Science of Nuclear Energy and Radiation

Nuclear Reactor Concepts

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1. Introduction

When we speak of a nuclear reactor, we mean a system that employs the fission reaction - the splitting of heavy (unstable) nuclei with neutrons in a chain reaction **(slide)** - not the fusion reaction, which joins light nuclei by forcing them together.

Don't expect to see commercial fusion reactors for some time yet, as there are challenging engineering problems still to overcome.

Uranium is unstable; it decays by emission of helium nuclei, and it fissions spontaneously. Each fission releases a few neutrons. A nuclear reactor is a geometrical configuration of fissionable materials and other materials that enables a self-sustaining, chain reaction.

Many types of nuclear reactors have been developed over the past 56 years:
- Research reactors to produce neutrons for nuclear research
- Reactors to produce radioisotopes (e.g. MAPLE) for medical or industrial uses.
- Power reactors to release nuclear energy for various applications, such as:
  - electricity
  - process heat, e.g. steam for marine propulsion, district home heating, desalination, other industrial applications
  - combined cycle uses, that is electricity and process heat

2. Types of power reactors

Like motor vehicles, there are many types of power reactors. They are classified by:
- fuel
- coolant
- moderator (to slow down fast neutrons from fission)

To sustain a chain-reaction, it is necessary to conserve neutrons. This is achieved by reducing their absorption, and escape from the reactor. The reactor size must be large enough (critical size), and a suitable material is used to reflect neutrons back inward.

3. Fuels:

- natural uranium: 0.7% U-235, 99.3% U-238
- uranium enriched in the U-235 isotope (the balance is U-238)
- plutonium mixture (Pu-239 is produced by neutron absorption in U-238.)
- U-233 mixture (U-233 is produced by neutron absorption in thorium.)

Fuel forms: metal alloy rods, oxide ceramic pellets, molten salt mixture, etc.

50% of the energy produced from natural uranium in a CANDU reactor comes from the fission of plutonium - it produces 40% of the energy from a LWR.
Only ~1% of the potential fission energy in the fuel is released in most reactors.

4. Moderators: for thermal neutron reactors, to slow down neutrons without absorption

- **normal water** ($H2O$) - used in "light" water reactors (LWRs) like the PWR and BWR

(Hydrogen is an excellent moderator, but it absorbs neutrons.)

- **heavy water** ($D2O$) - used in heavy water reactors (HWRs), such as the CANDU

(One atom in 6700 of normal hydrogen is the deuterium isotope. D is less efficient than H as a moderator, but D is a much weaker absorber of neutrons than H.)

- **graphite** (C) - used in most British and in some Russian reactors

(Note that C is less efficient than H or D as a moderator, but is a very weak absorber.)

- **beryllium** (Be) - used in the SLOWPOKE research reactor
- **no moderator** - used in "fast" reactors, such as breeder reactors, where most fission reactions are by neutrons that have not been slowed down to be in thermal equilibrium

5. Coolants: to transfer fission energy (heat) for the application, e.g. electricity, etc.

- natural water
- heavy water
- gas, such as $CO2$, helium, hydrogen, mercury
- liquid metals, such as sodium, lead, bismuth (in fast reactors)
- molten salt (which may include the fuel itself - homogeneous reactor

6. Which reactor type to use?

They are all designed to be adequately safe. The choice depends on the following considerations:

- capital cost (CANDU is ~$2000/kWe)
- operating cost (CANDU ranges from 1 to 3 cents/kWh)
- fuel availability
- flexibility to use different fuels over the 40 to 60-year plant life. The CANDU can use:
  - natural uranium-oxide (0.7% U-235, balance U-238)
  - depleted uranium-oxide (0.3% U-235, balance U-238) breeds Pu-239 fuel
  - slightly enriched uranium-oxide (0.9 to 1.2% U-235)
  - recovered uranium-oxide (reprocessed used LWR fuel) - RU @ 0.9% U-235
  - mixed oxide (MOX), e.g. 2% Pu-239 oxide in depleted uranium-oxide
  - thorium-oxide (three times more abundant than uranium) breeds U-233 fuel
- reactor supplier (providing financing, localization/jobs, technology transfer, service)
- performance (reliability, availability, load-following capability, maintainability)
- political factors
- public attitudes

In this course, I will discuss mainly the CANDU reactor which uses natural uranium oxide fuel and D2O, heavy water, for both the moderator and the coolant.

