PROLOGUE

CANDU in Context

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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 in this textbook.

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1 Energy in Society

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 7 billion in the year 2013 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.

One has only to reflect on early societies to appreciate the central role that access to energy has played in our development. Food and water are essential commodities for the human race. To supply these in adequate quantities to society has always been a challenge. Ancient civilizations have met this challenge with remarkable feats of engineering such as those at Angkor Wat and Machu Picchu. The Roman aqueducts such as the Pont du Gard also demonstrate significant ingenuity to provide a single commodity. Most of these were built using human power only, which limited the rate of implementation and hence development. This changed with the industrial revolution when first water power and then steam power became a source of energy to assist in the supply of food and water as well as clothing and transport. This supply of energy enabled society to implement new ideas and advance technology at a greater rate and to sustain an increase in population. Thus the human race became dependent upon another essential commodity, namely energy.

It is well established that for the prosperity of any nation, a plentiful supply of cheap energy is the key to economic growth. Countries where energy in some form or another is readily available have become wealthy. Others have had to use their ingenuity to provide this resource. Over time natural resources become depleted and new resources have to be found or developed. Some key resources which have sustained society are wood, coal, oil and now uranium. Although uranium may not generally be considered an essential resource some countries currently cannot do without it.

A suitable environment is an important factor for human survival. People are adaptable and various sectors of humanity have managed to live in all parts of the world from the frigid Arctic to the burning deserts. Hardships in these regions can be alleviated with a supply of energy enabling increased development and access to more resources. In essence, an artificial environment has been created in which to live. The human race is becoming more and more dependent upon such an artificial environment or inner environment which includes heating and air conditioning and promotes productivity. This requires increasing dependence on energy. On the other hand there is the outer environment into which waste products from the inner environment and energy production are dumped. No matter how good the inner environment the outer environment still needs protection to sustain humanity.

The development of technology has put increasing stress on the outer environment but has also provided the means to protect it. In the generation of power and the use of energy through fossil fuels, various solid pollutants such as fly ash and gaseous pollutants such as sulphur dioxide and nitrogen oxide are produced. The former have been significantly reduced by the use of electrostatic precipitators and fabric filters in coal fired plants and the latter by the implementation of alternative fuels to eliminate smog and the development of on board diagnostic systems to reduce automobile emissions. Nevertheless, the outer environment is adversely impacted by the extensive use of fossil fuels. The only practical and economic way that these effects can be reduced is by burning less hydrocarbon fuel.

This problem of energy use and power production can be overcome by using electrical energy to replace hydrocarbon fuels and generating this energy by water and wind as well as by the nuclear fission of uranium. Most sites for hydro power have already been developed, and future development in this area is limited by possible detrimental local environmental effects. Wind power is intermittent and variable so that, beyond a certain capacity relative to the grid capacity, the electrical grid becomes unstable. Moreover, reserve capacity has to be provided for the loss of wind power. This leaves nuclear power as the only choice for long term base load energy production with minimal impact on the environment. There are no carbon dioxide emissions from nuclear power, and a relatively small amount of radioactive waste is produced. By recycling this waste the very long lived transuranic products can be returned to the reactor to be destroyed leaving only the shorter life fission products to be stored. A huge advantage of nuclear energy is the vast amount of energy obtained from a very small amount of uranium. 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. This is illustrated in Figure 1. Natural uranium that is mined from the ground is 0.7% U-235 and 99.3% U-238. The results of fission are fission products that are radioactive, gamma 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 generat-

