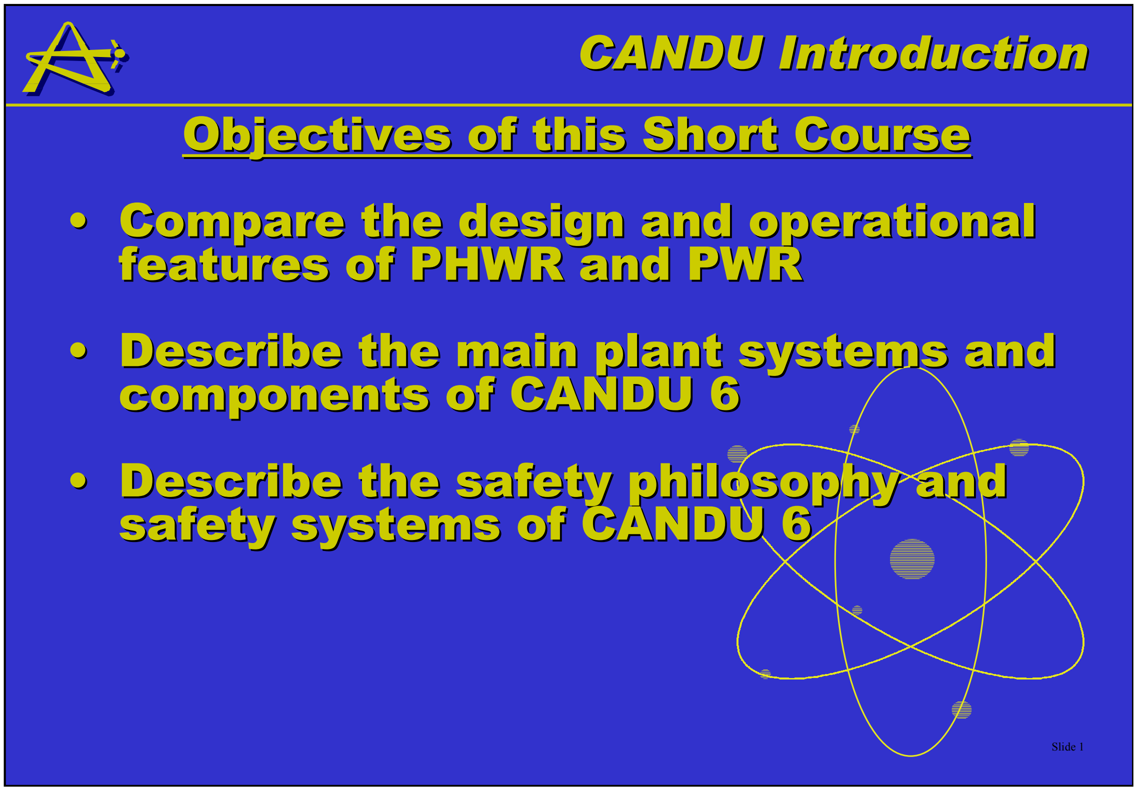
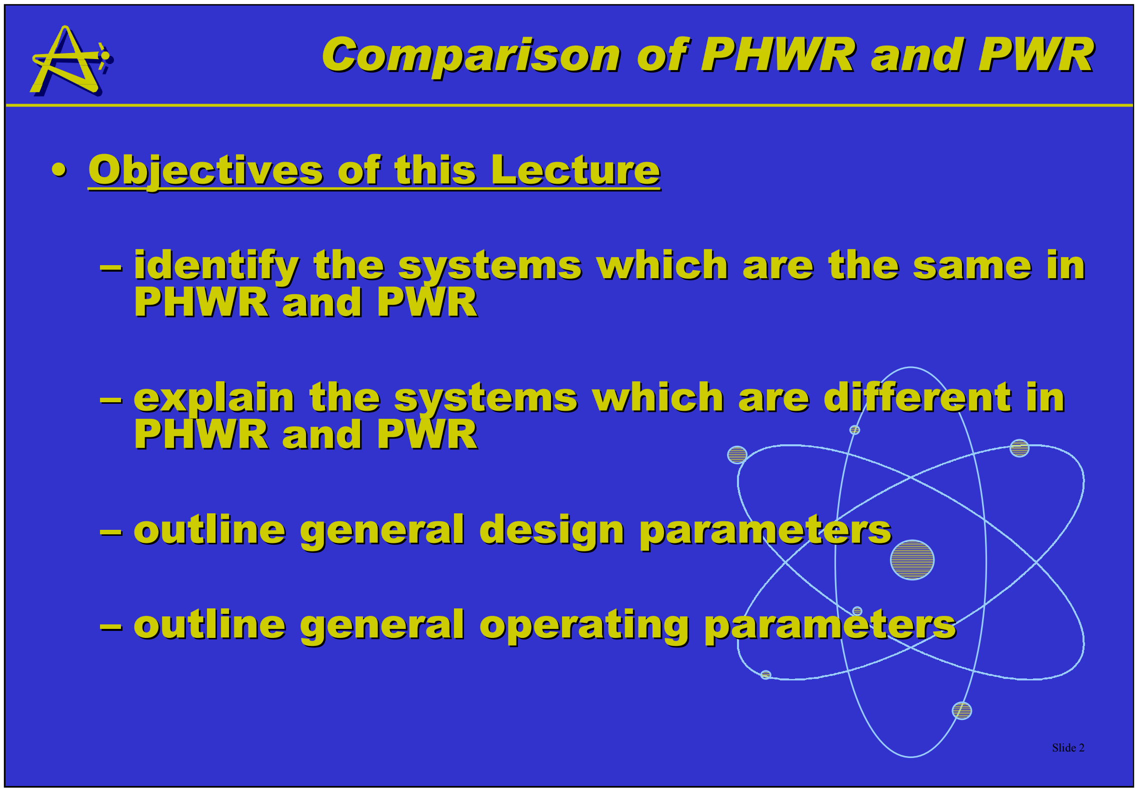
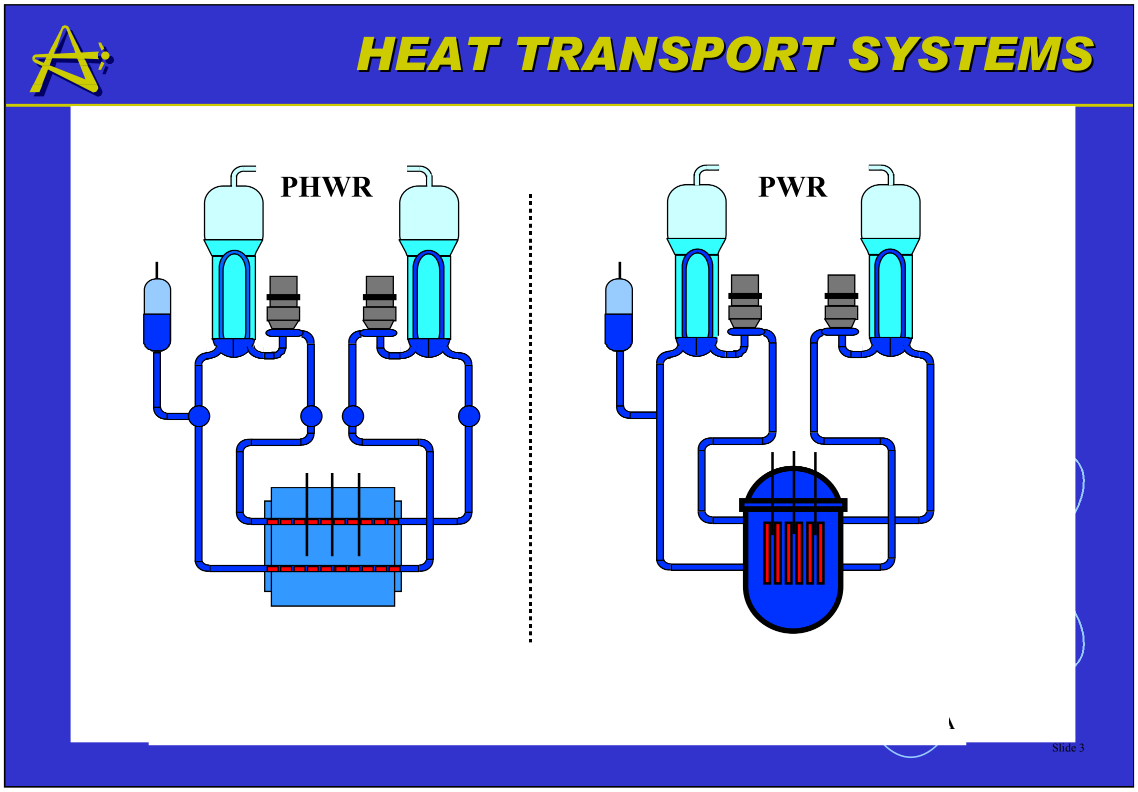


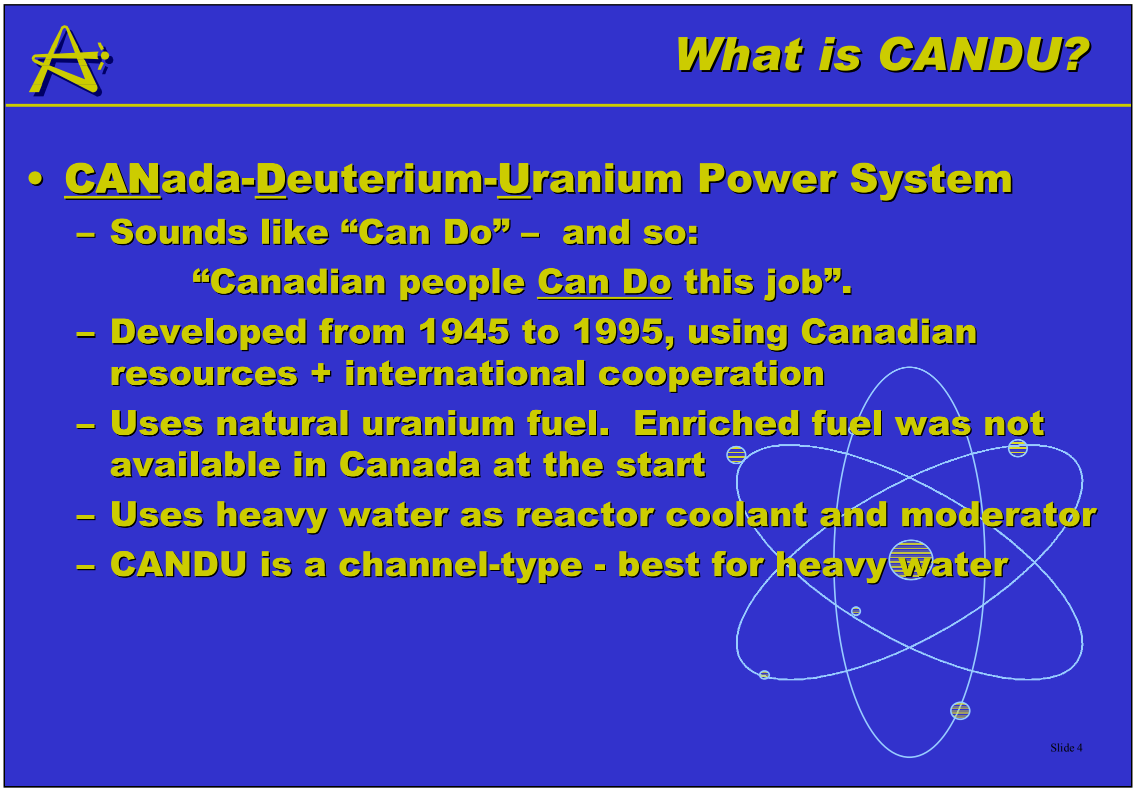
- Welcome, and thank you for this opportunity to speak to you.
- CANDU technology is not understood as well in China as is the PWR. But, many of you will be responsible for some part of the successful operation of two large power stations using CANDU 6 reactors. So the need is clear.
- Some of you are starting a long operations training program. This program will tell all of the details of the whole CANDU system, as you need to run the plant. Today we will only begin this learning by telling you the general information.
- In this course I will give basic descriptions of the systems of CANDU 6 that are different from equivalent systems in a Pressurized Water Reactor. Then I will describe the most important plant systems and components of CANDU 6. Finally I will describe the safety philosophy, and the safety systems which are installed in CANDU 6. The specific plant descriptions will refer to the equipment used in the CANDU 6 plant at the Qinshan site.



