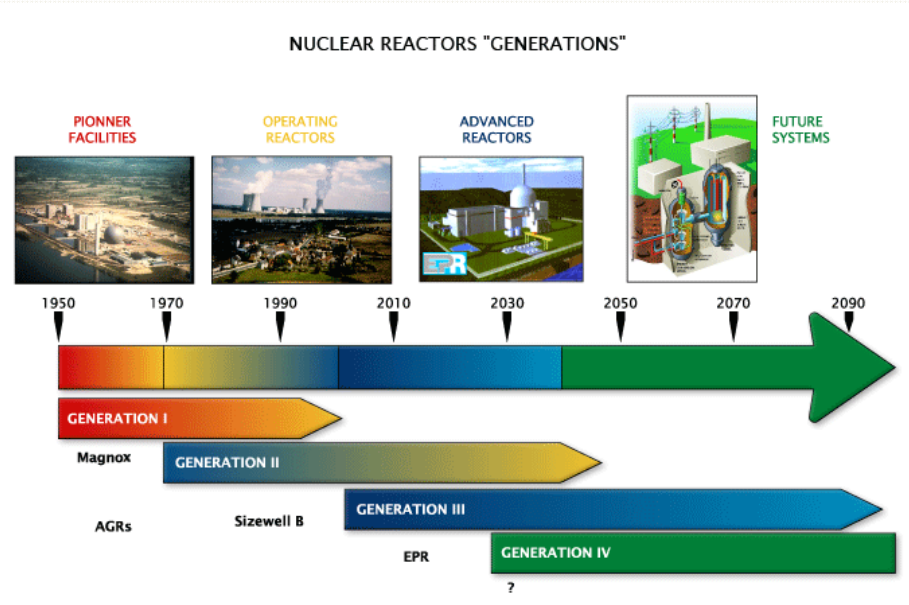
The Rise of Power Reactors

Mario van der Borst
KIVI/NNS Symposium
Delft, 3 November 2017



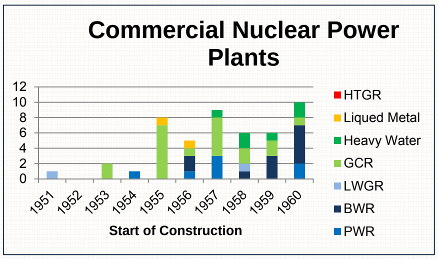
Categorisation of reactor designs

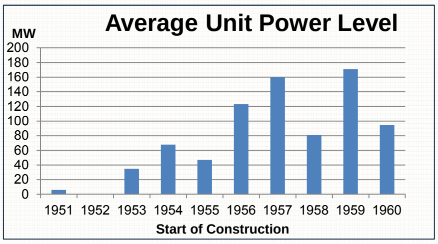
NOT-BREEDING | BREEDING

Cooling Medium	Liquid Metal/ Salt/Oil	Na, Pb, PbBi, LiF, BeF_2
	Gas	CO_2, He
	Light Water	Boiling, Pressurised
Moderator	No Moderation	Fast Reactor
	Graphite	Blocks, Pebbles
	Deuterium Water	Pressurised
	Light Water/Oil	Pressurised, Boiling
Fuel Configuration	Fuel Bundle	Square or hexagonal
	Pebbles	Pebbles
	Homogeneous	Suspension Reactor

The Fifties

The first prototypes; Search for the best technology
The world divided in have and have-not enrichment technology



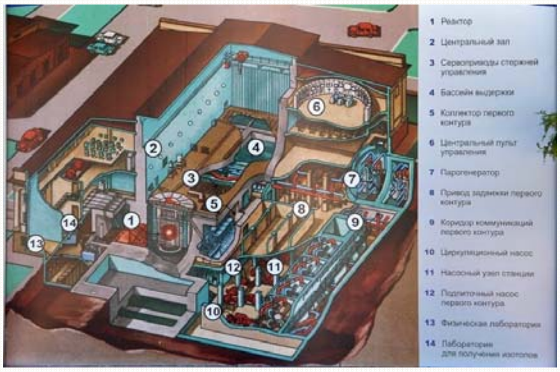


Examples of first prototypes

Naam	land	type	power	start	COD	decom
Obninsk	USSR	LWGR	6	1951	1954	2002
Calder Hall 1-2	UK	GCR	35	1953	1956	2003
Shippingport	USA	PWR	68	1954	1958	1982
Chappelcross 1-4	UK	GCR	60	1955	1958	2003
Marcoule G2	F	GCR	43	1955	1959	1980
Dounray DFR	UK	FBR	15	1955	1962	1977
Dresden-1	USA	BWR	207	1956	1962	1978
Agesta	S	PHWR	12	1957	1964	1974
Hallam	USA	GNa	84	1959	1963	1964
Piqua	USA	Oil	12	1960	1963	1966

