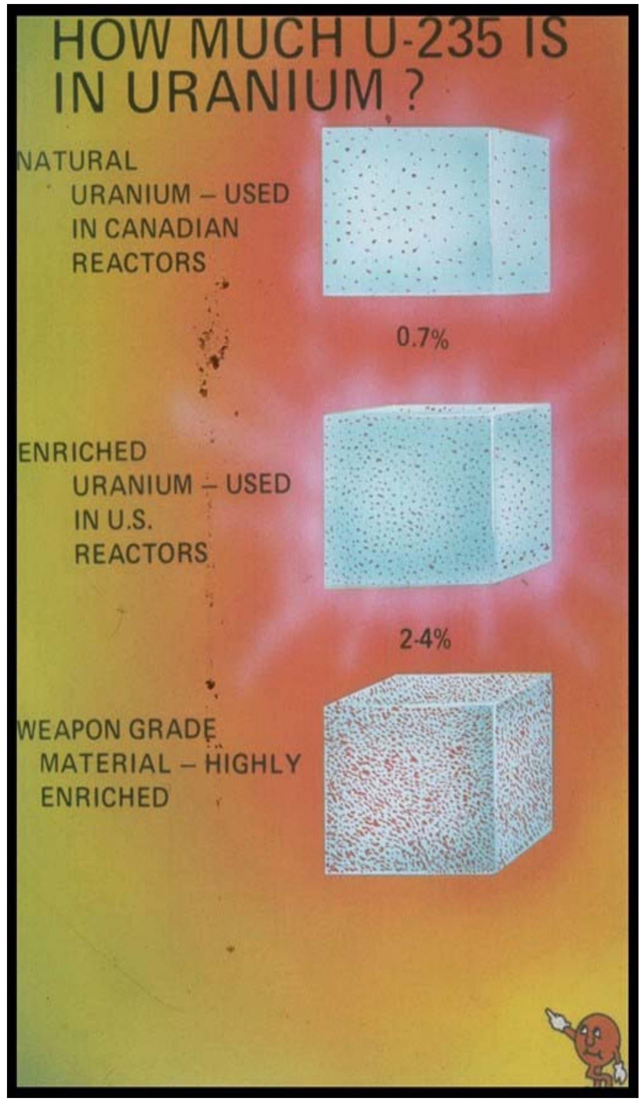

Figure 3 Uranium enrichment.

2.3 The moderator: slowing down those speedy neutrons

The best moderator to slow down a speedy neutron is something that is the same size as the neutron itself. This is true because if a neutron hit a massive target, it would just bounce off in a different direction but with little loss in energy like a hard ball against a wall. If the neutron hit an object much smaller that itself, it would just continue on virtually unaffected. But if it hit a hydrogen atom, which is just a proton and an electron that is almost exactly the size if a neutron, it could lose all its energy in one collision, just like in a game of billiards. However, hydrogen does absorb neutrons as well and we want to preserve these precious neutrons so that they can cause fission. The deuterium isotope of hydrogen, at twice the mass of hydrogen, is almost as good a slowing down agent but, since it already has an extra neutron in the nucleus, it has a very low absorption cross section. So, overall, deuterium is a far better moderator than hydrogen. By using deuterium in the form of heavy water, natural uranium can be used as a fuel. If ordinary water is used, the fuel must be enriched in U-235.

Other possible moderators include graphite and gases such as carbon dioxide and helium. A good moderator has a high scattering cross section, a low absorption cross section and slows down the neutron in the least number of collisions.