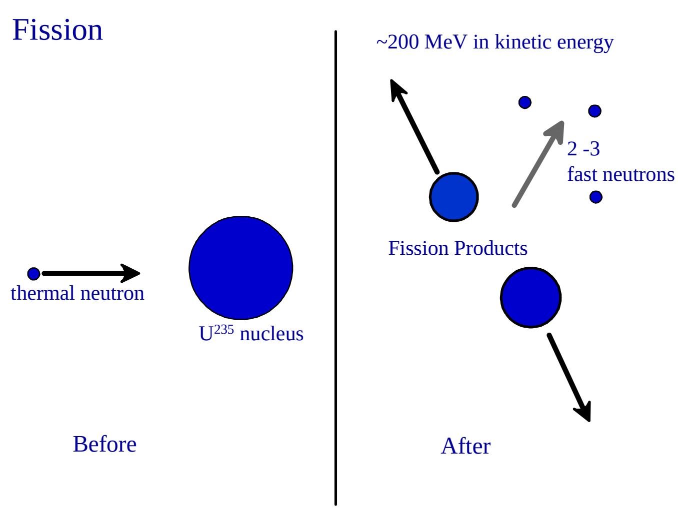

Figure 1 Fission

ing more neutrons and thus sustaining a chain reaction. So the neutrons need to be slowed down (i.e., thermalized or moderated), which is done by using a moderator such as water. The heat generated needs to be removed. The process is controlled 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.

From this the basic functional requirements of a reactor are directly derived. Needed are:

- 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, these requirements are discussed in turn to gain some insight on how and why CANDUs (and other reactor types) 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, AGR, RBMK, 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.

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 mass of 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 which runs counter to the need 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 probability. 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 or beryllium 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 2 illustrates the fission and moderation processes.

