Nuclear Power - Overview

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Human technology
Proof that People Resist Technology Change
1st U.S. Bathtub 1842

First bathtub was built in Cincinnati. It was a 1750 lb, seven foot mahogany box, lined with sheet metal. Local criticism followed although the Greeks and Romans had used tubs as far back as 1200 B.C. Cincinnati doctors were quick to condemn this outrageous contraption and local politicians slapped on a $30 luxury tax. A law was passed forbidding the use of a bathtub during the cold months as a health hazard. Quick acceptance of new inventions is never likely.
Components of a Reactor

- Control Rods
- Fuel
- Coolant
Chemical Reactions
Basic chemical reactions

**Fire**

\[ CxHy + O_2 \rightarrow CO_2 + H_2O \]

**Metallurgy**

\[ 3CO + Fe_2O_3 + 2Fe + 3CO_2 \]

**Food**

\[ C_6H_12O_6 \rightarrow 2 \text{CH}_3\text{CH}_2\text{OH} + 2 \text{CO}_2 \]
The Atom

✓ A few electron volts!

electrons

NUCLEUS
protons & neutrons
The nucleus of atom
✓ 100s of millions of election volts!

✓ $E = mc^2$
The nucleus splits in two halves and releases some neutrons, and radiation during fission there is also a small loss of mass, that is transformed into ENERGY, which is released also.
First Reactor:

1) water cooled
2) U235 enrichment ~3%
Africa
The Jungle of Gabon
The Oklo Mine had a fission reaction... 2 Billion Years Ago

Scientific American, July 1976
Mother Nature’s Nuclear Reactor

15 natural reactors discovered

16,000 MW-years

Used 5 tons uranium

5 tonnes waste

1.5 tonnes of Pu
Human discovery of fission:

1) no coolant
2) U235 enrichment ~0.7%
1920 Rutherford postulated neutral particle and approximate mass Chadwick called it the neutron in his paper published in the Feb 1932, issue of *Nature*.

In 1935, Sir James Chadwick received the Nobel Prize in physics for this work.
“Bombardment of heavy nuclei with neutrons, these nuclei breakup into several large fragments which are actually isotopes.”
In 1939, Hahn, Maitner...

Otto Hahn and Fritz Strassman carried on experiments bombarding uranium with neutrons → couldn’t explain the results → Lise Maitner explained and gave the name FISSION.

1944 Nobel Prize For his discovery of fission

woman and a Jew fleeing Nazi persecution, did not have her name on Hahn’s seminal paper
What is Nuclear Fission?

If the nucleus of a heavy atom (such as Uranium) absorbs a neutron, the nucleus can become unstable and split.

This is called **NUCLEAR FISSION**.
First fission chain reaction

1) no coolant
2) enrichment of U235 ~0.7%
3) moderator: carbon
Fermi 1942

The first artificial nuclear reactor created with uranium fuel at the University of Chicago.

Controlled, this reaction potentially had untold benefits for Mankind. Uncontrolled, it could unleash awesome power.

- Szilard, who had worked with Fermi, 1942
The Chain Reaction

• If the extra neutrons released during a fission event strike other nearby Uranium atoms, these atoms will split as well, releasing more neutrons and more energy.
• The CHAIN REACTION can be stopped just by blocking the neutrons from hitting new atoms.
How the chain reactions starts and sustains it’s self
SCRAM
Chicago Pile - 1
Criticality

Neutron Population

- Supercritical
- Critical
- Subcritical

Time
Circle of (neutron) Life

Start Here

Example of $k=1$, critical condition, aka "chain reaction"
First fission reactor to produce electricity

1) sodium/potassium (NaK) coolant
2) enrichment of U235 ~20%
3) moderator: none
Sodium reactor development
First water cooled reactor to produce electricity

1) water coolant
2) enrichment of U235 ~3%
3) moderator: water
## Fission Energy: Fast and Slow Neutrons

### Energy Breakdown

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ff^*$</td>
<td>166</td>
</tr>
<tr>
<td>Prompt $\gamma$</td>
<td>6</td>
</tr>
<tr>
<td>Delayed $\gamma$</td>
<td>6</td>
</tr>
<tr>
<td>Neutrons</td>
<td>5</td>
</tr>
<tr>
<td>Neutrino</td>
<td>10</td>
</tr>
</tbody>
</table>