7. **Radiation** is a form of energy.**(slide)**

During each fission reaction, radiation is released as:
- kinetic energy of fast neutrons
- photons (gamma-rays and X-rays)
- kinetic energy of electrons (beta-rays)
- neutrinos (pass through everything)

After each fission reaction, the unstable fission products continue to decay with different half-lives, releasing energy as radiation, mainly as gamma-rays and beta-rays.

The reactor structure and coolant become radioactive due to their absorption of neutrons.

So the design of all reactors includes:
- shielding to absorb the radiation
- long-term cooling to remove the decay heat
- many physical barriers to prevent the release of radioactive atoms to the employees (working near the reactor) and to the surrounding environment.

8. Extracting useful nuclear energy

When the uranium nucleus splits, two fragments are usually produced plus a few neutrons. One fragment has a positive charge of ~40 and the other fragment has a positive charge of ~50. So they repel one another electrostatically and separate. Most of the fission energy is released as the kinetic energy of these fragments, which appears as heat in the fuel.

The mass of the original uranium atom and the neutron exceeds the mass of the fission fragments and the fission neutrons. The total energy released is: $\mathbf{E = \Delta m \cdot c^2}$

So the fuel material becomes very hot, like the heating element in an electric kettle. This flow of heat must be transferred (very reliably) to a coolant, in order to obtain useful energy and to prevent the fuel from melting and releasing radioactivity.

The reactor design must allow for adequate heat transfer to a coolant (pumped or moving by convection), and the design must enable the coolant to transfer the flow of heat, reliably, to the application - to the steam generators, or directly to the turbines (BWR).

If the application (load) is somehow disconnected, the flow of heat must be transferred to a heat sink (sea, lake, river, air, ground, etc.) or to a back-up heat sink, and the power of the reactor must be reduced to be within the capability of the heat sink to remove the energy at the rate that it is being produced by the reactor.

Stopping the fission reaction does not stop the flow of heat from the fuel. This is because the fission products (FPs) continue to release radioactive energy. On a prompt shutdown from full power, the rate of energy production from FP decay decreases slowly, starting from a few percent of full reactor power.

9. Comparing CANDU reactors with LWRs (slide)

There are ~450 power reactors in operation world-wide:

~250	PWRs
100	BWRs
38 + 4	HWRs (mostly the CANDU type)
35	gas-cooled
15	LW graphite
3	LMFBR

To achieve a reasonable thermal hydraulic efficiency (>30%), the coolant is heated to a high temperature (~300°C or higher), which results in a pressure of ~100 atmospheres or higher, if water is used as the coolant.

The core size of an HWR is larger than the size of a LWR of the same power because a longer distance is needed to thermalize fission neutrons in D2O than in H2O.

When natural uranium fuel is used, it is necessary to add fresh fuel frequently (daily) because of the low concentration of U-235. It is like shoveling coal into the steam engine of a train. The CANDU-6 reactor has 12 fuel bundles in each of 380 fuel channels, and roughly one channel is refueled on-power, every day, using the two refueling machines.

LWRs must use fuel assemblies that are enriched with U-235 because of the high neutron absorption of ordinary water. The fuel is designed to last for at least 12 months of full power operation. At the end of this mission, LWRs are shut down, opened, and fuel is replaced. This is a batch-type process, appropriate for the marine propulsion reactors used in the Navy. This type of reactor was later adopted for peaceful applications.