- The fifties are dominated by the UK with MAGNOX: main product is Plutonium, electricity is by-product
- All possible technologies were tested
- In the UK, F, S ,I, CH, ESP, CAN, ARG prototypes were developed that could work on natural uranium
- The USA developed 7 BWR prototypes
- USA is starting slowly in comparison with Europa
- First BWR in Germany was Kahl (16MW, start1958 en COD 1962, same year as Dresden-1
- All reactors from the fifties are definitely shutdown now

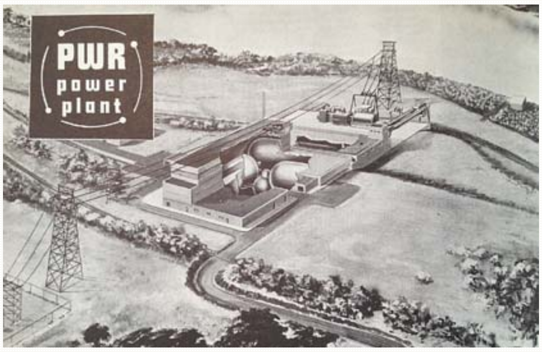
Obninsk Nuclear Power Station



P-therm	30 MW
P-elec	6 MW
Enrichment	5%
Type	RBMK
Operation	1951-1954

R&D, isotope-production and elektricity to the grid

Shippingport Atomic Station
(Beaver Valley Nuclear Station; Ohio river)

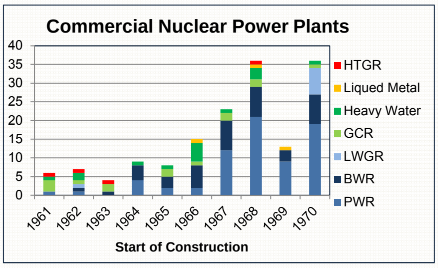


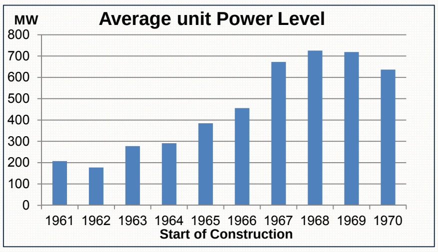
P-therm	236 MW
P-elec	68 MW
Enrichment	93%
Type	PWR
Operation	1958-1982

Seed/blanket/reflector design
Breeding-factor 1,01
Blanket: Thorium oxide

The Sixties

Development of prototypes continues; low enriched uranium globally available; construction of 2nd generation reactors is accelerating caused by the enormous growth of the electricity demand



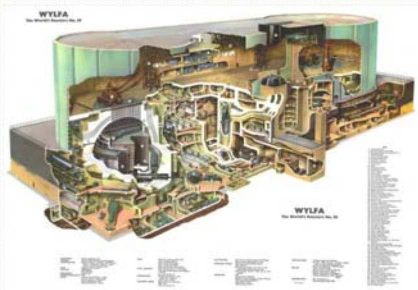


Examples first commercial reactors

Naam	land	type	power	start	COD	decom
Chinon A3	F	GCR	360	1961	1966	1990
Chooz A	F	PWR	305	1962	1967	1991
Wylfa MAGNOX	UK	GCR	2X490	1963	1971	2015
San Onofre 1	USA	PWR	436	1964	1968	1992
Dodewaard	NL	BWR	55	1965	1969	1997
Dungenes B AGR	UK	GCR	2X615	1965	1985	-
14X USA	USA	LWR	~800	1967	~1974	-
Borssele	NL	PWR	482	1969	1973	-
Doel-1	B	PWR	433	1969	1975	-
Bilibino 1-4	USSR	LWGR	4X12	1970	1977	-

- Mid sixties the USA is starting the construction of large (>200 MW) nuclear power plants
- In the USA the PWR and BWR technology are selected for most projects
- Also mid sixties the USSR starts the construction of the first commercial LWGR reactors (RBMK)
- There still 15 RBMK's in operation, including the four mini Bilibino units

Wylfa Power Station



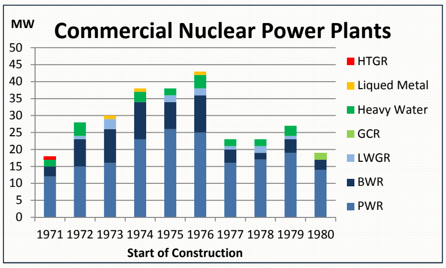
Type	Magnox
Reactor vessel	concrete
Power	2X490 MW
Start construction	1963
COD	1971
Shutdown	2015
Wylfa-2	Horizon