Total Energy = 200 meV
Uranium Fuel Pellets (one pellet equals 2,000 lbs of coal)
BWR Fuel Assembly

- Upper End Plug
- Fission Gas Plenum
- Plenum Spring
- Fuel Pellets
- Fuel Cladding
- Lower End Plug
Boiling Water Reactor (BWR)
Boiling Water Reactor
Cooling Towers
1. Reactor pressure vessel
2. Control rod drives
3. Raised suppression pool
4. Gravity Driven Cooling System (GDCS) pools
5. Main steam lines
6. Feedwater lines
7. Safety relief valves
8. Depressurization valves
9. Isolation condenser steam lines
10. Equalizing line
Passive Safety …

Passive Containment Cooling System (PCCS) and Gravity Driven Cooling System (GDCS)

Isolation Condenser System (ICS)

Ultimate Heat Sink

PCC Pool

GDCS Pool

GDCS Injector Line

PCC Vent Line

Suppression Pool

Equalizing Line

Containment Boundary

DPV = Depressurization valve
– Explosive valve
– Motor operated valve
– Solenoid valve
– Safety Relief Valve

Containment

Steam Supply

Condensate Drain

Vent Line

Suppression Pool

IC Pool

RPV

Core
Simplification …

Plant Design Reduces Operator Challenges – Direct Cycle With Major Simplifications
Pressurized Water Reactor

1) water coolant
2) enrichment of U235 \( \sim 3\% \)
3) moderator: water
Pressurized Water Reactor (PWR)
Pressurized Water Reactor

Nuclear Steam Supply System

MB 3618A
Containment Building
Fuel Building
We have the same sunsets, however, we all see different horizons.
The Evolution of Nuclear Power

**Generation I**
- Early prototype/demo reactors
- Shippingport
- Dresden, Fermi I
- Magnox
- First demo of nuclear power on commercial scale
- Close relationship with DOD
- LWR dominates

**Generation II**
- LWR-PWR, BWR
- CANDU
- HTGR/AGR
- VVER/RBMK
- Multiple vendors
- Custom designs
- Size, costs, licensing times driven up

**Generation III**
- ABWR, System 80+, AP600, EPR
- Passive safety features
- Standardized designs
- Combined license

**Generation IV**
- Highly economical
- Proliferation resistant
- Enhanced safety
- Minimize waste

Timeline:
- 1950: Atoms for Peace
- 1960:
- 1970:
- 1980:
- 1990:
- 2000:

Events:
- TMI-2
- Chernobyl
- Chernobyl
- Chernobyl

For further details, please refer to the sources provided in the document.
Fast Reactors
Fast-Spectrum Reactors

The Integral Fast Reactor Program pulled together the basic elements

- Safety
- Closed fuel cycle

Target was breeding to sustain significant growth: not an issue today

- Uranium resources not limiting
PRISM – with Advanced Multi-Cavity Rectangular Containment
Characteristics of Seismic Isolation System

- Safe Shutdown Earthquake
  - Licensing Basis 0.3g (ZPA)
  - Design Requirement 0.5g

- Lateral Displacement
  - at 0.3g 7.5 inch.
  - Space Allowance
    - Reactor Cavity 20 inch.
    - Reactor Bldg. 28 inch.

- Natural Frequency
  - Horizontal 0.70 Hz
  - Vertical 21 Hz

- Lateral Load Reduction > 3

Rubber/Steel Shim Plates
Protective Rubber Barrier

Seismic Isolators (66)
Reactor Vessel Auxiliary Cooling System (RVACS)

Always on
Removes ~ 0.5 MWt

Flow Annuli & Silo Cross Section
Canadian Deuterium-Uranium
Summary
Nuclear Energy

Weapons —- Versus —- Power

Pu$^{239}$

Fuel

Max 4%

Shape

Ball

Can

Force

None

Use

Peace

MAD

Need more

2 ton TNT per person

Yes
Backups
BORAX-III 1955

Experimental boiling-water reactor was the first reactor in the world to provide all of the electricity to an entire town, Arco, with a population of 1,000.
Energy Equivalents

One uranium Fuel Pellet has as much energy as….

