UNIVERSIDAD POLITÉCNICA DE MADRID
www.upm.es

Innovative Fission Reactors for this Century

Emilio Minguez Torres
Nuclear Engineering Department
Institute of Nuclear Fusion

(emilio.minguez@upm.es)

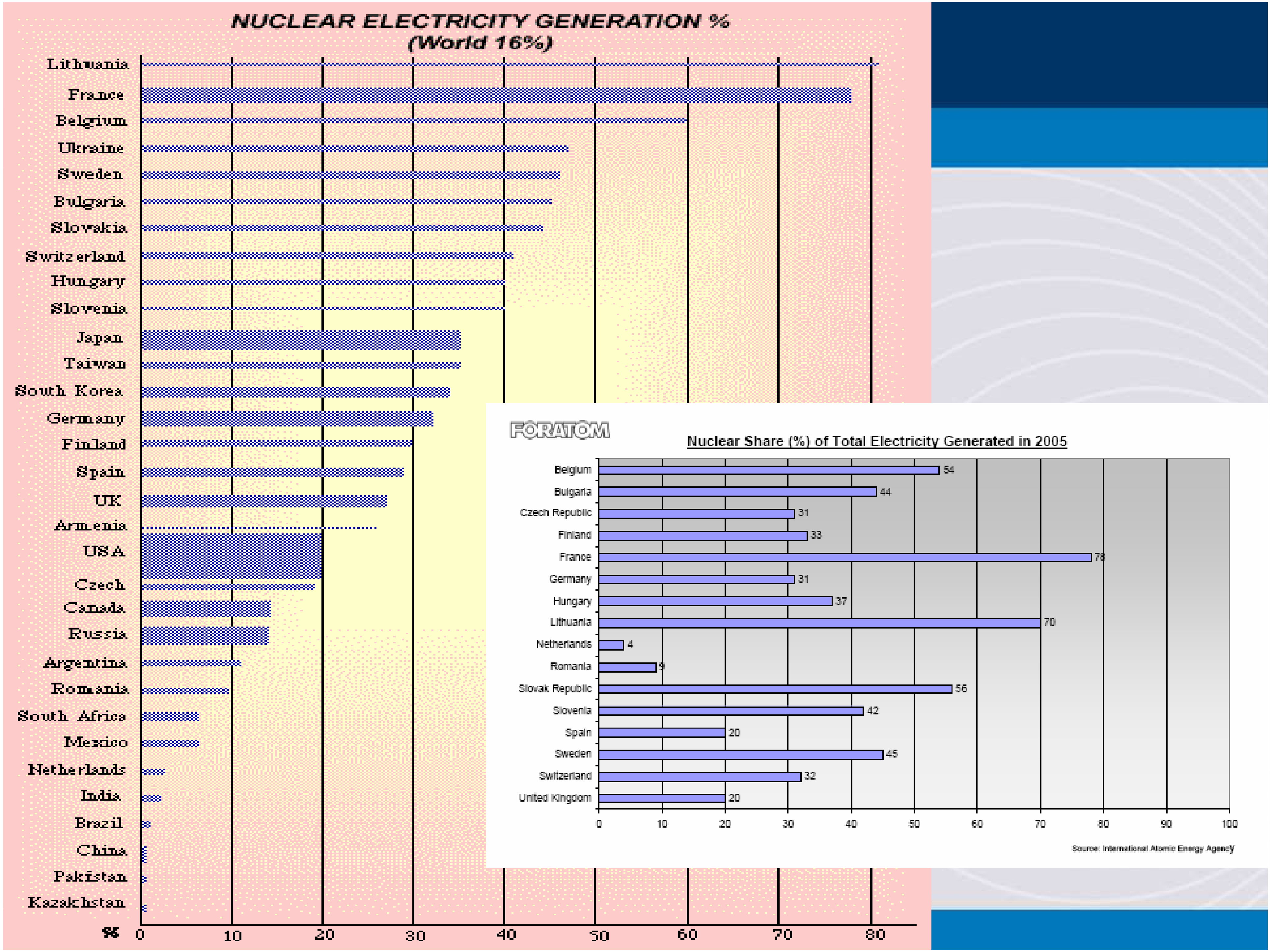
ICENES 2007
Istanbul
June 2-8, 2007

Outline

- Present state of Nuclear Energy
- Several innovative concepts
- Strategies for the future