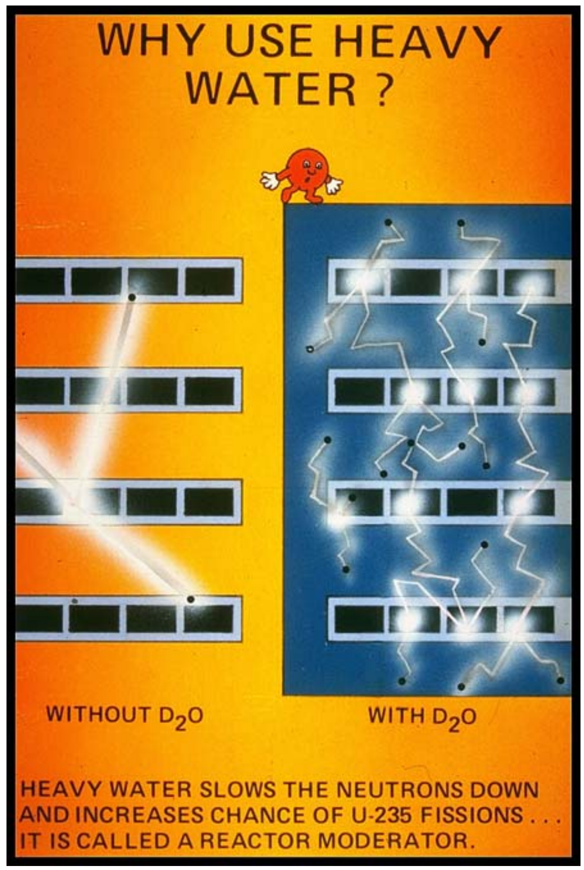

Figure 4 The slowing down process

2.4 The coolant: to take away the heat generated by fissioning

The fissioning process generates energy, predominately in the form of vibrational kinetic energy of the fission products. Such vibrating molecules constitute a familiar phenomenon to all of us – the fuel heats up! If we don't cool the fuel, it will melt and the radioactive fission products, now that they are mobile, may find a path to the environment. To prevent this, a coolant (water is commonly used) is passed over the fuel. So far, we have fuel, moderator and coolant. We can conceptualize our CANDU as in the illustrations in figure 5, below.