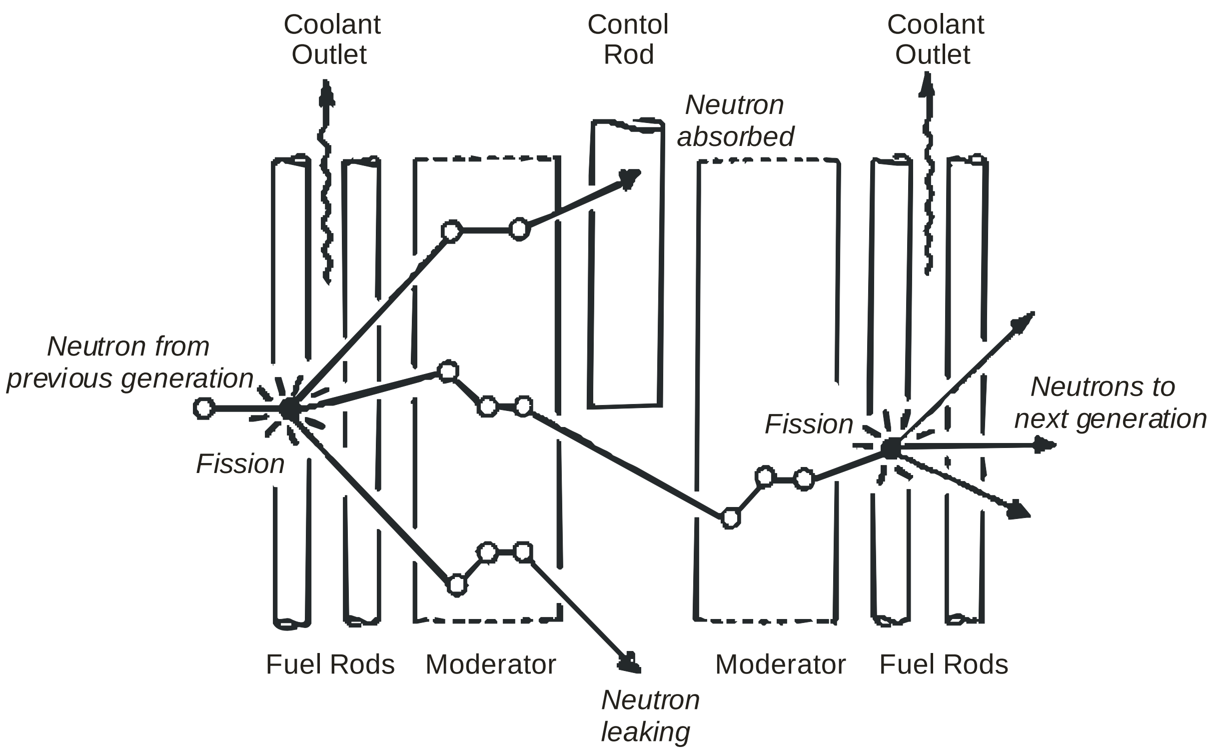

Figure 2 Nuclear reactor components

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

The fissioning process generates energy, predominately in the form of kinetic energy of the fission products which, after a few collisions with the immediately surrounding material matrix, manifests itself as heat. A coolant (commonly) is passed over the fuel to remove this heat so that it can be used productively for energy generation. So far, we have fuel, moderator and coolant. We can conceptualize our CANDU as in the illustrations in Figure 3, below.