Nuclear Power Plants in Operation

REACTOR TYPE	MAIN COUNTRIES	NUMBER	GWe
Pressurised Water Reactor (PWR)	US, France, Japan, Russia	260	243
Boiling Water Reactor (BWR)	US, Japan, Sweden	92	83
Pressurised Heavy Water Reactor "CANDU" (PHWR)	Canada	34	18
Gas-cooled Reactor (Magnox & AGR)	UK	32	12
Light Water Graphite Reactor (RBMK)	Russia	13	14
Fast Neutron Reactor (FBR)	Japan, France, Russia	4	1.3
other	Russia, Japan	5	0.2
	TOTAL	440	371



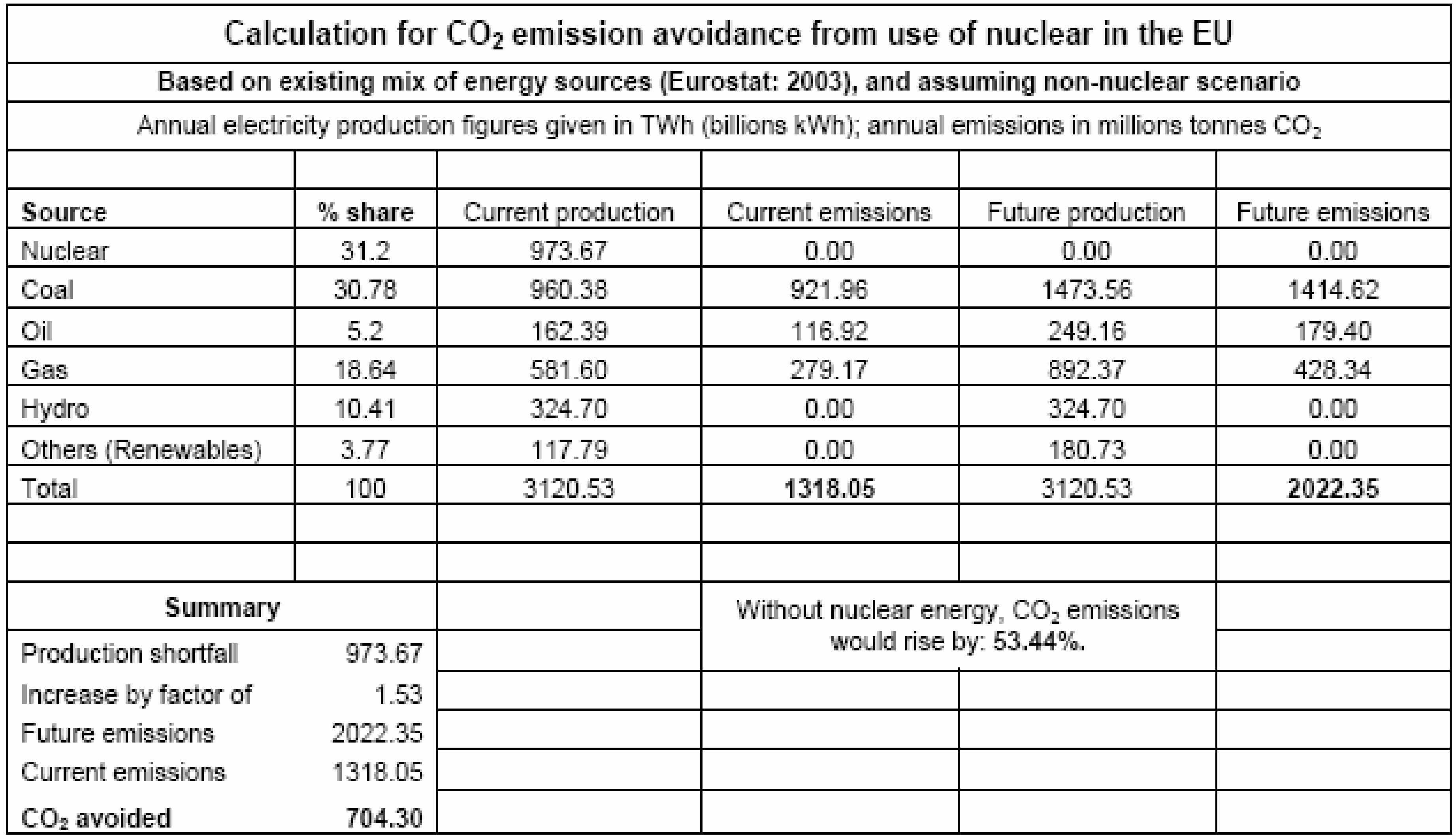
NUCLEAR ELECTRICITY GENERATION %
(World 16%)