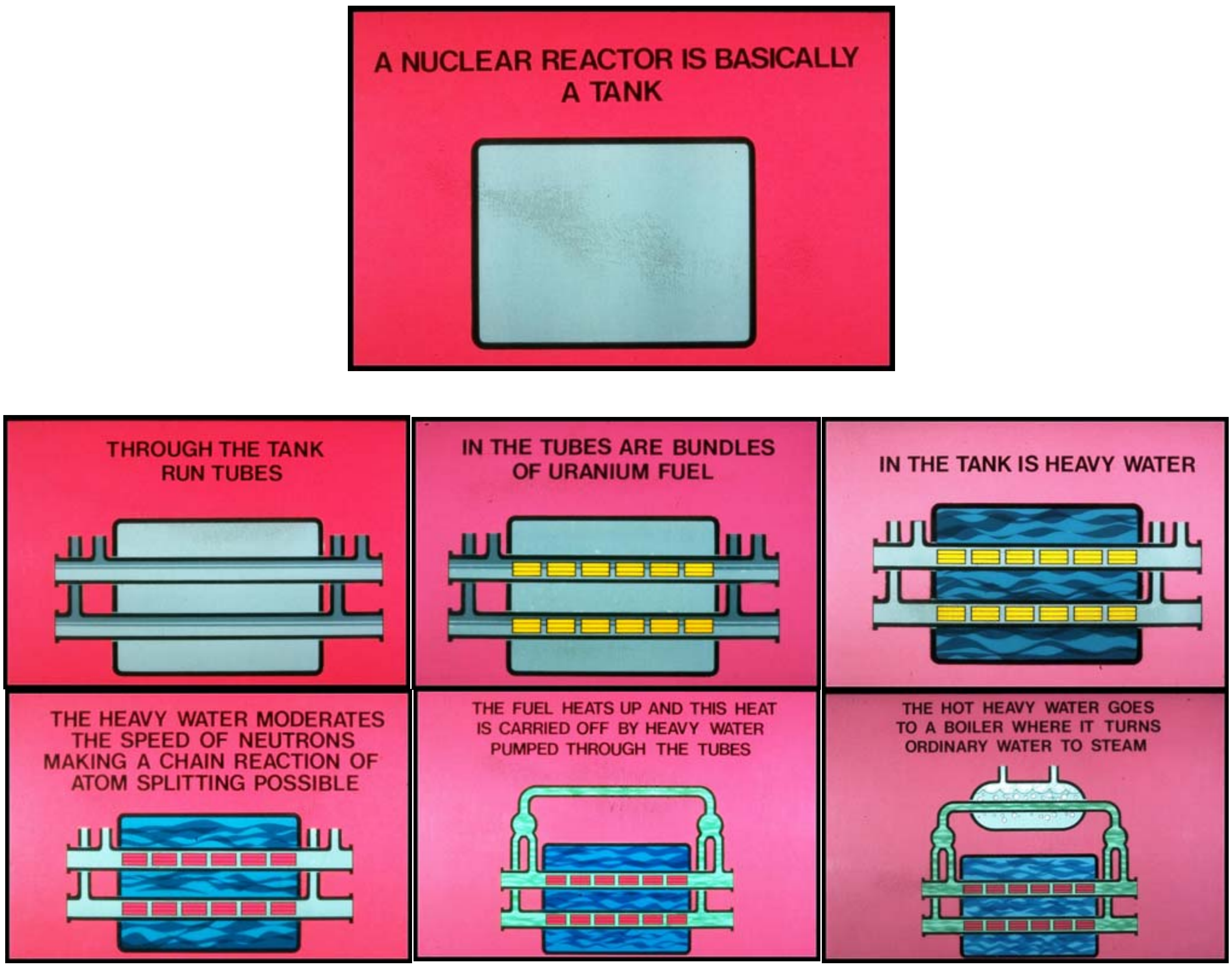

Figure 5 A conceptual CANDU

We typically use the 'heat engine' process to turn this heat into a more useable (that is, flexible, transportable, convenient, etc.) form of energy. As illustrated in figure 6, this heat is used to boil water and the resulting steam drives a turbine which drives an electrical generator. Electricity is a very convenient form of energy - today it is so ubiquitous that it is hard to image life without it.

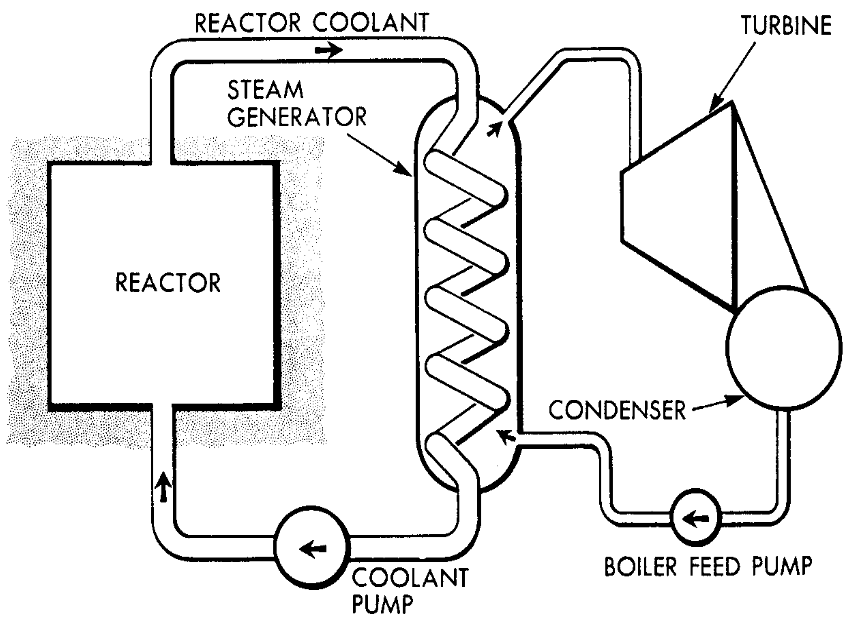

Figure 6 Basic power reactor schematic

2.5 Control: staying within desired and safe limits of power

Control of the fissioning process is achieved most easily by simply adding or removing neutron absorbers. Materials such as cadmium readily absorb neutrons and can be conveniently formed into solid rods. So by having a number of these control rods partially inserted into the moderator tank (also called the calandria) amongst the fuel and moderator in guide tubes, the neutron population and be controlled. Figure 7 illustrates the layout.

Hence the fissioning process and the resultant heat output can be controlled. For safety's sake, in CANDUs, these control rods and the associated control system electronics and measurement devices are build for reliable, fail-safe operation, are highly redundant, and employ such additional safety concepts such as group separation.