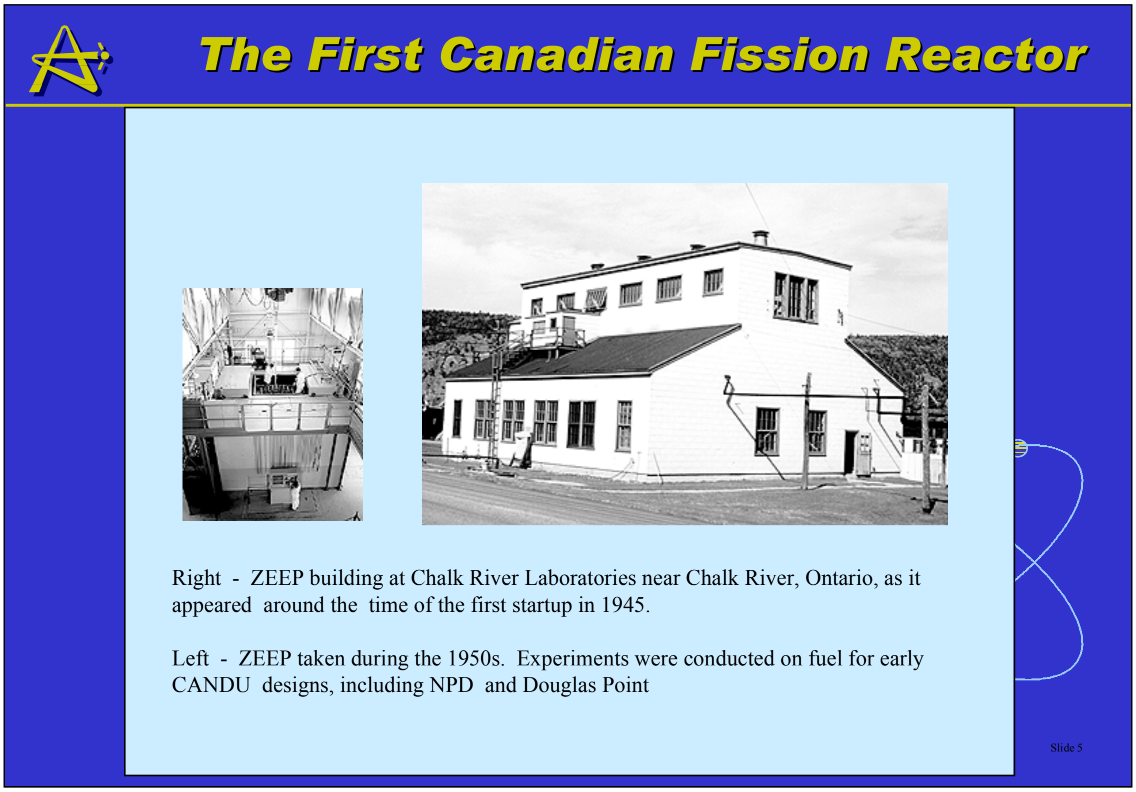
- Systems which are called <u>the same</u> in these two reactor types usually are different in detail, but carry out almost the same functions in almost the same way. For example, today can say that all of the turbine-generator and electrical systems of the two plants are <u>the same</u> -- even if they include some details which are different.



- The CANDU is really a pressurized water reactor. It uses a closed primary circulation loop to transport heat to the steam generators. In a second closed loop which includes the turbine, light water steam acts as the working fluid. The primary loop is (almost) completely full of liquid heavy water.
- This figure shows the primary heat transport circuits of a CANDU-PHWR and a PWR. The CANDU 6 has two steam generators and two pumps in each "figure of eight" circuit. There are two circuits, one from each half of the reactor core. Usually, a PWR of the same output has only two steam generators and two pumps in two circuits.
- In a CANDU 6 the primary water is heated by the fuel in many small fuel channels. In a PWR this heating takes place in a large pressure vessel, where all of the fuel is located.
- Pressure control is maintained in both of these systems by a steam space in a pressurizer connected to the circuits.
- Power output of each plant is adjusted by changing the fission rate in the reactor.
- CANDU 6 has two diverse, redundant, and independent safety shutdown systems, which operate in the cool, low pressure moderator. (This feature now is recommended for new PWR's)
- All CANDU systems have a separate full pressure Residual Heat Removal (RHR) System to remove fission product decay heat.
- Outside the reactors themselves, the two power systems are very similar.



- This project was started before the end of the Second World War. At that time Canada was a developing country. In about 1955, the Province of Ontario used all of its hydraulic generation. They had no oil, no coal, no gas -- and so, No Choice but Nuclear!
- Many British, French, and other scientists moved to Canada to escape the war - they started the Canadian nuclear power program.
- The most basic decision was to use natural uranium fuel - No Choice!
- After this, it was decided to use heavy water as the moderator -- Better than Graphite!
- AECL wanted to use a pressure vessel for the first demonstration. This idea was stopped by the electric utilities - They Wanted Big Reactors!
- A pressure vessel of this type using heavy water would be too big for manufacture in Canada. (the German design in Argentina gives the proof.) The design group changed CANDU to a channel-type design.
- First prototype was 20 megawatts electric (MWe), second prototype was 200 MWe, and the first commercial power plant was 2000 MWe (4x500 MWe) The second commercial plant was 3400 MWe (4x850 MWe)
- CANDU 6 design was taken from the first commercial plant (but a single unit)
- CANDU 9 design was taken from the second commercial plant (also a single unit)
- Several generations of CANDU plants are operating in the world - about 35 in total.



1945 The ZEEP research reactor is completed at Chalk River, Ontario and sustains the first controlled nuclear chain reaction outside the United States

1947 The National Research Experimental (NRX) reactor starts up at Chalk River -- the most powerful research reactor in the world

1952 The Canadian Government forms the Crown corporation Atomic Energy of Canada Limited, or AECL, from precursor organizations dating back to the early 1940s

1954 AECL, Ontario Hydro, and Canadian General Electric (now G.E. Canada Inc.) form a partnership to build Canada's first nuclear power plant, Nuclear Power Demonstration (NPD)

1957 The National Research Universal (NRU) reactor starts up, and today is still considered one of the world's finest for its versatility and high neutron flux

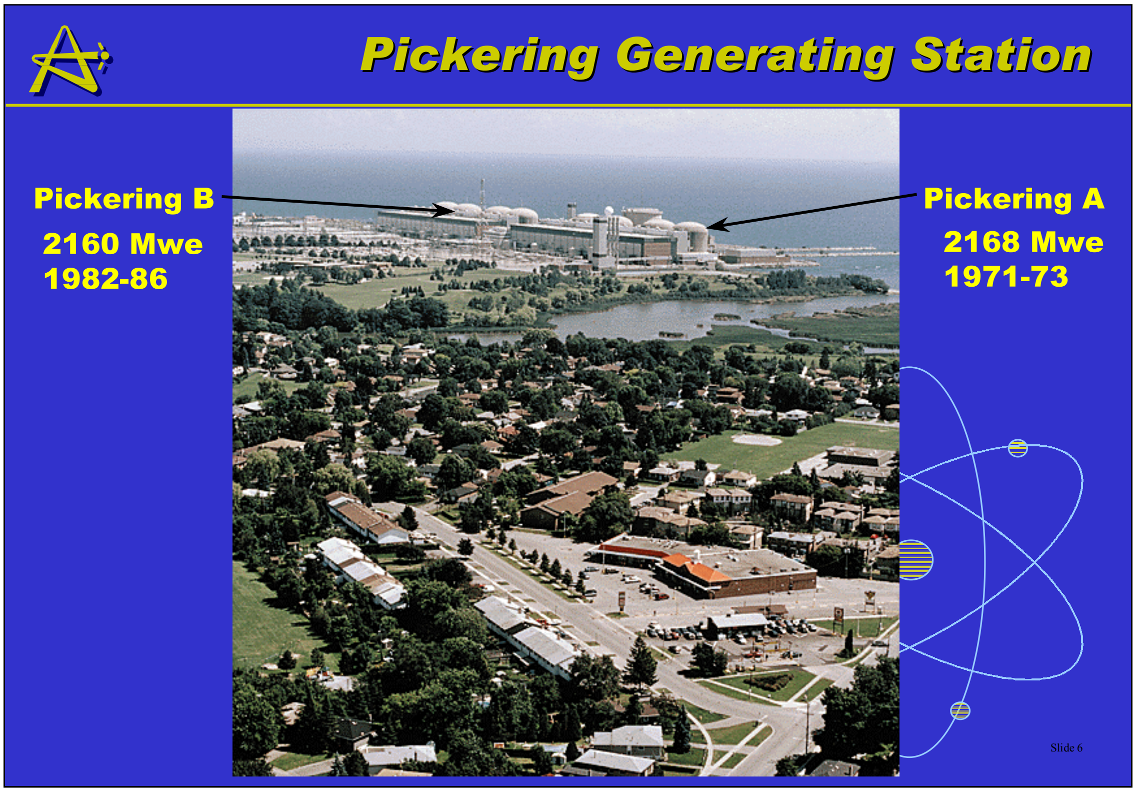
1960 Work begins on a 200 MWe CANDU prototype at Douglas Point, Ontario

1962 The Province of Ontario receives nuclear-generated electricity for the first time from the NPD station

1965 The Douglas Point station starts up

1973 The Pickering Nuclear Generating Station in Ontario is completed, producing more electricity than any nuclear power station in the world at that time

1974 AECL makes its first international sale to Argentina -- a single- unit CANDU 6 reactor, derived from the multi-unit Pickering station



1977 Pickering Unit 3 achieves the highest capacity factor in the world

1981 Canadian Prime Minister Trudeau visits Wolsong during construction of Unit 1

1982 AECL begins construction on an Underground Research Laboratory for investigation of long-term disposal of nuclear fuel waste

1983 Four CANDU 6s in Argentina (1 unit), Canada (2 units), Republic of Korea (1 unit) start commercial operation and CANDU wins seven of the top 10 places for lifetime performance among the world's reactors

1987 CANDU wins one of the ten Canadian awards for the top engineering achievements of the past century

1990 The Republic of Korea orders Wolsong Unit 2

1992 The Republic of Korea signs for two more reactors, Wolsong Units 3 and 4

1994 Bertram Brockhouse is awarded the Nobel Prize in Physics for his discoveries using neutron scattering at the NRU reactor.