FORATOM

Nuclear Share (%) of Total Electricity Generated in 2005

Source: International Atomic Energy Agency

CO2 emission avoidance using nuclear energy



Calculation for CO_2 emission avoidance from use of nuclear in the EU

Based on existing mix of energy sources (Eurostat: 2003), and assuming non-nuclear scenario

Annual electricity production figures given in TWh (billions kWh); annual emissions in millions tonnes CO_2

Source	**% share**	Current production	Current emissions	Future production	Future emissions
Nuclear	31.2	973.67	0.00	0.00	0.00
Coal	30.78	960.38	921.96	1473.56	1414.62
Oil	5.2	162.39	116.92	249.16	179.40
Gas	18.64	581.60	279.17	892.37	428.34
Hydro	10.41	324.70	0.00	324.70	0.00
Others (Renewables)	3.77	117.79	0.00	180.73	0.00
Total	100	3120.53	**1318.05**	3120.53	**2022.35**

Summary	
Production shortfall	973.67
Increase by factor of	1.53
Future emissions	2022.35
Current emissions	1318.05
CO_2 avoided	**704.30**

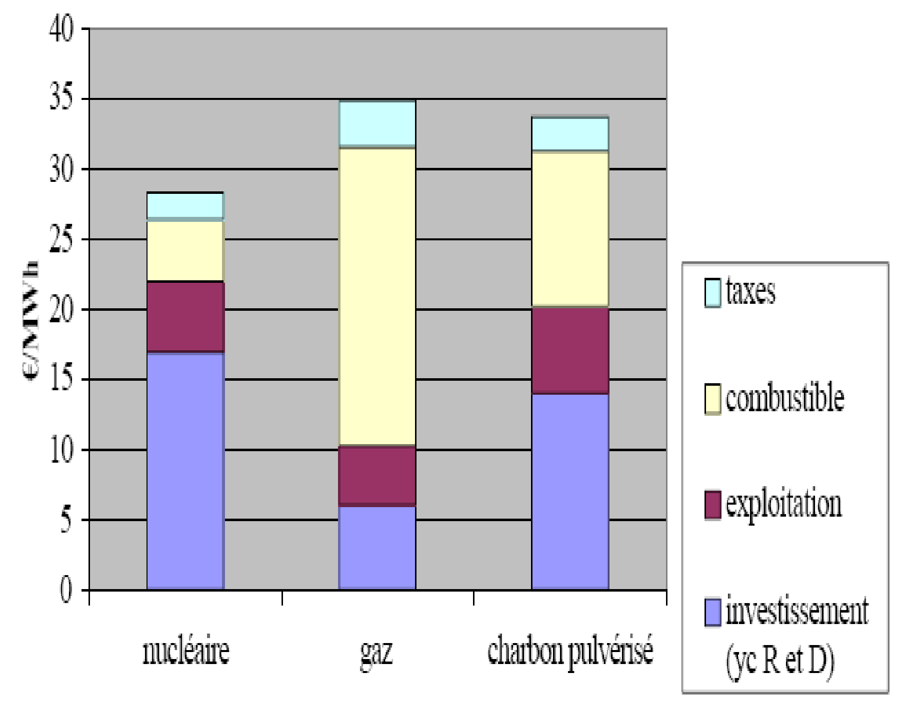
Without nuclear energy, CO_2 emissions would rise by: **53.44%.**