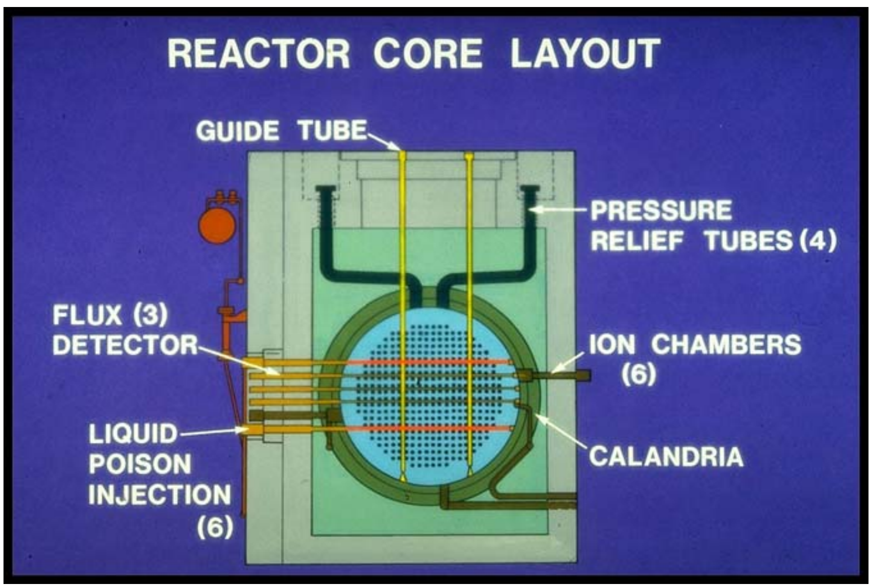

Figure 7 Core layout

2.6 Shielding: providing protection from radiation

Uranium isotopes are not very radioactive by themselves and do not constitute a direct radiation hazard. You can safely hold a fresh CANDU fuel bundle in your hands. Your biggest concern would be dropping it on your toes since a typical bundle weighs about 20 kg or so. It is the fissioning process that creates the nasty radioactive fission products. These ARE dangerous and must be kept isolated from us. Radiation takes on a number of forms. Alpha and beta particles are energetic charged particles that cannot penetrate solids to any significant degree. So as long as the radioactive fission products are contained by a fuel sheath or some other pipe or wall, there is no concern. Neutrons are not charged and can penetrate solid walls. We protect ourselves from them by thick walls that slow down and absorb the neutrons. Combinations of hydrogenous materials (like water and hydrocarbons) and absorbing materials (like boron and cadmium) make good neutron shields. Gamma radiation, essentially very energetic photons (ordinary light is low energy photons), are best stopped by dense material like lead and concrete.

So constructing good shielding is not an onerous task, but it is an important one. Like in the control systems, safety is enhanced by redundancy. In this case, this means layering the shielding systems, one inside the other like a Russian doll set, as in the illustrations of Figure 8.