1994 Pickering Unit 7 sets a world record for continuous operation (894 days) without a shutdown

1995 The HANARO research reactor, with a core based on MAPLE technology, starts up in the Republic of Korea

1996 Cernavoda Unit 1 attains criticality in Romania on April 16 -- first CANDU in Europe

1996 The Peoples Republic of China orders two CANDU 6 reactors for Qinshan site

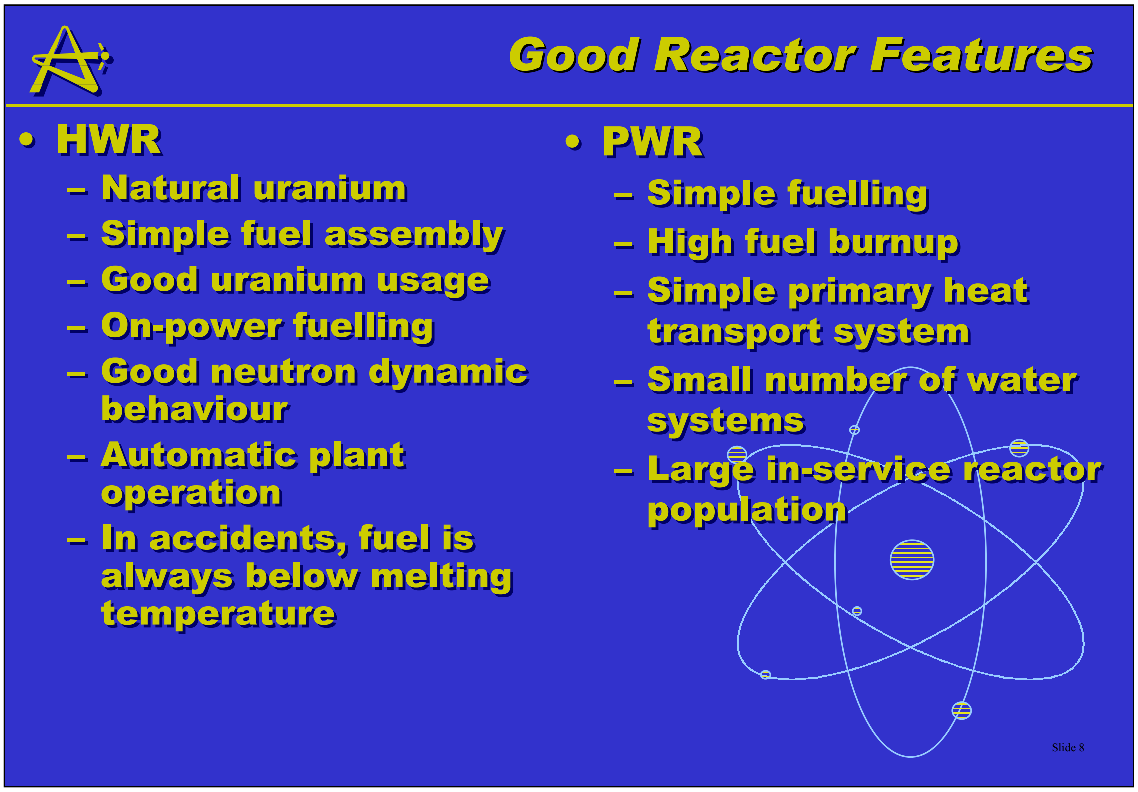
1998 First permanent concrete poured for Qinshan Phase III units

Successful Reactor Designs

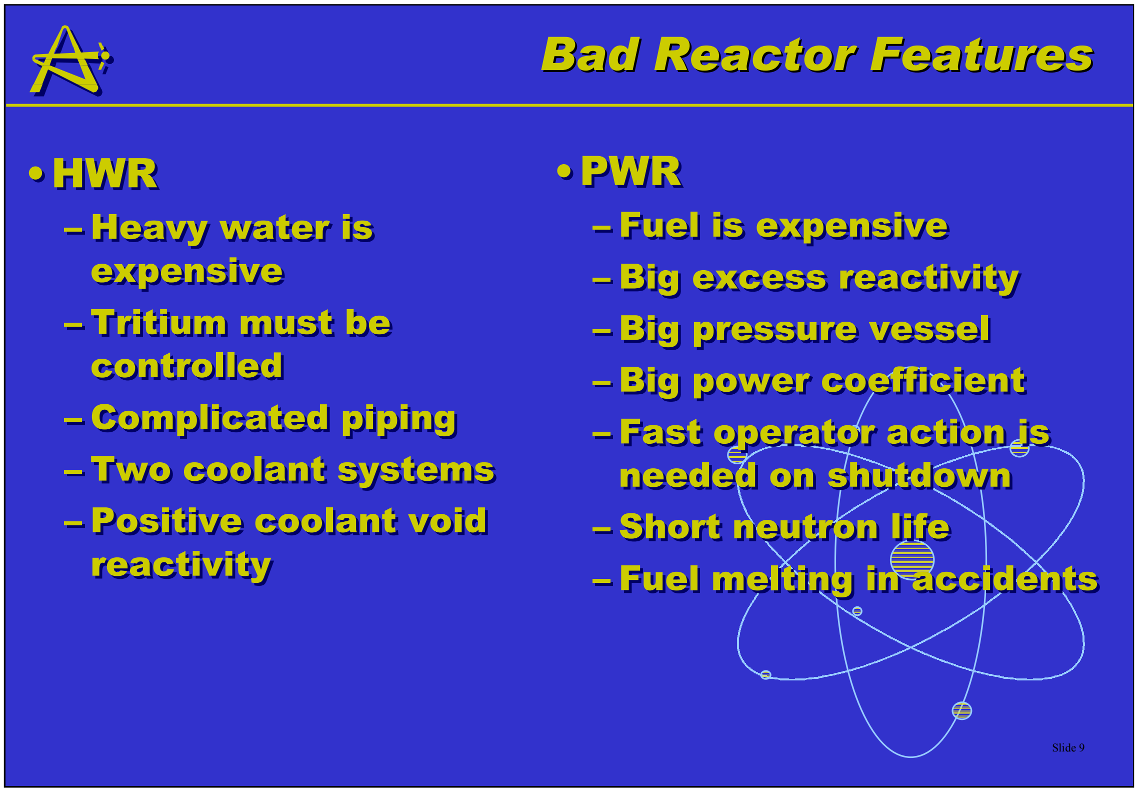
THERMAL REACTORS										FAST REACTORS	
GRAPHITE				WATER		HEAVY WATER					MODERATOR
Molten Salt	CO_2	H_2O	Helium	H_2O	H_2O	H_2O	D_2O	Hydro-Carbon	CO_2	Sodium/ NaK	COOLANT
											FUEL
	Mag-nox					BLW	PHWR	OCR			Natural U
	AGR	RBMK	HTGR	PWR	BWR	SGHW	Atucha		KKN, EL4		Enriched U
MSBR			THTR	LWBR							Thorium - U
						Fugen				LMFBR	Plutonium-U

Slide 7

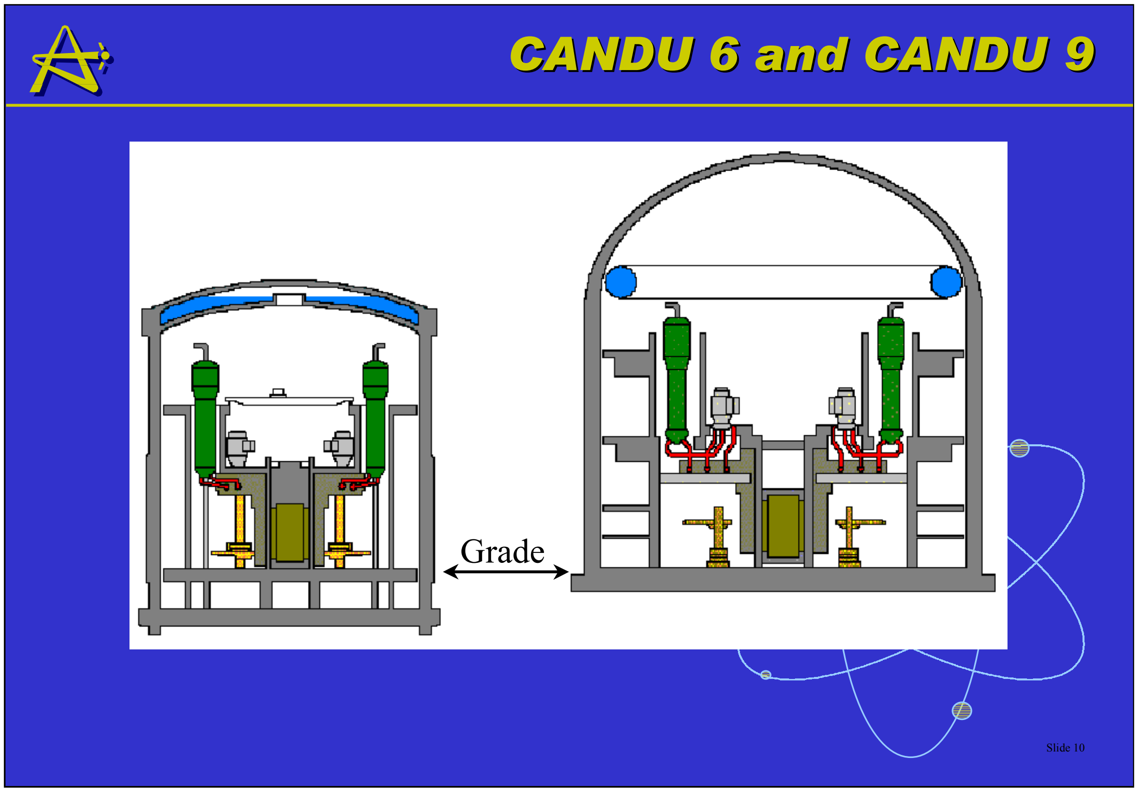
- Many reactor designs have been tested. Only two are successful today -- the PWR and the PHWR.
- The BWR might be successful, if it can meet cost requirements. Some Japanese electric utilities will be the most important reasons for its success, if this happens.
- The FBR and the HTGR might be successful in the future, if money is found to develop them.
- Success of the FBR depends on the uranium supply - it will be needed only if and when the uranium price is high.
- It is expected that FBR reactor plants will be installed in larger numbers beginning in about the year 2050. They likely will be used to produce large amounts of fissile material for burning in thermal reactors.
- Competition between PWR and PHWR is not as important today as is competition of all nuclear plant types against fossil fuels - coal and natural gas.
- Price will decide which technologies are accepted.
- The most important engine for development of new reactor types will be national governments.