So the LWR is in a pressure vessel with a wall thickness of 20 to 30 cm (8-12 inch). The CANDU is a larger, un-pressurized vessel with a wall thickness of 2.5 cm (1 inch). It is filled with heavy water moderator and fuel channels. Each pressure tubes has a wall thickness of only 0.4 cm.

Over many years (~30 y) of operation, the pressure tubes deteriorate due to neutron bombardment. We can replace the pressure tubes within a year (like an engine overhaul) and keep the reactor in service indefinitely.

10. Power station - energy transfer scheme (slide)

Pressurized heavy water is pumped through feeder pipes into the fuel channels in order to transfer heat from the fuel to the steam generators. In the SGs, this heat is transferred to ordinary water, which boils into steam. The steam is piped to a multi-stage turbine which turns an electricity generator. One-third of the energy in the steam is converted to electric energy, which is sold to local consumers (home owners, industry, etc.) or exported out of the province. Two-thirds of the energy in the steam is transferred in the condensers to a heat sink (sea, lake, river, air cooling towers, etc.).

Five percent of the fission energy is deposited into the moderator, which is maintained at ~60°C by pumping moderator water through heat exchangers, to transfer this heat to a heat sink.

The part of the circuit from the steam generators onward is more or less the same for a fossil-fired power plant.

Gas-turbine plants burn methane in a jet engine, which turns an electricity generator. Such plants have relatively low capital cost, but higher fuel costs. They depend on the supply of gas by pipeline from remote gas fields.

11. Slides: feeder pipes, steam generator, turbine, generator, Pickering NGS

The eight-reactor Pickering station has a capacity of 4000 MWe. It can supply all of the electricity needed by the City of Toronto. This building holds used fuel bundles after they have been stored in a water pool for at least six years. The pressure tubes that were removed from the "A" station, ten years ago, are kept in these cylinders.

12. Slides: Bruce A, Bruce B, Darlington, CANDU-6 reactors, CANDU program, other stations.

13. Plant control and special safety systems

There are two classes of systems in nuclear power plants:

- **process systems** to release nuclear energy from fission and to generate electricity
- **special safety systems** to provide confidence to everyone, that the plant will not have an accident, which would injure workers or release a large amount of radioactivity, to harm people and/or the environment.

CANDU process systems include an automatic plant control system, which features:

- dual, redundant control computers which operate independently of each other
- redundant sensors that measure plant variables, which are input to both computers
- automatic transfer of plant control to the back-up computer when a failure occurs in the computer that is controlling the plant.

Human operators observe the control room display of plant variables. They intervene to shut the plant down when the automatic system fails. Some functions are under human control, such as refueling the reactor on-power to compensate for burn-up of the fuel.

The reactor control system is a part of the plant control system. It measures the neutron flow (rate of fission) over the entire reactor power range, from the spontaneous fission level to full reactor power.

The sensors include:

- “start-up instrumentation” (neutron counters) for the very low reactor power range
- out-of-core neutron detectors which measure reactor power on a logarithm scale, from 10^{-7} to 1.5 of full power
- in-core neutron detectors for accurate power measurements in the high power range

The power control devices (neutron absorbers) employed to reduce the rate of fission are:

- in-core compartments, which are filled with ordinary water (or emptied), for both spatial and bulk power control
- cadmium control rods, above the reactor, which can be moved slowly or dropped
- steel rods, in the core, which are raised when a local power adjustment is needed
- boron or gadolinium, dissolved in the heavy water, which can be added or removed

There are also radiation sensors to protect workers from overexposure and to prevent unacceptable releases of radioactivity from radioactive areas.