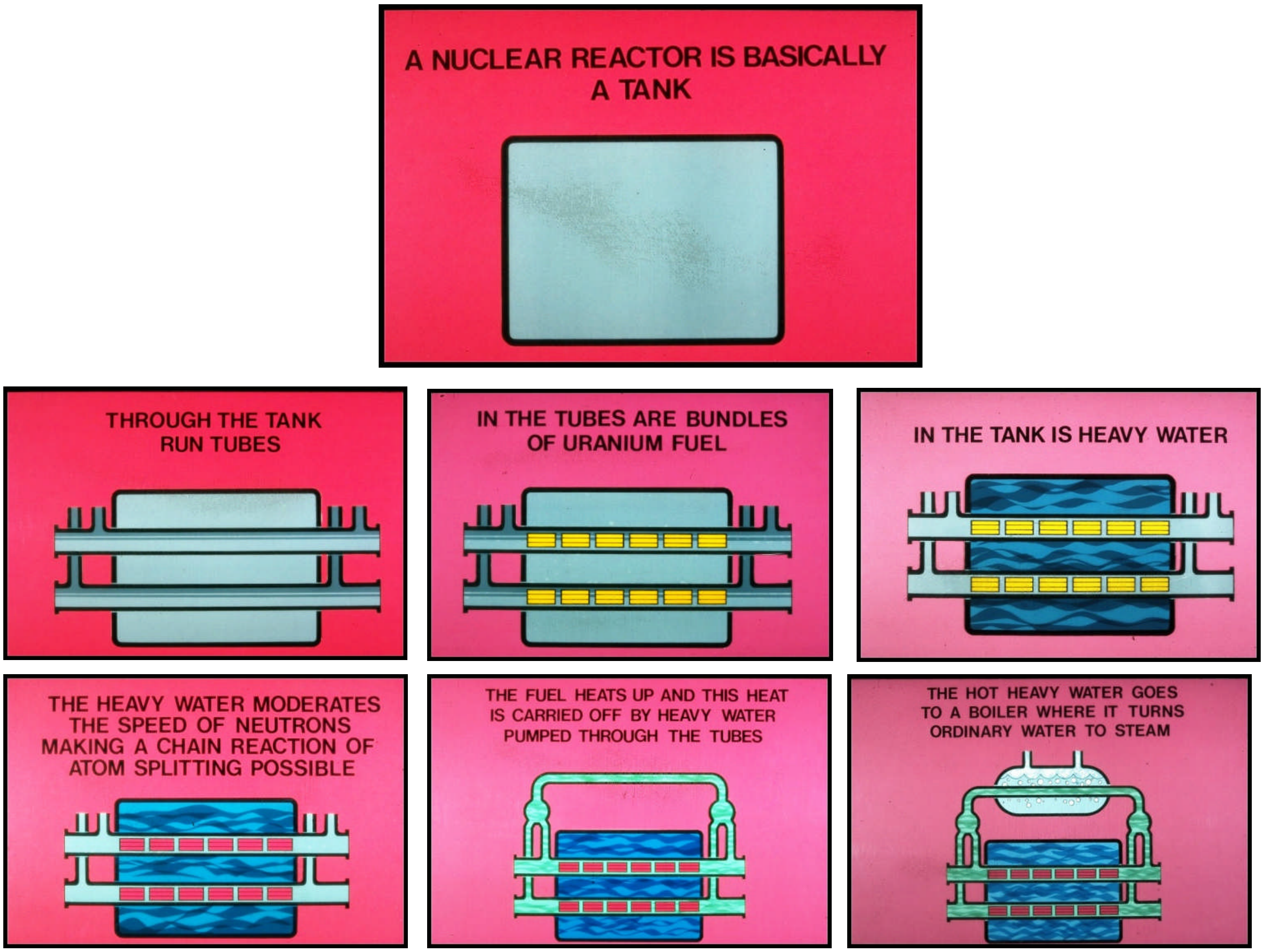

Figure 3 A Conceptual CANDU

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 4, 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.

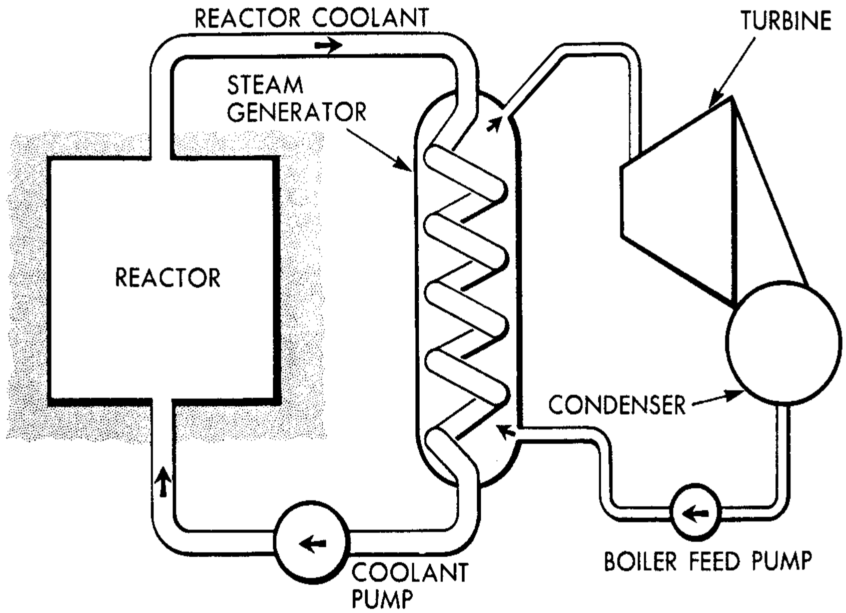

Figure 4 Basic power reactor schematic

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 can be controlled.

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 built for reliable, fail-safe operation, are highly redundant, and employ additional safety concepts such as group separation.

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.

2.7 The system that pulls it all together

The various requirements related to fuel, moderation, cooling, control and shielding to conceive a stylized CANDU are pulled together as illustrated in figure 5. 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 by the outer containment shell.