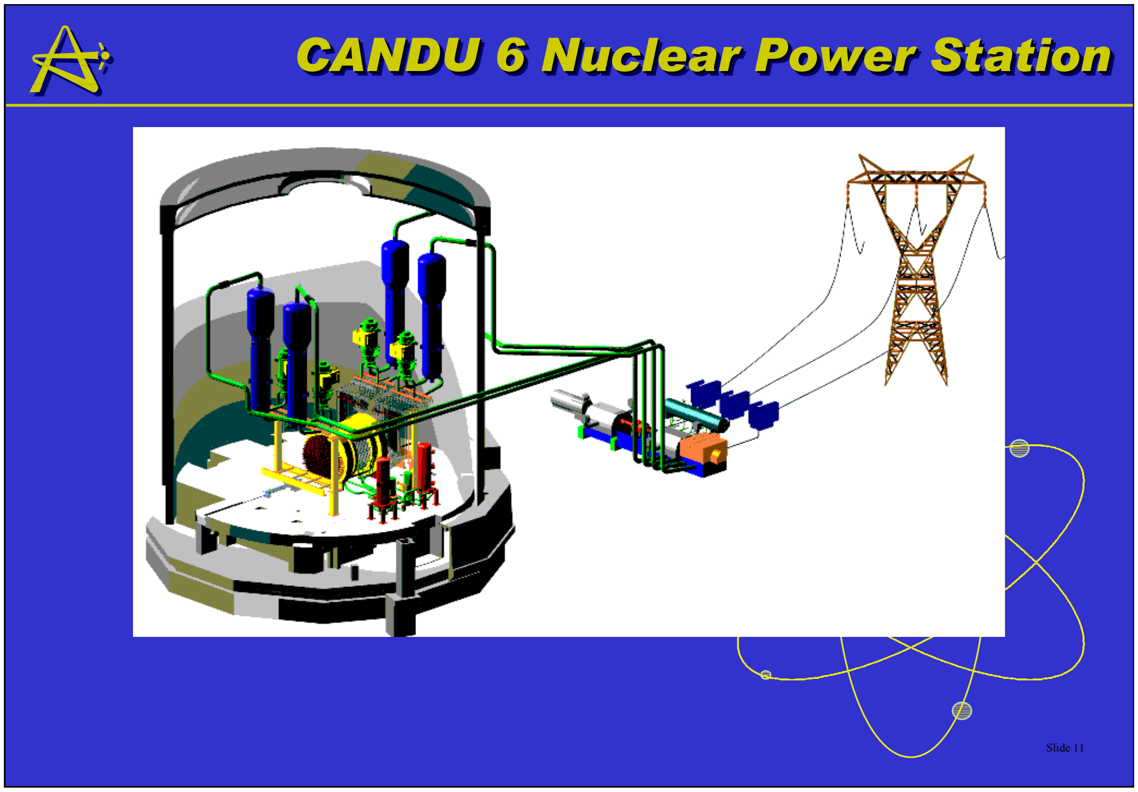
- Each reactor type has advantages and disadvantages. Design strategy is to choose the reactor type which has the most useful characteristics, and then to design a plant which minimizes the inherent disadvantages of the type.
- When comparing these reactor types, we should assume that the total electricity cost per kilowatt-hour from each of them is the same. This is true in the real world.
- The first advantages of HWR are related to fuel. Natural uranium plus simple fuel assembly mean cheap fuel. Combined with relatively high energy output per unit of uranium mined, this means low fuelling cost.
- On-power fuelling gives high capacity factor, on-power replacement of failed fuel, and constant neutron dynamic parameters. This capability is achieved at a cost -- fuel handling systems are complicated and need regular maintenance. But the payback in extra electricity generation is very large.
- Automatic plant operation gives the operator freedom to think about inspection and maintenance most of the time -- and he supervises the automatic systems.
- Reactor meltdown is almost impossible in the CANDU-PHWR
- For the PWR, off-power fuelling is required only once a year (or less). This is <u>much</u> simpler than the HWR fuelling system. And high burnup is possible by use of enriched fuel.
- The PWR has much less piping because of the single pressure vessel and 2-4 heat transport circuits.
- The PWR has only light water systems, so has a small number of water systems to be monitored, managed, and maintained.
- Finally, the world has many PWR's, so it is cheaper for a PWR owner to share design and operating information.



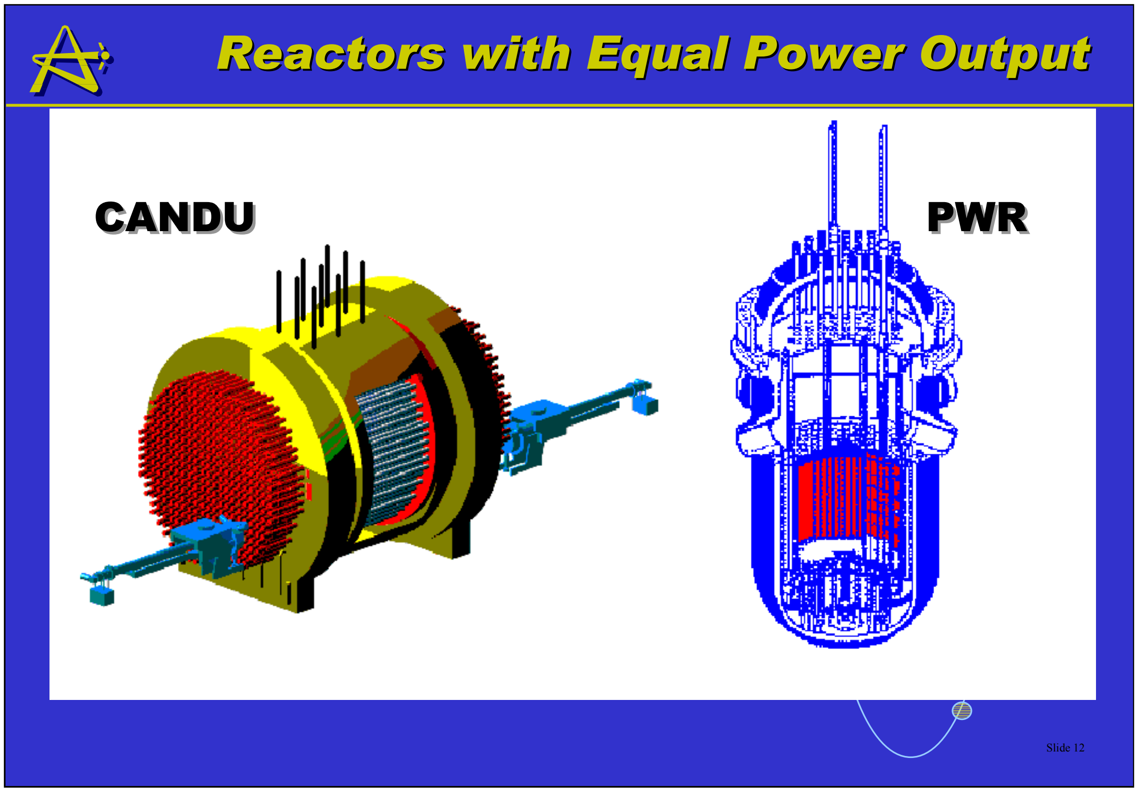
- Some bad features of each design:
- The HWR needs very pure heavy water. Therefore, water systems must be carefully sealed and monitored. Rooms containing heavy water must have water collection and air drying systems.
- Tritium is produced inside the HWR reactor, from capture of neutrons by deuterium. This tritium must be carefully controlled at all times, for worker and public safety
- Cooling circuits for the reactor are complicated; each fuel channel has its own feeder pipes.
- The HWR design includes both heavy water coolant systems <u>and</u> light water cooling systems. This means twice as many water systems than the PWR.
- If a pipe breaks and water boils in a CANDU reactor, the power goes up. This is the unsafe direction -- so designers must install very reliable methods for safe shutdown.
- In the PWR the water is cheap but the fuel is expensive because of the enrichment process.
- Because PWR refuelling is done only once a year, a lot of extra enrichment must be put in to balance reactivity loss during operation. The excess reactivity requires dissolved boron in the moderator - a possible safety hazard.
- The big pressure vessel is difficult to manufacture except in big, industrialized countries. Also, the pressure vessel is sensitive to local temperature changes, and to steel embrittlement in the long term.
- The power coefficient in PWR is strong and negative. Big control movements needed to raise power.
- Many operator actions are needed whenever a PWR is shut down -- these actions must be done precisely, on time. (A CANDU can be shut down to zero-power hot conditions by computer alone.)
- The neutron lifetime is short, so power increases very fast with positive reactivity addition.
- If coolant is lost from the reactor for any reason, the fuel melts very quickly. This is a big safety question.