Economics of nuclear energy

- Existing nuclear power plants have very low and stable running costs (O&M + fuel)

- Nuclear electricity is the cheapest option in most cases in countries considering new plants

- Gas prices are high and volatile; renewable sources are not yet competitive



Radioactive waste disposal

- The volumes of radioactive waste are small but they need long-term stewardship
- The safe disposal of all radioactive waste is technically and economically feasible
- Implementing repositories requires dialogue with stakeholders
- Separation and Transmutation: and advanced technology for reducing radioactive wastes

Clab (Sweden)

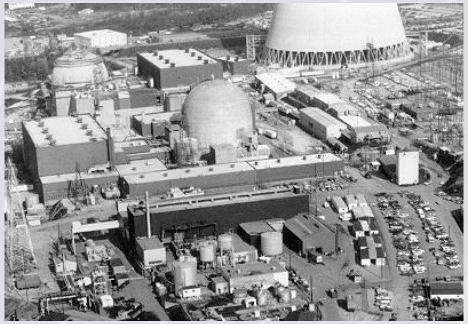
Habog (Holland)

Surry (UEA)

Evolution of Nuclear Power Systems

Generation I

Early Prototype Reactors



- Shippingport
- Dresden,Fermi-I
- Magnox

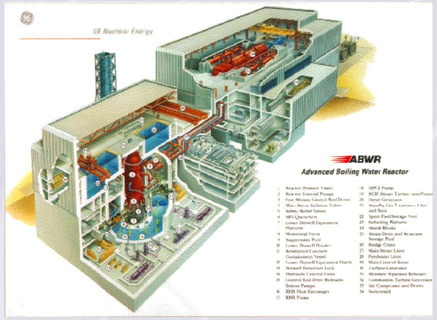
Generation II

Commercial Power Reactors

- LWR: PWR/BWR
- CANDU
- VVER/RBMK

Generation III

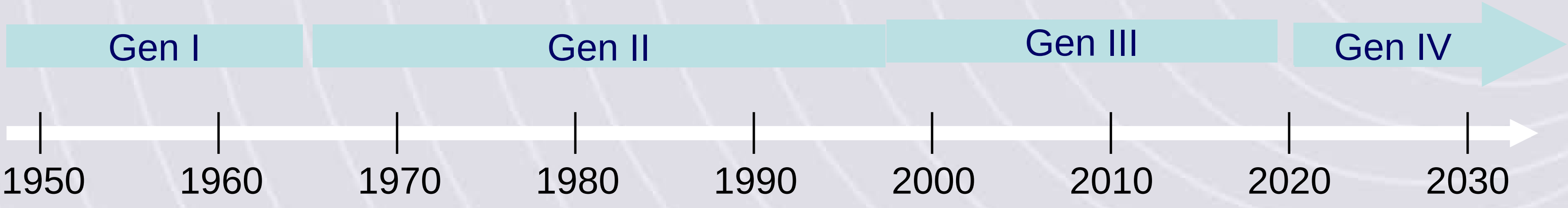
Advanced LWRs



- System 80+
- EPR
- AP600
- ABWR

Generation IV

- Highly economical
- Enhanced Safety
- Minimized Wastes
- Proliferation Resistance



Innovative Challenges in Nuclear Fission

- **Scientific and technological : R&D**
- **Engineering Demonstration**
- **Industrial Deployment**