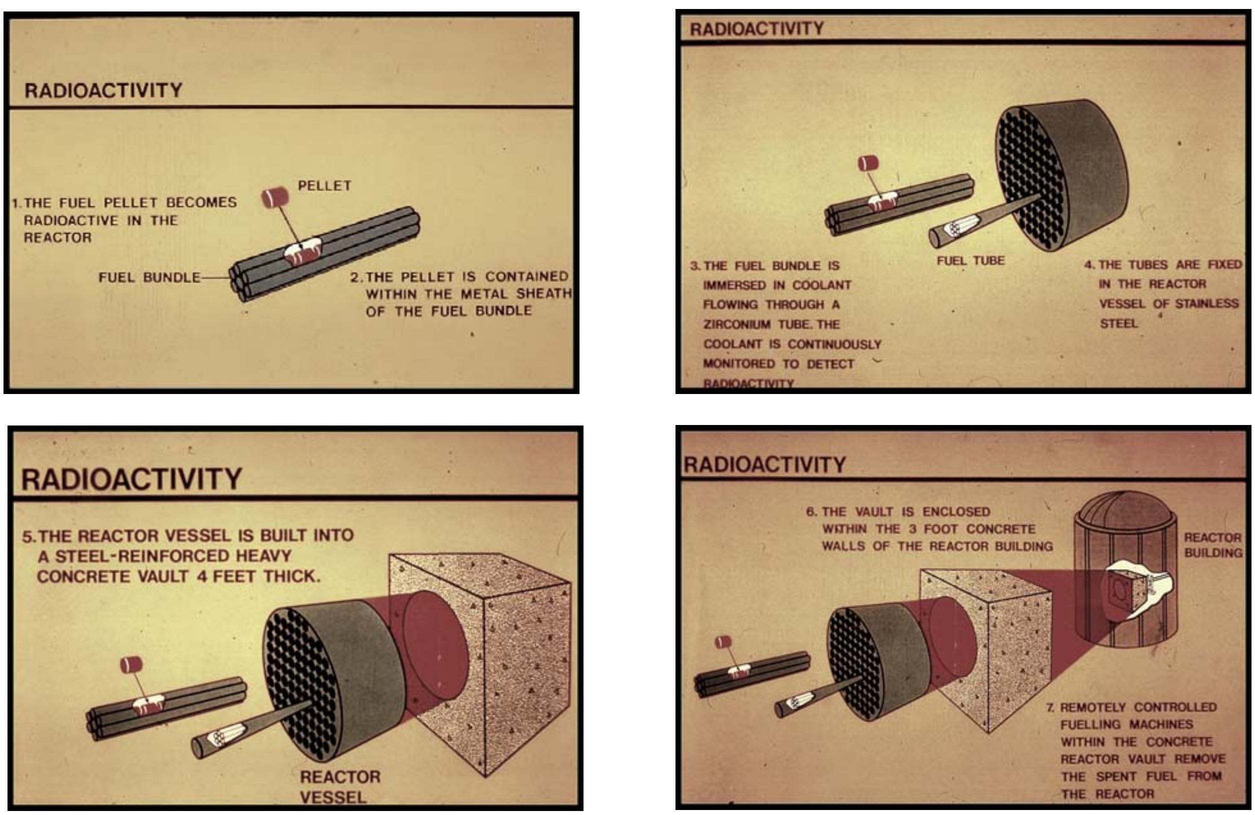

Figure 8 Defense in depth

2.7 The system that pulls it all together

We pull together the various requirements related to fuel, moderation, cooling, control and shielding to conceive a stylized CANDU as illustrated in figure 9. At the heart of the plant is the reactor core containing the fuel and the moderator. Heat generated there is transported away by the cooling system to the conventional side of the plant (steam generator, turbine and electrical generator).

Recall the layered, defense-in-depth approach wherein the radioactive fission products are kept from the environment by multiple protective barriers, culminated be the outer containment shell.

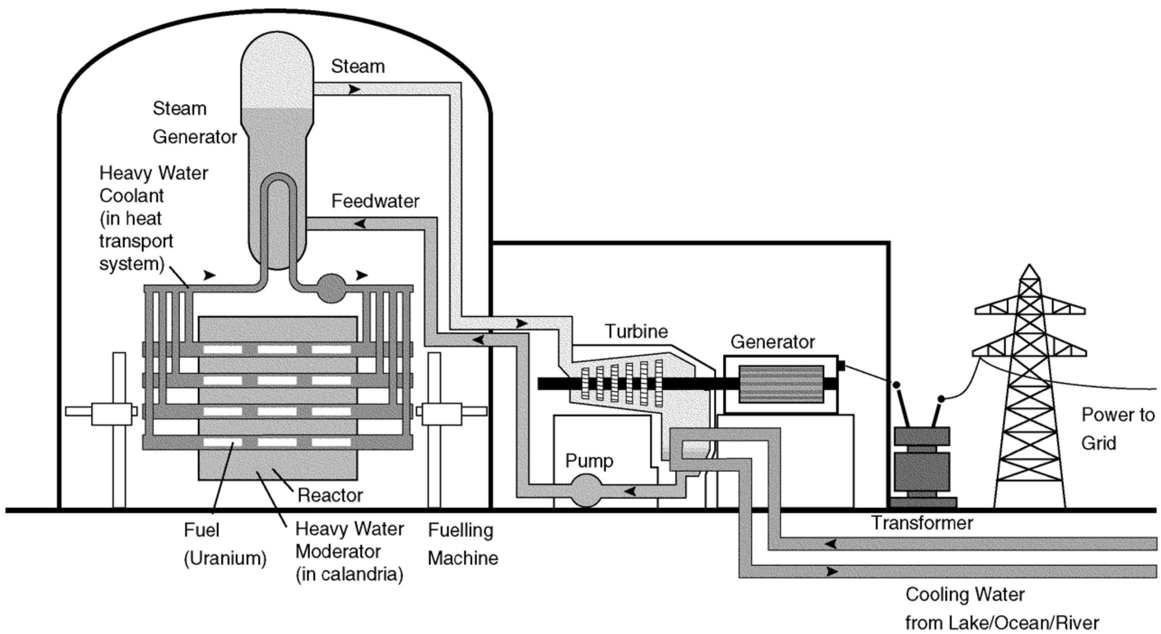

Figure 9 The overall CANDU nuclear plant

Obviously, a real CANDU is far more complex that the illustrations and designing a nuclear plant is not a trivial exercise. There are many systems and sub-systems that interact. How do we keep all this organized and how do we decide how this all fits together to make an effective reactor, one that is safe, cost effective, and meets the design intent? We'll look at that issue next.