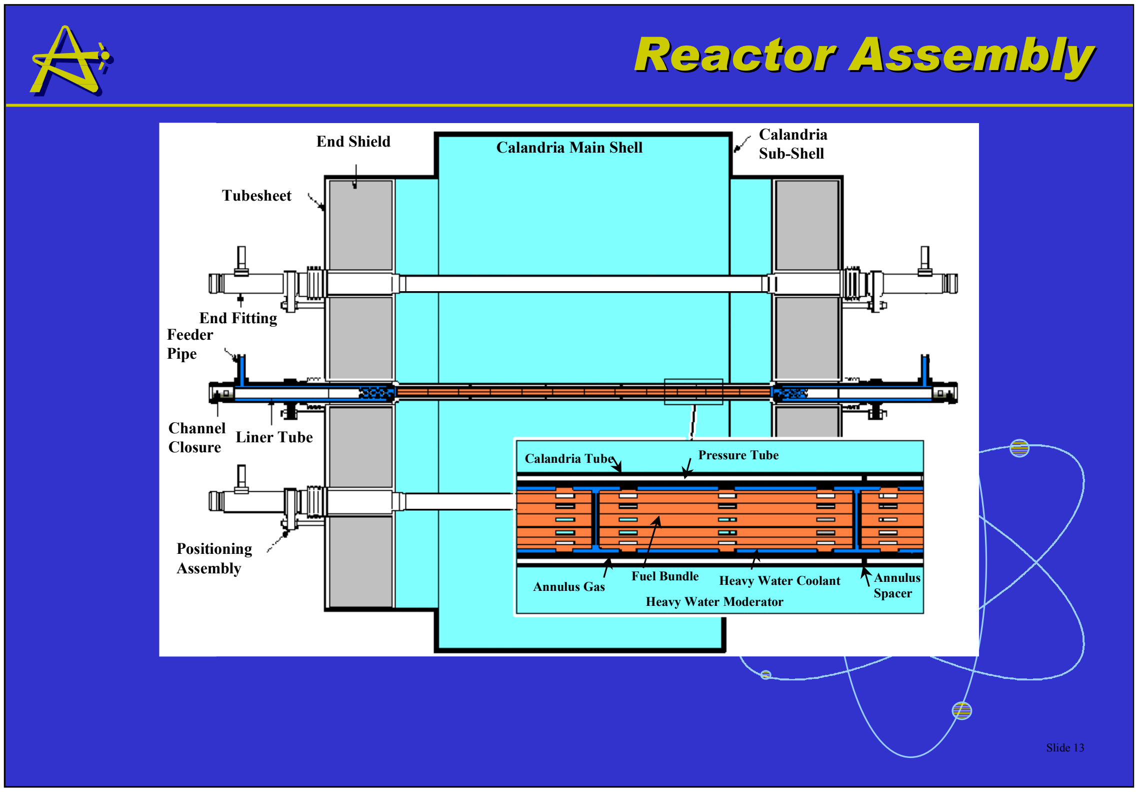
- These pictures show the CANDU 6 reactor building layout along with the larger CANDU 9. These two reactors were designed nearly 20 years apart.
- CANDU 6 uses a post-tensioned reinforced concrete containment building with epoxy liner. CANDU 9 uses the same type of containment building but with a steel liner, as requested by potential customers.
- Both designs have water tanks at the top of the containment building. But CANDU 6 uses some of this water to spray into the building after a pipe break (to reduce internal pressure). The CANDU 9 building is designed for full pressure, so it needs no spray water. In the CANDU 9 design this water is used for emergency supplies and to improve the natural response to accident conditions.
- Steam generators, pumps, fuel channels, and piping are very similar. CANDU 9 uses "interlaced" feeder piping to reduce maximum coolant void reactivity.
- Fuel handling systems in CANDU 9 are support from the floor and not from a bridge system as in CANDU 6. This allows better arrangements for used fuel discharge outside containment and for easier maintenance of fuel handling components.



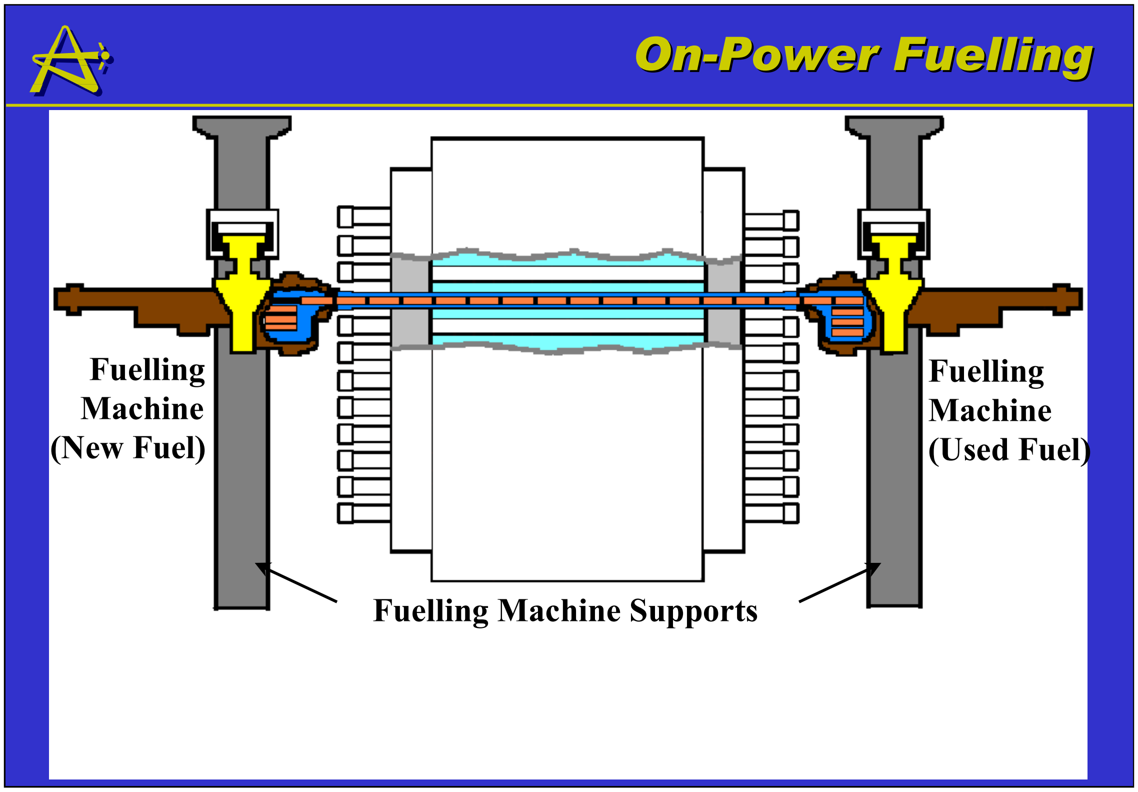
- This picture (drawn from AECL’s 3D CADD system) shows CANDU 6 with inside concrete taken away, and connection of Nuclear Steam Supply System (NSSS) to the turbine-generator, electrical systems and finally to electricity supply lines.



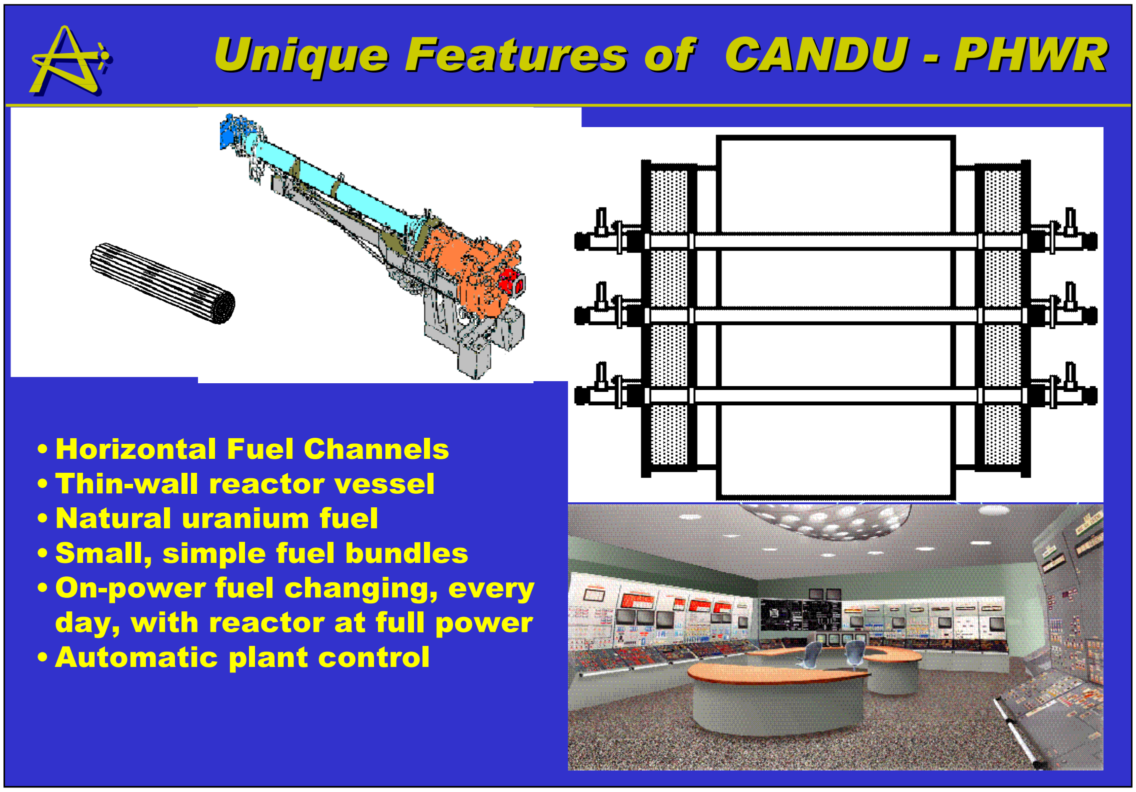
- Here is shown a CANDU 6 reactor on the left and a PWR with approximately the same output on the right. Each of these is drawn to the same scale.
- The two reactors occupy about the same volume. The PWR core is more compact, but the surrounding pressure vessel uses a lot of space outside the core. Also, the top and bottom connections of instruments and control rods use even more space.
- The low-pressure PHWR reactor tank is surrounded by a second tank filled with light water, which is used for radiation shielding. (As a result, the reactor vault in which the reactor is placed needs no water cooling to protect its concrete. All control rods and instruments are placed in the low-pressure moderator.
- If a big accident happens, the CANDU reactor is surrounded by a large amount of cool water which can absorb fission decay heat over many hours. After a similar accident, emergency water must be supplied to the PWR immediately, to prevent fuel melting.



