A short History of Reactors:
The first Generation

Bertrand BARRÉ
Scientific Advisor AREVA
Pr. Emeritus INSTN
Fission 1938 - 1942

1938: Fermi plays with neutrons & U. Hahn-Meitner say «fission!»

1939: Joliot et al. «chain reaction»

1942: Staggs Field
The 50s: Nuclear Electricity

1951: EBR 1 lits 4 Bulbs)

1954: Obninsk, 5 MWe

1956: Inauguration of Calder Hall by Elisabeth II
Obninsk 5 MWe NPP

Calder Hall: from Opening to Decommissioning

Prospects & Prerequisites to Renaissance – B. Barré Gassummit 2009
Paleontology
Many Possible Combinations

<table>
<thead>
<tr>
<th>Category</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissile Material</td>
<td>U235, Pu, U233</td>
</tr>
<tr>
<td>Fertile Material</td>
<td>U238, Th232</td>
</tr>
<tr>
<td>Moderator</td>
<td>D2O, Graphite, H2O, or none</td>
</tr>
<tr>
<td>Fuel Composition</td>
<td>Metal, oxide, carbide, nitride, salt, solid, liquid, suspension</td>
</tr>
<tr>
<td>Fuel Geometry</td>
<td>Cylinder, rod, pin, sphere, particle</td>
</tr>
<tr>
<td>Coolant</td>
<td>Air, H2O, D2O, CO2, He, Na, Pb</td>
</tr>
<tr>
<td>Cycle</td>
<td>Direct, indirect</td>
</tr>
</tbody>
</table>
The 50s’ ebullient Creativity

(Coffee Shop, Idaho Falls, 1973)
Characteristics of Gen I

- Incredible creativity: almost every possible combination tried
- Very short design-to-operation time
- Very light regulatory framework
- Strong Government support
- Good public acceptance
- No time to correct mistakes
- From prototype to prototype to prototype
- Fast escalation in unit size
- No standardization
- Safety issues progressively raised and solved
Chicago Pile #1

Graphite

Natural uranium (metal & oxide)
<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>Sodium</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>Poor (boiling, corrosion)</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Thermal Transfer</td>
<td>Very good</td>
<td>Excellent</td>
<td>Mediocre (pressure, mass flow, Pvol)</td>
</tr>
<tr>
<td>Neutron capture</td>
<td>Mediocre (only thermal)</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Poor</td>
<td>Good</td>
<td>He : excellent</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO₂ : poor (HT)</td>
</tr>
<tr>
<td>Technology leaktightness</td>
<td>Medium</td>
<td>Medium (no pressure)</td>
<td>Leaks</td>
</tr>
<tr>
<td>ISIR</td>
<td>Excellent</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Safety Issues</td>
<td>Vaporization</td>
<td>Na-O₂ Na-H₂O</td>
<td>Loss of pressure</td>
</tr>
</tbody>
</table>
A Few Selection Factors

- Excess Ambition
- Technology Problems
- Poor performance
- Accidents (or risks)
- Bad « timing »
- U Utilization
- Independence
- Duality/synergies
- Industrial strength
- Tec breakthrough
- Waste management
GWe Installed in the World, July 2010

Operating: 438 Units, 372 GWe

Under Construction:
- 61 Units, 59 GWe
- 53 PWR+VVR

Reactor Types
- PWR*
- BWR
- GG
- RBMK
- Candu
- FBR

*VVR included

Source: IAEA PRIS
First to start a Power Programme:
- Soviet Union
- United Kingdom
- France
- United States
- Canada
- Sweden