3 The engineering approach

Like all engineered systems, the best way to understand and appreciate the CANDU reactor is to look at how it functions. Engineered systems are designed by functional decomposition, that is, they are broken down into subsystems based on a functional subgrouping, rather than by physical characteristics, etc. Examples would be the heat transport system of CANDU or the steering system of an automobile. We decompose the big problem (how to produce electrical energy, how to design a car, etc.) into progressively smaller, but interrelated problems (how to produce heat and how to convert the heat to electricity, or how to steer a car and how to stop a car, etc.). By breaking the big problem down into smaller and smaller problems, we systematically define problems that we can solve. These solved pieces, however, must be integrated back into a whole if we are to have a successful solution.

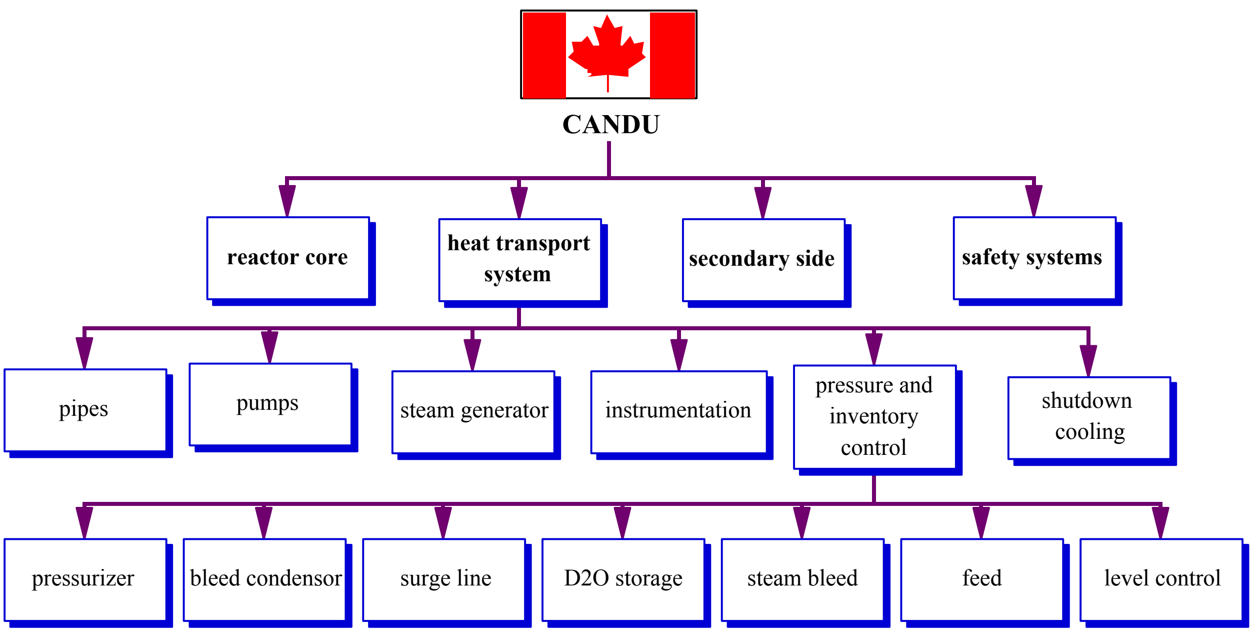

Figure 10 Functional decomposition

Implicit in such an approach is the question: "What does each subsystem have to do?". Thus the responsible engineer starts by asking "What are the functional requirements?". There are usually many ways to meet these functional requirements and it is the engineer's job to find a workable solution that meets these requirements effectively – meaning an optimum of efficiency, cost and safety, taking society and the environment well into account. Past experience usually plays a large role in engineered systems, but this is especially true for nuclear reactors because of the stringent quality assurance requirements and high safety standards. Many person-years of effort and many millions in funding have been spent to 'get the bugs out'. As a consequence, progress is more by systematic evolution, not revolution.