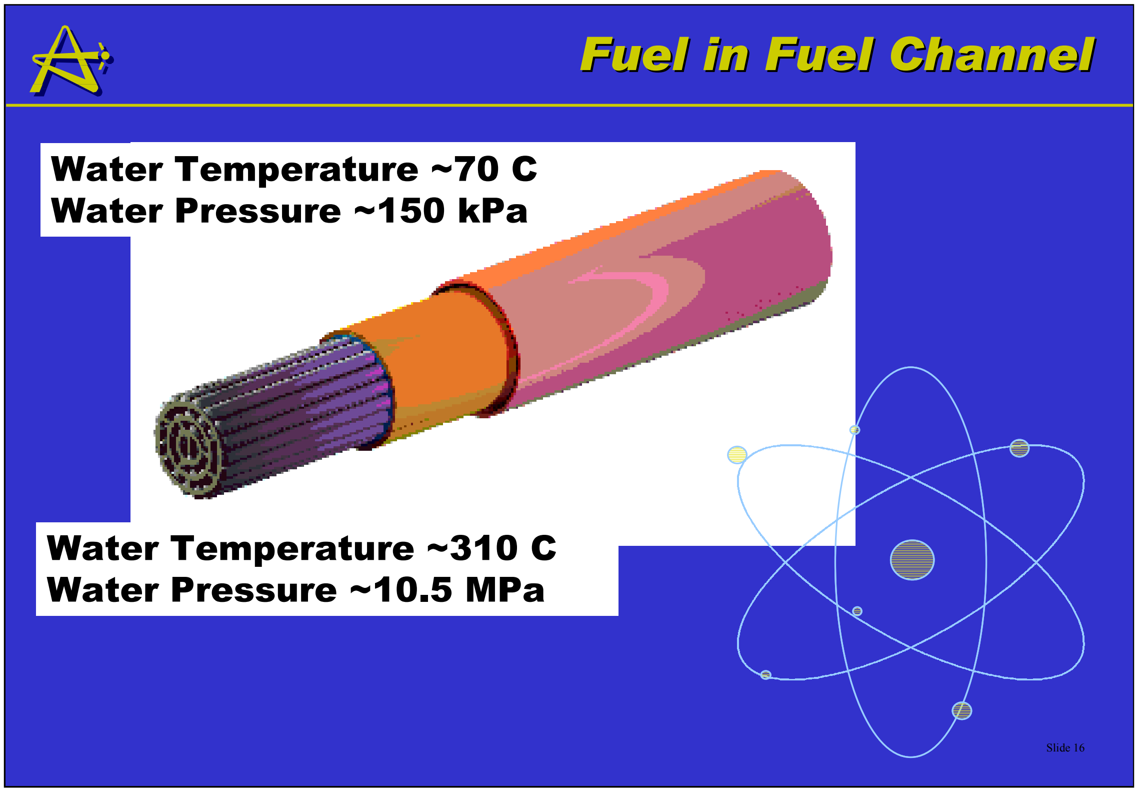
- A real CANDU 6 reactor has 380 fuel channels. Only three are shown here, not to scale.
- Each calandria tube is supported at each end by an inner tube sheet. The calandria tube is rolled into the tube sheet to seal the joint.
- The moderator tank has a separate cooling system to remove heat produced from slowing-down collisions of neutrons and gamma rays.
- End shields are located between inner and outer tube sheets at each end of the reactor. The end shield material is carbon steel in the form of spheres. Light water is circulated through the end shields to remove collision heat from nuclear collisions.
- Each pressure tube is supported by two bearings at each end, located at the positions of the inner and outer tube sheets. During operation the pressure tube also is supported by the calandria tube via four annulus spacers.
- Each pressure tube is connected at each end to the end fitting. The end fitting-pressure tube-end fitting assembly is clamped at one end by a positioning device attached to the outer tube sheet.
- Each end fitting is sealed at its outer end by a removable plug. A shield plug rests inside the end fitting.
- Heavy water coolant of 25 kg/s enters the channel via the feeder pipe connection, flows through the core and to the outlet feeder at the other end. The flows in adjacent channels are in opposite directions.
- Twelve fuel bundles are placed inside the pressure tube by the remotely controlled fuelling machines which attach to opposite ends of each fuel channel. The average residence time of fuel in the reactor is about one year.



- With the reactor at full power, fuelling machines are located by computer control to a single channel. The channel plugs and then the shield plugs are removed and stored inside a revolving magazine inside each fuelling machine. New fuel is pushed into one end of the channel by hydraulically-driven rods. Used fuel is accepted into the opposite machine and stored in the rotating magazine.
- Normally, eight fuel bundles are replaced each time fuelling machines are connected to a channel.
- Plugs then are replaced in the channel, seals are checked for leaks, and fuelling machines are moved to the fuel storage location to discharge used fuel and picked up more fresh fuel.
- The complete fuelling cycle takes about 2 1/2 hours. Normally, 2 or 3 channels are fuelled each full-power day.
- A three dimensional reactor simulation code keeps track of the actual burnup conditions of each fuel bundle. An expert system based on previous operating experience selects the channels to be fuelled each day, subject to approval by the shift supervisor.
- A fuelling-machine operator monitors the fuelling process from a console in the control room.



- This picture summarizes unique features of the CANDU-PHWR.
- All components can be manufactured in developing countries. Technology transfer is done in stages, to match the local capabilities. Fuel will, for example, be manufactured in China from the beginning of Qinshan Phase III operation.
- The CANDU system is fully developed, well-supported, and is a good choice for future electricity generation.
- Most important --- <u>It Works!</u>



- Now we should see a little more detail about the PHWR
- This diagram shows a fuel bundle inside a pressure tube, inside a calandria tube. This is the most difficult part of the design from the point of view of materials.
- High temperature, high stress, long life (replacement is possible, but not easy)
- Large pressure differences
- Large temperature differences
- High neutron fluxes, especially fast neutrons
- Water-metal interactions - these reactions tend to weaken the highly-stressed pressure tube, slowly over time.
- Any failure of the pressure tube is a failure of the primary pressure boundary - this is a Loss of Coolant Accident (LOCA). A LOCA is a serious challenge to the plant safety systems'
- Designer and operator response