Exports and Licenses (Japan, Germany)
Soviet Union 1: The Beginnings

- 1946: F1 at Kurchatov Institute = CP1, still operational
- 1954: Obninsk APS1 5MWe connected, ancestor RBMK
- 1964: Beloyarsk 1, 100 MWe RBMK and Novovoronezh 1, 210 MWe VVR + B2, NV2
  - « Dual Purpose » RBMKs restricted to SU proper, while VVR exported to satellites (except Yugoslavia & Romania) + Finland, with spent fuel return
- First generation (1973-79) = 12 units, 5.8 GWe, 4 VVR 440/230, 4 RBMK 1000 and 4 Cogen Bilibino
- FBR units BOR 60 and BN 350 (desalination)
Soviet Union : Generation 2

- In Russia : 18 units, 16,5 GWe: 7 RBMK, 2 VVR 440/213, 7 VVR 1000, 1 FBR BN600
- In Ukraine, Lituania : 4 RBMK 1000, 2 RBMK 1500, 2 VVR 400, 13 VVR 1000
- April 26 1986: Accident at Unit 4 Chernobyl
- 1990: End USSR
VVR (or VVER) : Russian PWRs

Kozloduy

Intro 1 – B. Barré GA2010. - p.20
VVER 1000 Primary Circuit

1. Reactor
2. Steam generator
3. Reactor coolant pump (RCP)
4. Main coolant pipeline (MCP)
5. Pressurizer
6. Relief tank
7. Emergency core cooling system accumulators (ECCS)
8. ECCS pipelines
Containment Areas

Reactor Floor

Core: diameter 12 m, height 7 m
The British Saga (1)

- Tube Alloys associated to the Manhattan Project
- 1945 AERE Harwell, military priority GLEEP 1947-90
- No $D_2O$, no SWU $\rightarrow$ GCRs
- Windscale production piles 1950-51
- Magnox series (Calder Hall, October 1956) : 11 sites, 26 units, 5 consortia
- U enriched $\rightarrow$ Oxide/SS $\rightarrow$ AGR (Windscale 1962) 6 sites, 15 units

No standardization, Magnox = reprocessing

vision : Pu from Magnox to Breeders
Lots of Magnox… too many Vendors

Berkeley

Dungeness A

Oldbury A

Bradwell

Hinckley Point A

Sizewell A
Gas Cooled Reactors (Magnox & AGR)
Magnox 300 MW & AGR 600 MW

Oldbury A

Dungeness B
The British Saga (2)


Dragon Project

French Nuclear Program: early years

- 1945 Creation of the CEA (Commissariat à l’Énergie Atomique)
- 1948 Criticality of ZOE
- 1956 First experimental generation of nuclear electricity (G1)
- 1963 First EDF Nuclear Plant Chinon A1
- 1970 Decision to switch from UNGG to LWR at Fessenheim
- 1972 Westinghouse License to Framatome
- 1974 « Messmer » Program
- 1975 PWR selected, CEA replaces W as Framatome shareholder
Confirmation of Fission. Joliot Patents 1939-1940

Joliot, Halban & Kowarsky
D Day for the French Nuclear Program

December 15
1948

Criticality of «ZOÉ»
Découverte à La Crouzill
du premier gisement français d'uranium.

Usine d'extraction du plutonium, à Marcoule.
The Pionneers (UNGG - Magnox)
Refueling Machine UNGG
From UNGG to PWR: Le Bugey
Nuclear Power in the United States

Priority to the Bomb...then to the Submarines
USA 1 : The Beginnings

- 1946 : Mc Mahon Act, establishes USAEC
- 1948 : Westinghouse involved in submarine design
- 1950: General Electric, ditto
- 1951: MTR, EBR1 at INEL (picture 20-12-51)
- 1953: S1W, land-based sub, ancestor PWR. Atoms for Peace Speech.
- 1954: Atomic Energy Act opens Nuclear to private industry and declassifies relevant data
USA 2 : The Heydays

- 1957: Shippingport 60 MWe PWR, 1st US NPP connected (Shut down 1982, green field 1987)
- 1963-1966: First turnkey Plants W & GE (costs overruns)
- 1966: 20 orders in the year, « truly commercial »: B&W, CE and GA join the gang, and A/E intervene
- 1972-1972: > 40 orders/year
PWR Fuel Assembly