Designing is, to a large degree, the process of narrowing choices from many to one, of making choices from a set of alternatives. For a given design sub-task, many alternatives can be quickly eliminated (too expensive, unsafe, to big, etc.). The alternatives that are left need to be weighed to see which one is the most desirable. Thus the process is 'exclude and rank'. Too illustrate, consider the task of choosing the correct heat exchanger for a given application.

The experts here are engineers and, hence, tend to use first principles in their thought processes. On the most fundamental level, the governing equations can be written. But this large equation set cannot usually be solved even if all the constitutive relations were known. This level of detail is reserved for fundamental R&D where experimental and theoretical work are compared to each other and to computer simulations. The results of such scrutiny are practical correlations that are embodied into design and analysis codes. These practical tools permit the design engineer to scope out a number of designs in some detail. But this is still not sufficient for good design for at least two reasons:

1. Detailed calculations of the heat transfer, fluid mechanics and mechanical design are usually quite time consuming;
2. There are many other aspects to consider that affect the design, such as chemistry, fouling, past experiences, cost, reliability, service, etc.

Clearly, the designer cannot adopt a strategy which is entirely based on first principles, that is, design the heat exchanger starting from a clean sheet of paper; the task would be overwhelming in the intellect, time and effort required. The designer must be more pragmatic.

Heat exchanger design is now in a mature state; many viable designs exist covering the spectrum of applications. Time has eliminated most of the possibilities, leaving a manageable number (about 50) major classes of heat exchanger types that have proved successful in practice. The designer finds that the workable strategy is to first select a few candidates from these classes and to then refine the design using past experience to guide the design process. This is the heuristic approach; rules of thumb are used to guide the search, to narrow down the choices. Hence, the expert invokes a meta-knowledge, that is, a knowledge about his knowledge. The equations need not be solved in detail for the expert to make some comment about pressure drop and how that affects selection.

And so, each engineering team designs the various systems and subsystems. The design process is highly interactive and iterative. Each sub-system has to work as part of the whole collection of systems, ie the whole plant. Engineers simplify the interactions where practical by making the systems as independent as possible. The design task is never linear; systems often have to be re-analysed and re-worked before the die is cast. But the design task is engaging and the design solutions are often quite elegant.

4 The Various Type of Reactors - CANDU vs PWR vs BWR vs ...

Since the inception of nuclear power reactors in the early 1950's, many designs have been conceived, quite of few of these designs were actually built and a handful have been successful. The figure below maps the predominant types that have persisted over time. The types are distinguished by the major design features of fuel type, coolant type and moderator type. The current market share is held by the Pressurized Water Reactor (PWR) which uses enriched fuel, high pressure light water combined coolant / moderator in a pressure vessel. But CANDU, which uses natural uranium, high pressure heavy water coolant in pressure tubes, low pressure heavy water moderator, is a viable competitor. In the end, the choice depends on achieving a balance of technical issues such as cost, safety, operations, design infrastructure, etc. and non-technical issues such as electrical grid planning, institutional and societal preference, international politics, funding arrangements, indigenous resources, etc. It is not the purpose of CANTEACH to explore the relative competitiveness of CANDU vs other viable reactor types. Rather, herein we explore the why's and how's of CANDU itself in an effort to capture the design knowledge for educational purposes.

		Reactor Types: Prototypes and Successes										
		THERMAL REACTORS										**FAST REACTORS**
	MODERATOR	**Graphite**				**Water**		**Heavy Water**				not applicable
	COOLANT	Molten Salt	CO_2	H_2O	Helium	H_2O	H_2O	H_2O	D_2O	Hydro-carbon	CO_2	Sodium / NaK
FUEL	Natural U		Magnox					BLW	CANDU	OCR		
	Enriched U		AGR	RBMK	HTGR	PWR	BWR	SGHW	Atucha		KKN-EL4	
	Thorium-U	MSBR			THTR	LWBR						
	Plutonium-U							ATR				LMFBR

Table 1 Reactor Types

Further reading:

- The Virtual Nuclear Tourist - a very popular site run by Joe Gonyeau, a dedicated nuclear engineer.
- The CANTEACH website - be sure to visit the site library for extensive information on CANDU reactors.