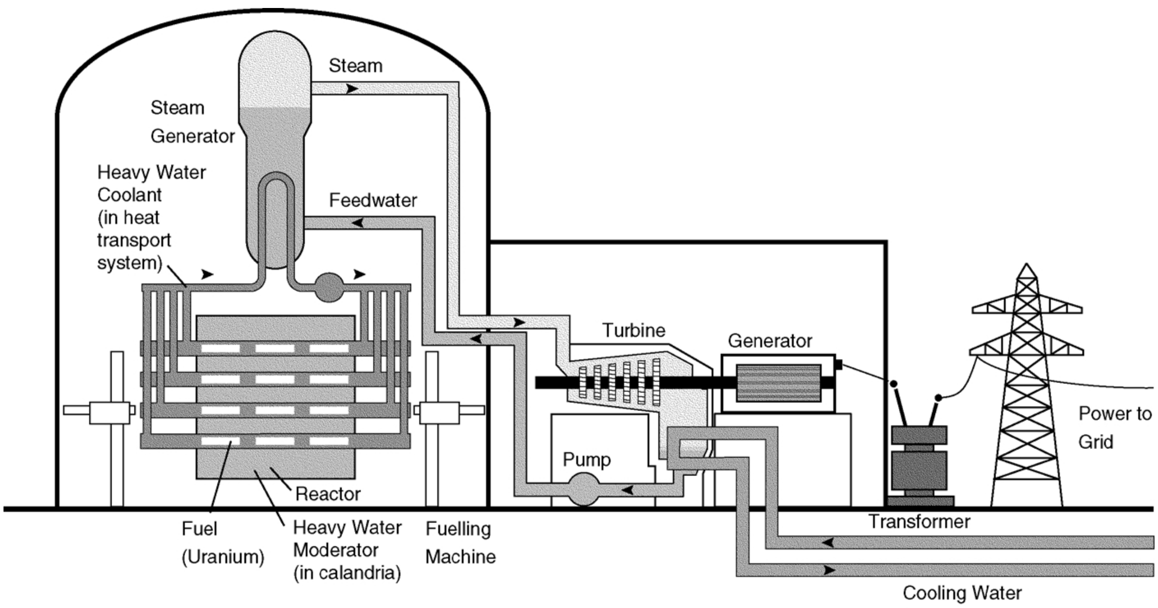

Figure 5 The overall CANDU nuclear plant

Obviously, a real CANDU is far more complex than the illustrations and designing a nuclear plant is not a trivial exercise. There are many systems and sub-systems that interact.

3 Textbook Organization

Presenting educational material on a complex physical system such as a nuclear power plant is problematic in that some knowledge of the physical plant is needed in order to give context to the physical phenomena studied, yet some knowledge of the physical phenomena is needed to make sense of the physical plant. So some iteration in presentation is unavoidable and, from a learning perspective, will prove helpful.

So we begin in the introductory chapters by putting the CANDU reactor in a societal context, give a very brief look at how the reactor functions, provide some historical context, and describe how it has evolved. From this the reader will appreciate enough of what a CANDU as a physical system entails to give context to the more in-depth chapters that follow.

The flow of the Chapters 3 to 11 is dictated by the focus on the Process Systems and the flow of power from the core to the grid. Subsequently Chapters 12 to 19 explore various key topics that arise directly as a result of the energy generating process.

The very core of the subject, literally is the fuel. The process (i.e. fissioning) aspects of the fuel and associated moderator are the subject of Chapters 3, 4 and 5 which cover the basic nuclear processes and the reactor physics topics of statics and dynamics. This sets the nature of the beast, as it were.

From both a process perspective and a safety perspective, cooling the reactor core and transporting the heat energy generated by the core is centrally important. Thermalydraulic Design and Analysis is covered by Chapters 6 and 7.

The overall plant dynamics are not so much determined by the dynamics of the individual components and systems such as the reactor core or heat transport system since each of these systems is controlled to keep each system within its own operating envelop. Overall plant dynamics is more characterized by how these systems interact with each other and is the subject of the chapters on Plant Systems (8) and Plant Operations (9).

Then a closer look at reactor and process system Instrumentation and Control (10) and Electrical Systems (11) is given.

Radiation is generated and so must be understood, quantified and handled (Chapter 12 Radiation Protection and Environmental Safety).

Fissioning is inherently an exponential process and entails substantial decay heat even after shutdown. Hence Safety (13) and Regulations and Licensing (16) are central issues.

The nuclear environment can be a harsh and demanding one. Physical integrity must be maintained over the long life of the plant, day in, day out. Hence Materials (14) and Chemistry (14) are key subjects.

The process characteristics of fuel as they relate to fissioning and heat transfer are treated in the early chapters. But there is much more to say about fuel, specifically its physics characteristics that enable it to perform so well under conditions that are so demanding. This is the subject of Chapter 17. The forward looking topics of Fuel cycles and storage and disposal are the subjects of Chapters 18 and 19 and are a fitting way to end our introductory textbook on the Essential CANDU.

4 Further reading

- The Virtual Nuclear Tourist at http://www.virtualnucleartourist.com/ - a very popular site run by Joe Gonyeau, a dedicated nuclear engineer.
- The CANTEACH website at https://canteach.candu.org/ - be sure to visit the site library for extensive information on CANDU reactors.