- Control rod cluster
- Top end fitting
- Guide-tubes
- Spacer/mixing Grid
- Fuel Pin
- Bottom end fitting
Boiling Water Reactors BWR

- Only one cooling circuit at Psat pressure ~7 Mpa
- Vapor generation close to the fuel. Same vapor goes to the turbine (direct cycle)
- Moderation ration varies axially
USA 3 : 1974, Annus Horribilis

- 1972 West Valley shut down for refurbishing, will not restart. GE abandons Morris
- 1973: Kippour War, 1st Oil shock, Project Independance, Watergate hearings
- 1974: Series of NPP cancellations – AEC split into ERDA and NRC, JAEC dissolved – Smiling Buddah
- 1976: G Ford stops commercial reprocessing
- 1977 (April 7): J Carter kills reprocessing and FBR-ERDA becomes USDOE - INFCE
- 1979 (March 29) TMI2 Accident. : National Nuclear Scare
Canada

- September 1945: ZEEP, first nuclear reactor outside USA
- 1947 NRX
- 1952 AECL (Chalk River)
- 1962 NPD 25 MWe PHWR (AECL, GE, Ontario Hydro) first nuclear electricity
- 1966 Douglas Point 200 MWe CANDU
- 1973: Pickering, 4 x 800 MWe CANDU (largest nuclear station) + KANUPP + Rajasthan
The CANDU® Nuclear Power System

CAANada Deuterium Uranium

- Steam Generator
- Turbine
- Generator
- Condenser
- Lake Cooling Water
- Calandria
- Fuel Channel
- Heavy Water
- Fuel Bundle
Today, when we think « nuclear reactors »...
AGESTA: District heating in Sweden
CHP in Bilibino
**Bilibino NPPs**

4 units  
(1974-1976)  
12 MWe + 20 MWt  
250/280°C  
273 Fuel Assemblies of 6 elements (tubes)  
7.2 t U 3%

**Fuel Assembly**

1. Gas gap  
2. Shielding plug  
3. Upper plenum  
4. Downcomer  
5. Tubular-type fuel element  
6. Graphite sleeve  
7. Spiral expansion joint  
8. Inlet orifice  
9. Bottom plenum
BN-350, Aktau (ex-Schevschenko), Kazakhstan
Fast Neutron Reactor 6 loops, sodium cooled, enriched U
Construction 1964, Operation 1976 to 1999
90/52 MWe and 120 000 m3 freshwater per day
Fly Nuclear Airlines!
Shielded Cabin for the Pilot of NB-36H
Nuclear Jet Engine

- General Electric develops a direct cycle engine from a modified J-47 turbojet
- 1956 Land-based prototype Heat Transfer Reactor Experiment HTRE-1
- HTRE-3 could feed 2 turbojets while located within the plane body (but never flew)
The SLAM Program (Pluto)

- A predecessor of the Cruise Missile, with a nuclear « ramjet »
- 1958: Contract given to Vought, Convair and North American
- Reactor first developed by General Electric, then Lawrence Livermore Lab
1961 Pluto Tests (TORY II-A)

- 600 MWt Reactor, no shielding
- Homogeneous cylindrical core 1m22 X 0.8 m diameter
- 10,000 elements: Hexagonal Ceramics « macaronis », BeO, ZrO₂, UO₂, 10 cm long, 0.6 cm I D
Nerva-Rover Program, NRX Tests, Jackass Flats
NRX Element

PyC Coated UC$_2$ Particles dispersed in graphitized Matrix

19 Coolant Channels coated with niobium carbide to prevent H$_2$ attack

Beryllium Reflector

2000 MWt/m$^3$

Inlet H2 Temp. : -183°C

Outlet H2 Temp. : 2500°C

~1 MW per Fuel Element
For More:
www.bertrandbarre.com