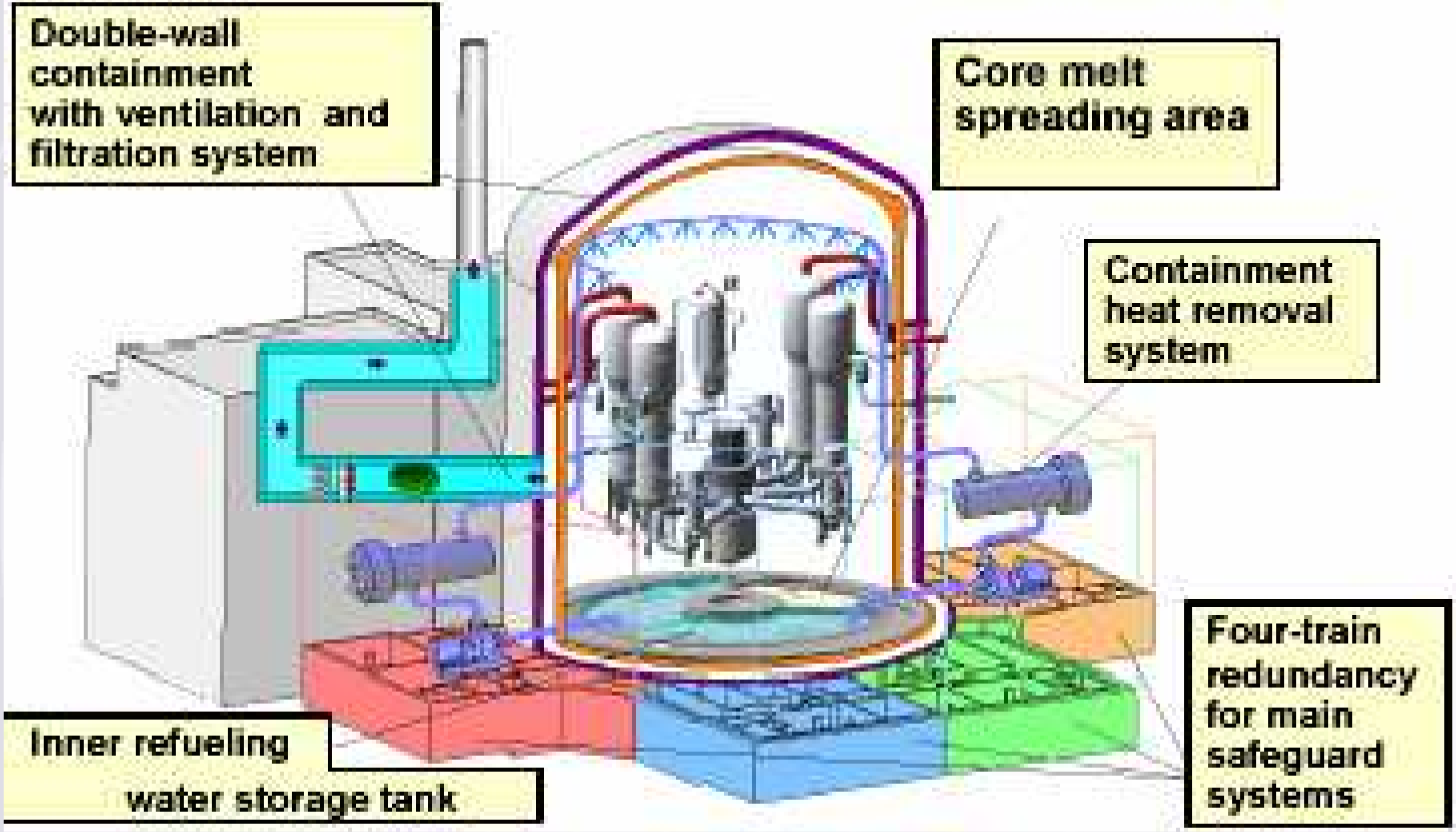
INNOVATIVE REACTORS

FUEL CYCLE

Generation III

- Standarised designs to :
  - accelerate licensing
  - reduce costs
  - reduce contruction time
- Robust designs (easy to operate and maintain)
- Large operating life : 60 y
- Enhance safety (low probability of severe accidents) and security
- Minimal environmental impacts