    best materials

    plenty of testing

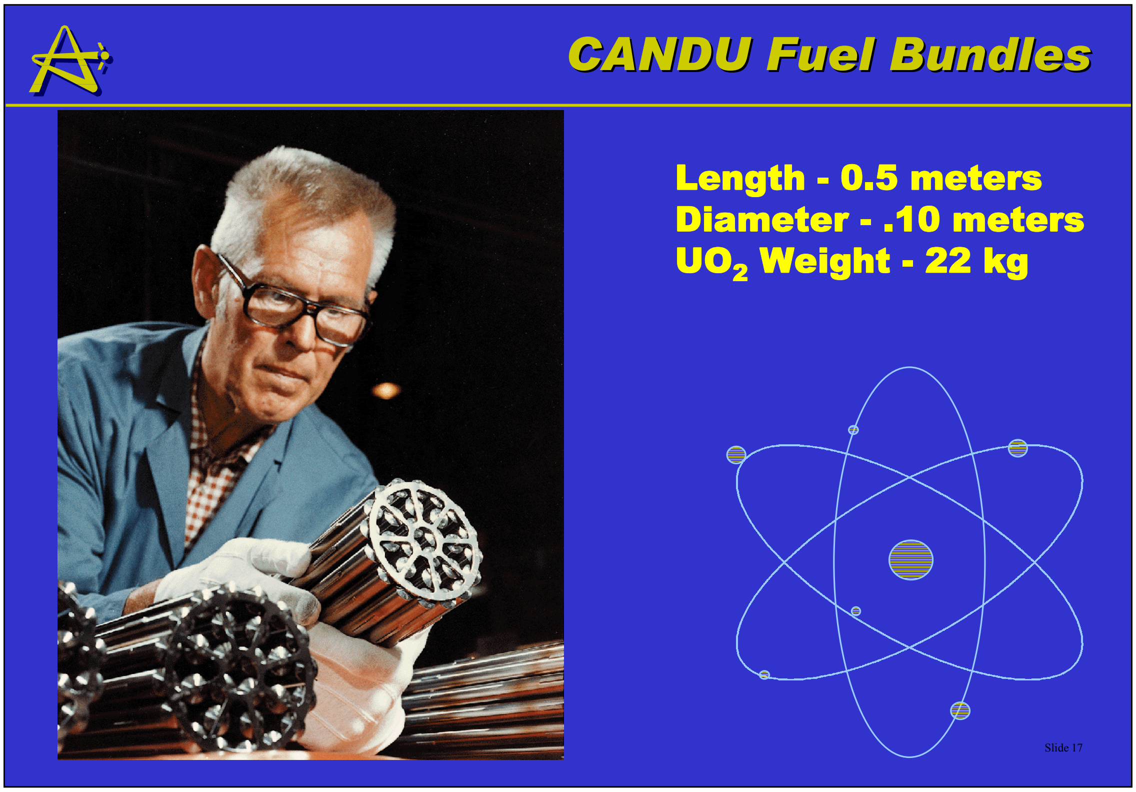
    high quality manufacturing, testing

    excellent construction

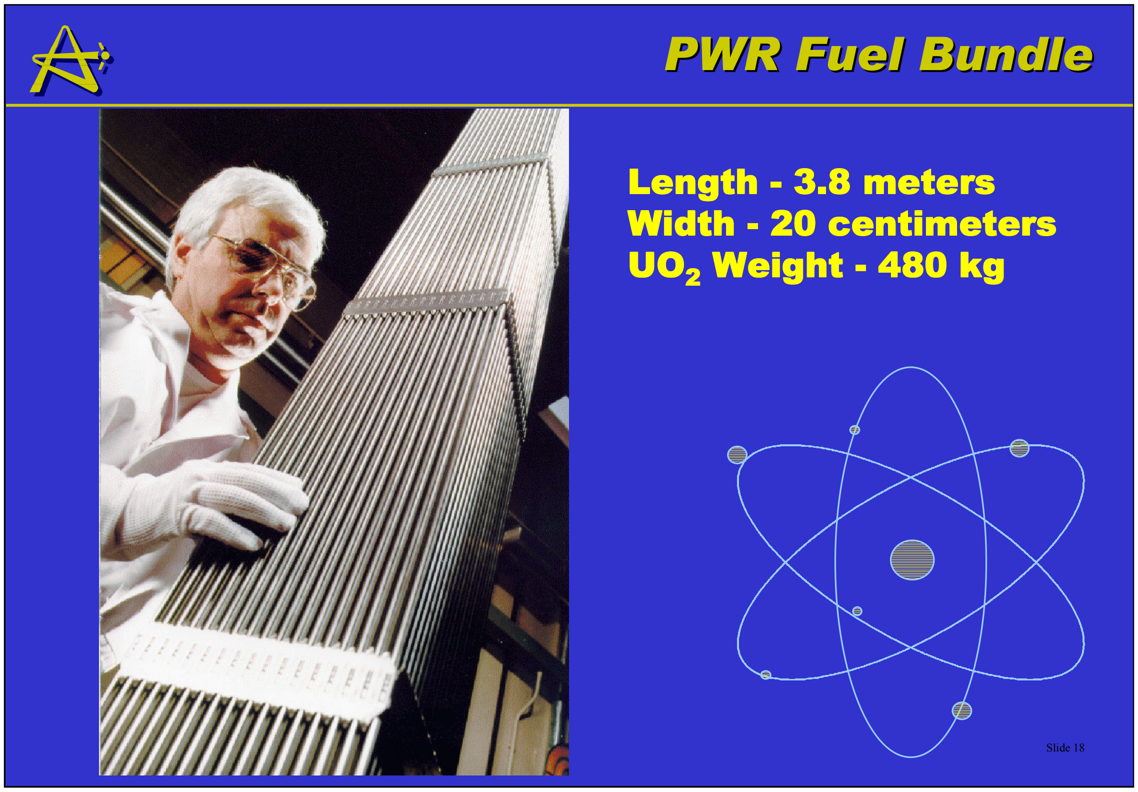
    in-service inspection

    failure detection

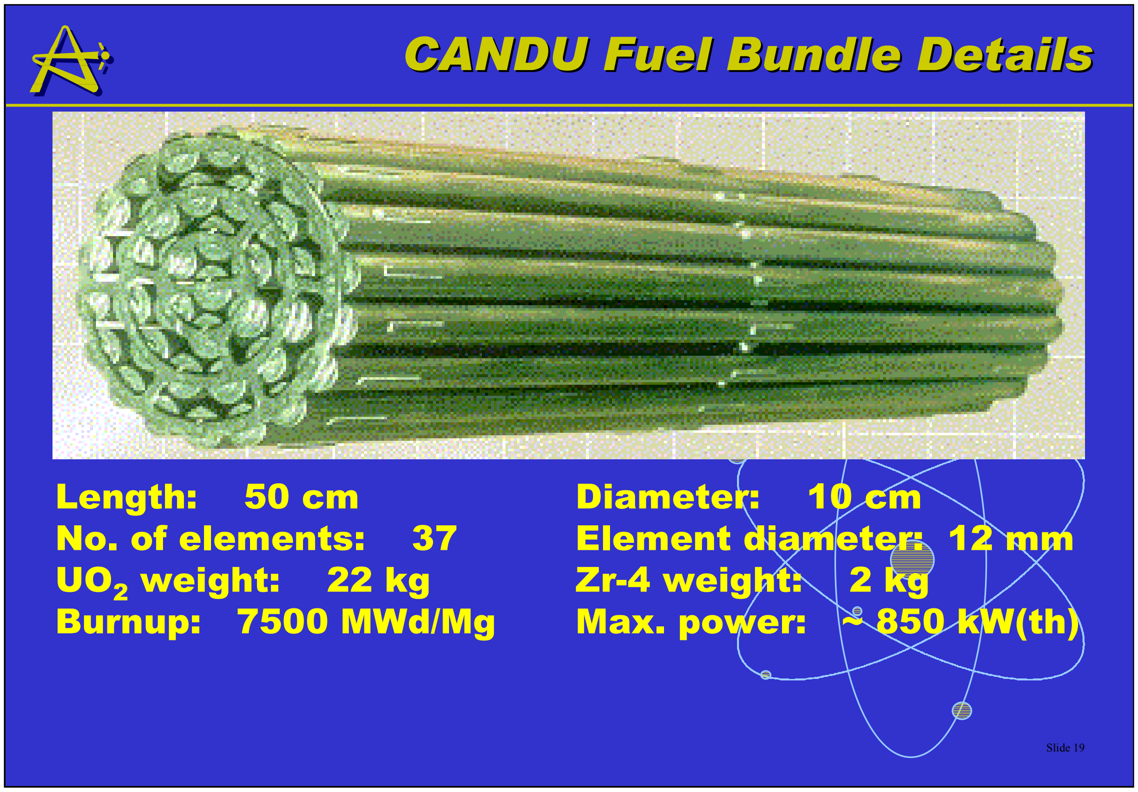
    reliable safety system response
- Results: excellent performance



- This fuel bundle is cheap to manufacture, is easy to handle, and is very reliable.
- Fresh fuel can be inspected directly and loaded by hand
- Discharged fuel can be inspected immediately at the plant, in the discharge bay
- Single element failure rates are less than 0.01 percent. Failed fuel elements are detected and removed quickly (less than 2 days after failure) with the reactor running at full power
- Failed fuel is put in sealed cans and stored with the rest of the fuel in the water-filled Spent Fuel Bay.
- Radiation levels in coolant are kept very low, so operating staff are not exposed to high radiation levels during operation and maintenance.



- PWR fuel is expensive (because of enrichment) and more expensive to manufacture because of its size, and because of the need for near-perfect performance (because failed fuel can be replaced only after shutdown).
- Bundles with graded enrichment normally are required to control neutron flux shape
- It is difficult to measure neutron flux accurately in the high temperature environment inside the pressure vessel
- Local failures in single elements can propagate into flow blockage and fuel melting accidents.
- Result is extreme conservatism in design conditions, which raises the operating cost



- This bundle is standard for all modern CANDU plants. It is manufactured in Canada, Korea, Argentina, and Romania. Russia also will manufacture the bundle as a carrier for ex-weapons materials. China plans to manufacture this bundle in a joint venture with a private Canadian company.
- The fuel sheath is collapsible at operating temperature. This decreases sheath strength requirements and increases fuel to coolant conductivity
- The pellet density is very high (>95% theoretical) so fission gas retention is good
- A coating is used on the inner surface of the fuel sheath to reduce pellet-clad interaction (PCI)
- There is no fission gas plenum required in this bundle because the oxide center temperature is low
- Zr-4 bearing pads separate the outer elements from the pressure tubes. Spacer pads are located between individual fuel elements

Design Parameters of PHWR and PWR

	PHWR	PWR
• Core power density	11 MW/m^3	60 MW/m^3
• Maximum fuel rating	57.3 kW/m	42 kW/m
• Neutron lifetime	9 E-4 sec	5 E-5 sec
• Fuel burnup	7.5 MWd/kg	35 MWd/kg
• Uranium usage	157 Mg/MWyr	213 Mg/Mwyr
• Operating Pressure (exit)	10 MPA	15.5 MPa
• Core inlet temperature	266 C	292 C
• Core exit temperature	312 C	329 C
• Steam temperature	266 C	283 C
• Heavy water inventory	.75 Mg/MWe	None
• Heavy water losses	<2.5 Mg/a	None
• Plant life	40-80 years	40-80 year

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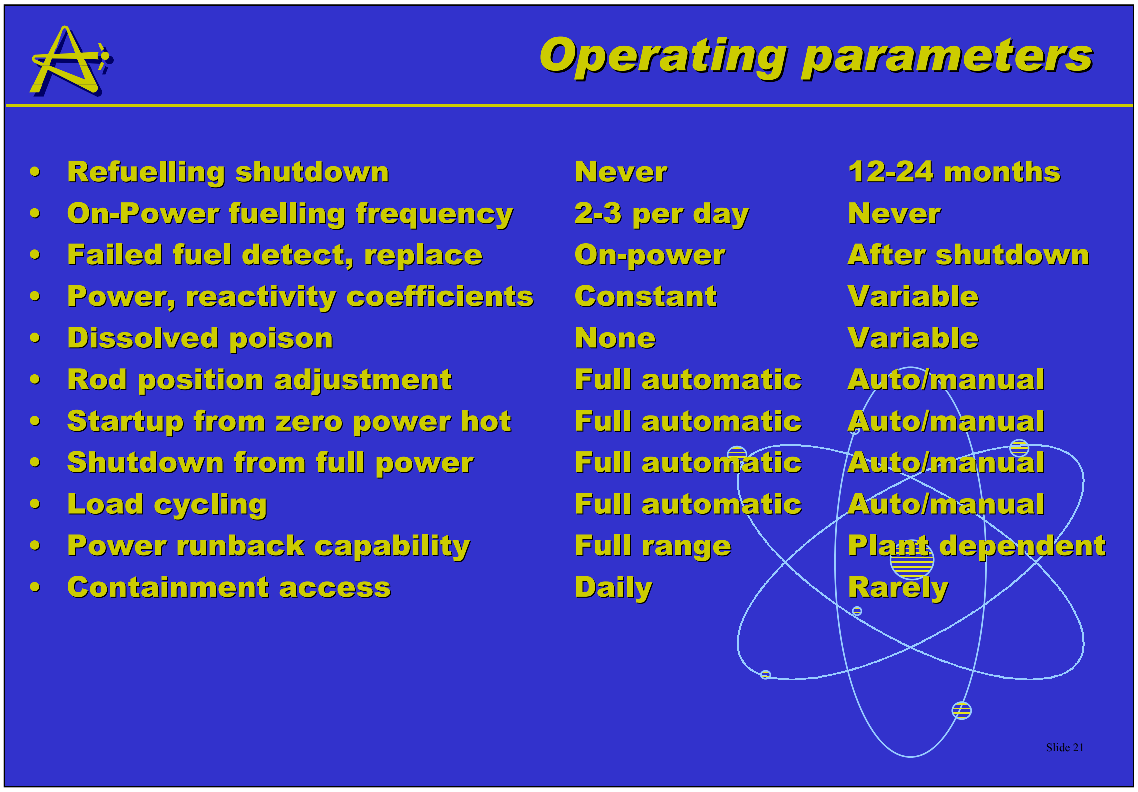
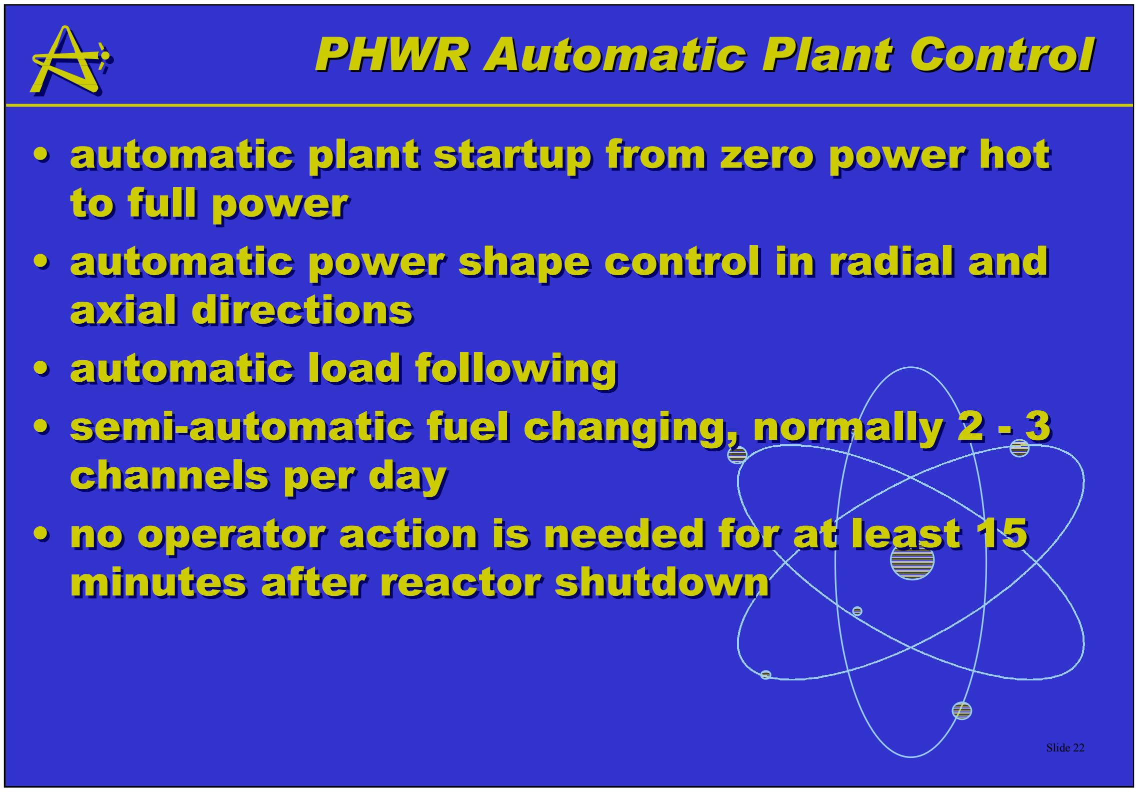
- These are typical values for the PWR. PHWR values are for CANDU 6
- CANDU steam temperature is optimum within constraints imposed by zirconium performance at the core exit temperature (312 C) and by pressure tube thickness requirement (fuel burnup)
- PWR steam temperature is limited by pressure vessel head performance at control rod nozzles, and by pressure tube thickness
- Heavy water losses are not very important
- Tritium buildup in moderator water leads to removal requirement after ~15 years of operation.
- Pressure tube replacement is required in PHWR after 30-40 years. Technology is available.
- Pressure vessel annealing is required in PWR after about 40 years. Technology may be available