14. Special safety systems - are independent of the normal plant process systems

- **Safety shutdown system(s)**
- provide confidence that the fission chain reaction will stop automatically in the event that the plant goes outside the safe limits of operation

In CANDU reactors, there are <u>two</u> such independent and very reliable shutdown systems:

- Shutdown system #1 drops many neutron absorbing rods into the reactor.
- Shutdown system #2 releases a pressurized neutron-absorbing gadolinium solution into the heavy water moderator.

- **Emergency core cooling**
- provides confidence that the fuel will not overheat in the event of a loss of normal cooling and release radioactive fission products from the fuel

In CANDU reactors there are very reliable cooling systems that provide:

- immediate high-pressure flow of cooling water, for at least 2.5 minutes
- medium-pressure cooling flow, for at least 13 minutes
- low-pressure cooling flow, for long-term heat removal.

- **Containment**
  - provides confidence that large quantities of radioactivity (fission products and/or tritium) will not be released from the reactor building in the event of a break in the heat transport system (Tritium is formed when a deuterium nucleus absorbs a neutron.)

CANDU reactors have the following provisions to contain radioactivity:

- pressure-resistant building, qualified for earthquakes, and other external hazards
- automatic water-spray to suppress steam
- air coolers
- filtered air discharge system
- airlock access
- automatic sealing of all building openings

- **Safety-support systems**
  - back-up supplies of electrical power
  - back-up supplies of cooling water
  - back-up control centre, for post-accident control and monitoring

15. Two safety-related events

- **Three-Mile Island, Unit 2**
  - core melted on 1979 March 28
  - no one killed or injured
  - small release of radioactive gases
  - public alarmed
  - large financial loss
  - successful clean-up operation
  - lessons learned were applied to most operating plants

- **Chernobyl, Unit 4 disaster**
  - core destroyed by power excursion on 1986 April 26
  - 28 plant workers died from radiation overdose
  - 3 workers died from fire and shock
  - 3 children died from thyroid cancer during the following 10 years
  - large populated areas were heavily contaminated with radioactivity
  - cleanup workers (200,000 to 600,000) received moderate radiation doses
  - surrounding population received low doses, evacuated, emotional stress
  - widespread public fear of nuclear technology
  - destroyed reactor was enclosed in a concrete building
  - most reactor design problems were corrected in the remaining RBMK reactors
  - safety culture of the reactor operators was improved

16. Assessment of current status

- 1st nuclear plant: Shippingport, Pennsylvania in 1957 December
- Forty years later: 450 nuclear power plants world-wide
- They provide: 18% of the world's electricity
- Current reactors: safe, but there were two serious events
- Current world energy situation:
  - 85% of the world's commercial energy comes from burning low-cost fossil fuels
  - supply of low-cost oil will peak soon and decline gradually
  - natural gas is very popular, but it will deplete soon
  - coal can supply the world's energy for centuries, but there is concern about CO2
  - hydro is excellent and renewable, but not widely available; has environmental issues
  - other renewable sources: solar cells, wind-power, etc. diffuse, intermittent, regional
- If the full potential of the world's uranium and thorium resources are used (in breeder reactors) nuclear power can supply a large share of the world's energy needs for many thousands of years.

17. Future challenges

- **Cost reduction**
  - simplify and standardize reactor designs, i.e. remove unnecessary components
  - reduce construction costs, i.e. shorten construction time and procurement time
  - reduce licensing costs, i.e. shorten licensing time and environmental reviews
  - reduce design costs, i.e. shorten design time by using computerized design tools: models, drawings, wiring, integrated design, material control, etc.
  - provide plant life assurance: facilitate plant maintenance as nuclear plants age
  - provide for plant life extension: replacement of worn and obsolete components

- **Improve nuclear safety**
  - continue reviewing the design and updating the plant safety report
  - learn from safety-related events
  - add worthwhile safety upgrades where cost-effective
  - reduce emissions where cost-effective

- **Build public confidence in nuclear technology**
  - communicate this advanced technology in simple language
  - communicate the real effect of low-dose radiation on health
  - reduce the frequency of incidents/accidents