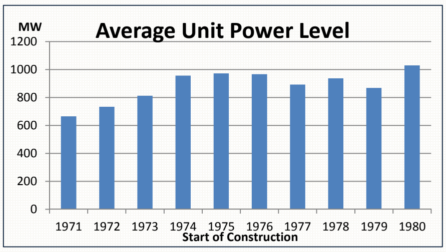
Kerncentrale Doel-1

Type	PWR
NSSS supplier	W
Power	433 MW
Start construction	1969
COD	1975
Shutdown	Lifetime 2025
Containment	Double
Upgrades	Bunker

The seventies

The golden years: PWR dominant, BWR, CANDU, AGR and LWGR at some distance





Examples of power plants

Naam	land	type	power	start	COD	decom
THTR	G	HTGR	300	1971	1985	1988
Fessenheim-1	F	PWR	880	1971	1978	-
Bruce-A1	CAN	PHWR	760	1971	1977	
Isar-1	G	BWR	878	1972	1979	2011
Goesgen	CH	PWR	1010	1973	1979	-
San Onofre	USA	PWR	1070	1974	1983	2013
Mülheim-Karlich	G	PWR	1219	1975	1987	1988
Doel-4	B	PWR	1033	1978	1985	-
Chernobyl-4	UKR	LWGR	925	1979	1984	1986
Heysham-B	UK	GCR	2X610	1980	1989	-

- During the seventies the construction of generation II reactors is really starting off with large units (>900MW).
- The 1st oil crisis was in 1974. (2nd in 1979)
- Starting in 1977 the ceiling of the global construction capacity was reached
- During this period some contracted projects were cancelled. (USA)
- Most reactors from the seventies are still in operation

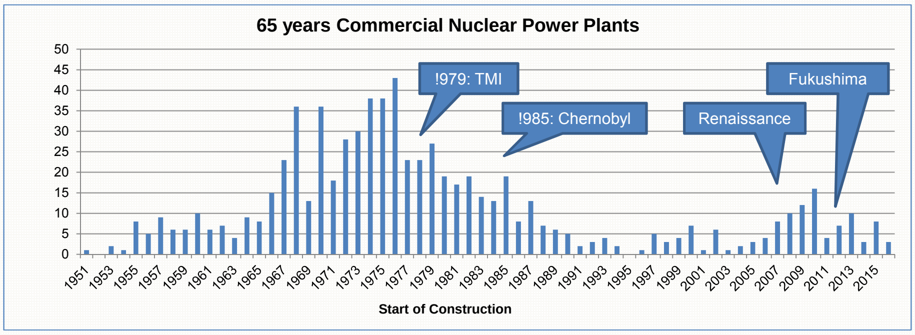
Fessenheim-1

Type	PWR
NSSS supplier	Framatome
Power	880 MW
Start construction	1971
COD	1978
Shutdown	-
Containment	Single

Bruce- A1

Type	CANDU
NSSS supplier	AECL
Power	760 MW
Start construction	1971
COD	1977
LT Shutdown	1997 – 2012
Special	Booster Rods(93%)
SG material	Incoloy-800

After the golden years



- 1979 TMI: Construction stagnation in the USA, but most of the projects were finished, after delays. Some projects were cancelled
- TMI triggered the development of improved emergency procedures and staff training/qualification
- The rest of the world continuous the construction of NPP's
- 1984: start development programme in the Netherlands
- 1985 Chernobyl: termination of all new build projects, except for China (China just started)
- Chernobyl initiated large upgrade projects at KCB and KCD. The costs proofed to be too high for KCD.
- In 2005 a global nuclear revival started (Nuclear renaissance)
- Because of Fukushima, but most of all new economical condition caused a new stagnation

What to do now?

Continue with expensive generation III reactors or make a jump to generation IV?

Causes of stagnation

- High costs(capex)
- Long and uncertain construction time
- Low electricity market prices
- Safety perception
- Perception of the waste problem

What is Gen. IV solving?

- Capex: small modules O
- Constr. time: small modules ☑
- Opex: small seems to be in contradiction O
- Safety: aim is inherent safe O
- Reduction long living waste O
- Increase supply of U/Pu O

1. Deregulated market: ROI > 20 years are not acceptable without guarantees
2. It is not been shown that modular construction decreases the kW rates
3. Modular construction does decrease the parked money problem during construction
4. Gen IV projects claim a low opex, but it is not clear how this will be delivered
5. Inherent safety is what is claimed, but real justifications are missing
6. 20-30% reduction of the long living waste is not really solving the waste perception problem
7. For the coming 3 decades uranium supply will not be a problem