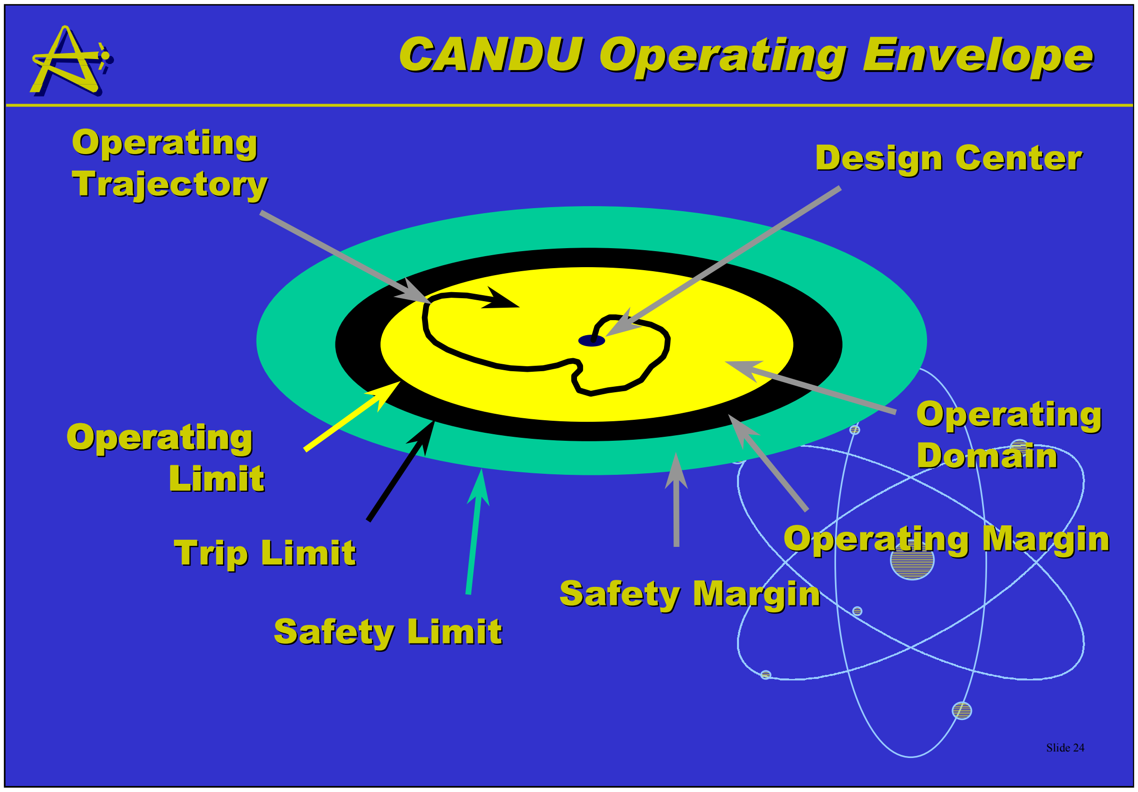


- The operating regime of these two designs is quite different. A PWR is shut down annually (on a pre-set schedule) for refuelling and scheduled maintenance. PHWR usually is shut down on a two-year cycle, but this can be adjusted to the utility's convenience depending on load and generation availability.
- The PHWR can load cycle daily to 60% reactor power, and to house load (6%) with steam bypass valves which discharge to the main condenser. Steam bypass can discharge any amount up to 100% steam flow.

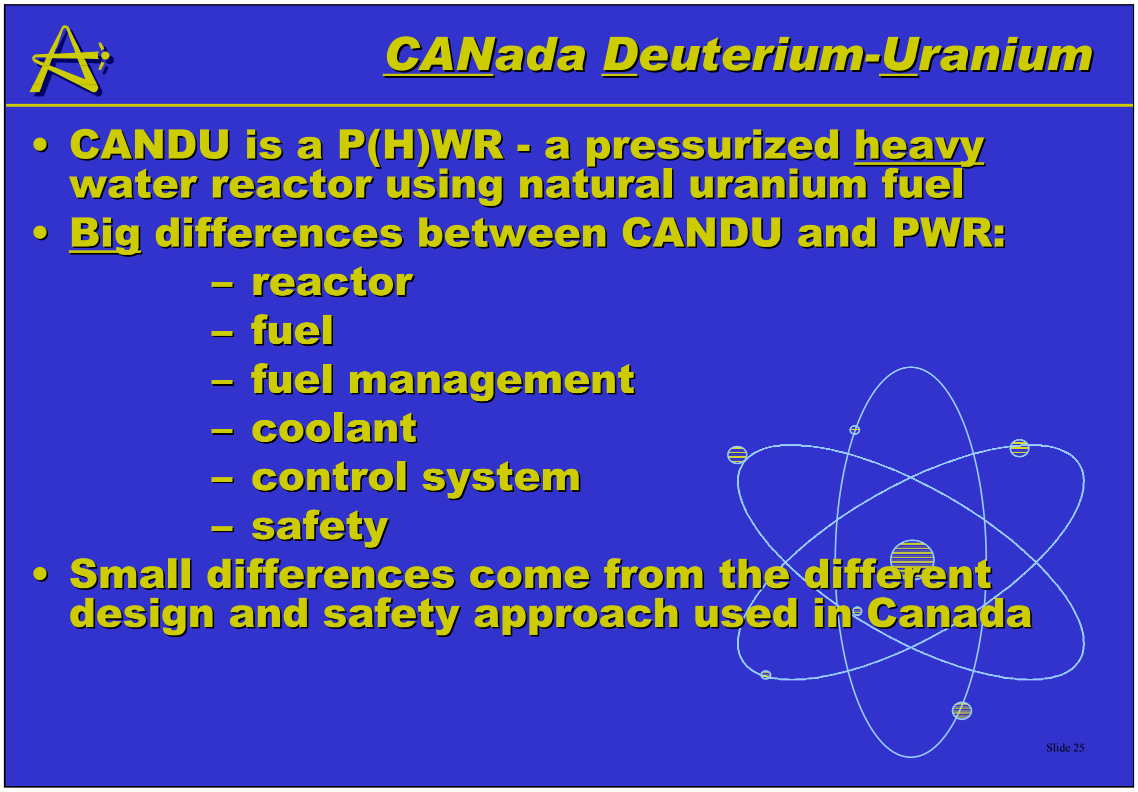


- Automatic turbine run-up controls are initiated by the main control computer.
- Operator inputs the final power level and the rate of power change which he wants. The control system does the rest.
- The same control actions are available for power reduction. The control system adjusts for Xenon buildup and decay.
- Secondary and tertiary levels of control are provided by means of adjuster rods (normally in the reactor), mechanical control absorbers (normally out of the reactor) and gadolinium poison addition (used only in abnormal situations. The mechanical control absorbers can be dropped into the reactor to reduce power to zero very quickly, if necessary.
- The first level of power control is by means of fourteen compartments which are filled and drained with light water according to the difference between actual measured power and desired power.
- Zone control compartments also adjust the power shape automatically to compensate for fuelling changes, Xenon fluctuations, and other disturbances.
- For fuelling, the fuelling engineer first runs the Expert System computer code to select 3-4 'best' channels to be fuelled. These recommendations then are approved by the first operator and Shift Supervisor. The first operator then tells the fuelling operator to fuel one particular channel. The fuelling operator starts the fuelling sequence and montors fuelling machine actions until complete.
- After shutdown, the system is capable of maintaining safe conditions for at least 15 minutes, without any action by the operators.

- This artist drawing shows the layout of the CANDU 6 control room proposed for the Qinshan project. A simulator with an exact duplicate of this control room, coupled with a comprehensive plant simulation and trainer console will be given as a given from Canada to TQNPC.
- In this type of automated control room, the first operator spends only about 5% of his time actually operating the unit. The rest of his time is spent checking automatic systems to see that they are working correctly, and in testing of inactive systems such as shutoff rods and poison injection tanks. Normally, the operator also supervises maintenance activities in the plant.
- Usually there are two first operators on shift, who alternate between control room duty and "walk around" monitoring of the rest of the plant.



- This diagram describes the general operating envelope of the CANDU reactor system.
- Design Center designates the nominal operating conditions of the plant as designed. The yellow circle indicates the Operating Domain (defined by power level, coolant flow, pressure, temperature, and so on) within which the plant can be operated safely.
- As operating conditions (fuelling, reactor demand power, turbine demand power, seam pressure, and so on) change, the black Operating Trajectory moves around this yellow circle. If the Operating Trajectory touches the black circle called Operating Limit, the control system responds to change conditions so that the vector is brought back inside the zone of operating domain.
- The control system can operate successfully for conditions anywhere within the black band called Operating Margin.
- If, for any reason, the operating trajectory touches the Trip Limit, the reactor will be tripped and shut down by the Special Safety Systems (to be discussed later).
- The safety systems are designed to protect the public, the plant operators, and the plant itself by responding to abnormal conditions within the band called Safety Margin..
- The performance requirements for safety systems to keep the operating trajectory inside the Safety Limit are defined by the regulatory authority in the country where the plant is operating.



- To summarize:

  CANDU is a pressurized water reactor

  It has some special advantages for an electric utility

- CANDU is different than a PWR

  The reactor is a channel type - it does not have a big pressure vessel

  The fuel is simple, cheap to make, economical in uranium use, and does not need to be enriched

  Fuel management is done only during plant operation

  Heavy water coolant and moderator require special design and operation procedures

  Automatic control frees the operator from repetitive, routine duties

  It is very safe - this subject will be discussed later.

- Many smaller design differences exist between CANDU and the PWR, but these are of less importance.

- Thank you for your kind attention. Questions??