3 Barrels of Oil
(42 gallons each)

1 Ton of Coal

2.5 Tons of Wood

17,000 Cubic Feet of Natural Gas

Science, Society and America’s Nuclear Waste
Einstein's Famous Equation

> \( E = \) Energy
> \( m = \) Mass
> \( c = \) Speed of light
> \[ 3 \times 10^8 \text{ m/s} \]

A very small change in mass will create a large change in energy
Pressurized Water Reactor: TMI

1) water coolant
2) enrichment of U235 ~3%
3) moderator: water
Simplified PWR Showing Three Mile Island Release Paths
TMI Lessons Learned

Industry is only as strong as the weakest plant.
Institute of Nuclear Power Operation (INPO) started.
Plant simulator use increased.
Conduct of plant operations formalized.
Safety systems worked; no one was harmed.
Degreed person required in control room.
Chernobyl Nuclear Power Plants

1) water coolant
2) enrichment of U235 \(<1\%\)
3) moderator: carbon
Chernobyl Nuclear Power Plants

- Located on the Pripyat river, 10 miles northwest of Chernobyl.
- Chernobyl is 60 miles north of Kiev.
- Population of Kiev: 2.5 million
- Population of Chernobyl: 49,000
Chernobyl Plant Characteristics

• Each unit is rated at about 3200 MWth (Four Units).
• Direct-cycle, boiling-water, pressure-tube reactors. Steam is produced within the assembly.
• The reactor fuel rods (~1700) are each contained in individual zircaloy pressure tubes embedded in a matrix of graphite blocks.
• Each pressure tube contains 18 zircaloy-clad UO₂ fuel pins, enriched to 1.8% U-235.
• The reactor is 40 ft in diameter and 26 ft high.
• The graphite matrix is enclosed within an inerted atmosphere and a stainless steel vessel, housed in a reactor vault.
• Six operating pumps circulate water to the inlet of each pressure tube through individual lines for each assembly.
• On-line refueling at a rate of about one assembly/day.
USSR RBMK - 1000

reactor building

risers

pressure tubes (fuel rods inside)

graphite

control rods

steam separator

downcomer

steam line

pump

turbine generator

condenser cooling water
Final Scenario

Test is begun:

1:23:02 Test begins at reactor power of 200 MWth.
1:23:04 Power in the reactor increases (500 MWth) due to void buildup and pressure increases; the 8 circ pumps still feed the core.
1:23:31 Operator manually initiates reactor scram, but it is too late, since 15-20 s required for control rod insertion.
1:23:40 Reactor is now on a high power ramp, and reactor power reaches 110% normal (estimate).
1:23:43 Doppler feedback curtails first burst.
1:23:44 Second reactor excursion to 4 times normal power.
1:23:45 Pressure falls and circ-pump flow returns to core; two audible/visible explosions observed.
Speculative Observations:
Reactor shield block destroyed, and all 1700 pressure tubes severed.

The audible explosions caused by a succession of events in sequence:
- Transient overpower reactor excursion
- Loss of flow
- Fuel-coolant interaction
- Hydrogen production
- Hydrogen combustion

Fuel hydrodynamic dispersal was caused, and eventual melting and slumping of remainder of fuel took hours.
Question?
What are the three components of a reactor?
Explain what was found at the Oklo Mine.
What did Madam Curie discover.
Explain alpha particle decay.
How did Chadwick use Curie’s alpha particle?
How was the neutron discovered?
What did Ida Noddack theory in 1935 regarding the bombardment of heavy nuclei?
What experiment did Otto Hahn and Fritz Strassman carry out?
Explain what nuclear fission is.
How did Fermi extend the fission process?
What is a fast and a slow neutron?
How much energy is released from the fission of one atom?
What does it mean when a reactor is supercritical, critical, and subcritical?
The energy content of uranium is equivalent to how many tons of coal?
Explain Einstein’s famous equation.
Explain how a boiling water reactor works.
What reactor supplied what town nuclear electricity for the first time?
What is the function of the turbine building?
Draw and explain the cooling towers used at both coal and nuclear power plants.
Draw and explain the containment building.
What is the spent fuel pool? What happens when it gets full?
What happened at the nuclear power plant at three mile island?
What happened at the Chernobyl nuclear power plants to produce the steam explosion?
What is a fast reactor?
How does a fast reactor burn up old nuclear waste?
How does a CANDU reactor work?