Reactor EPR



Double-wall containment with ventilation and filtration system

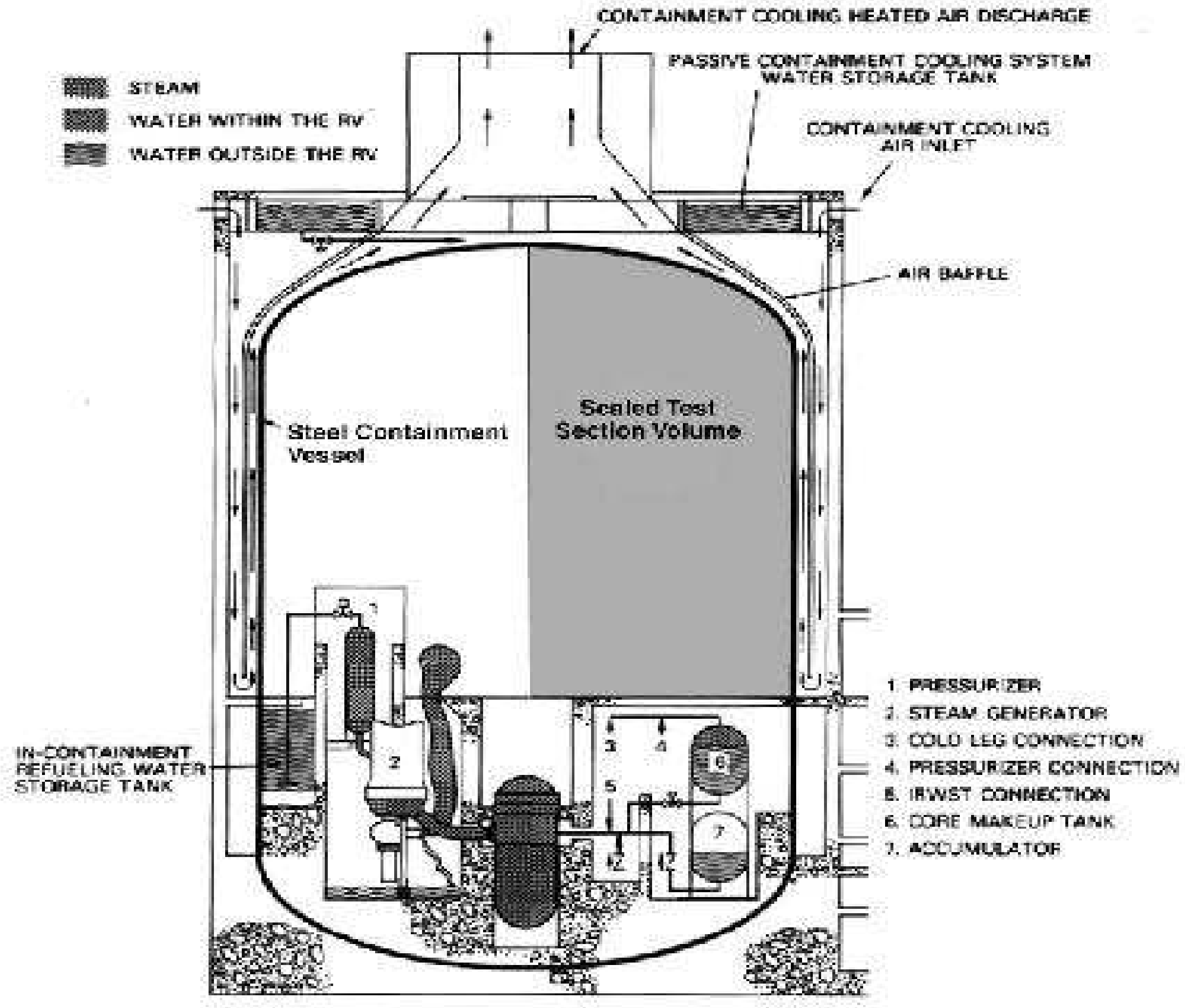
Core melt spreading area

Containment heat removal system

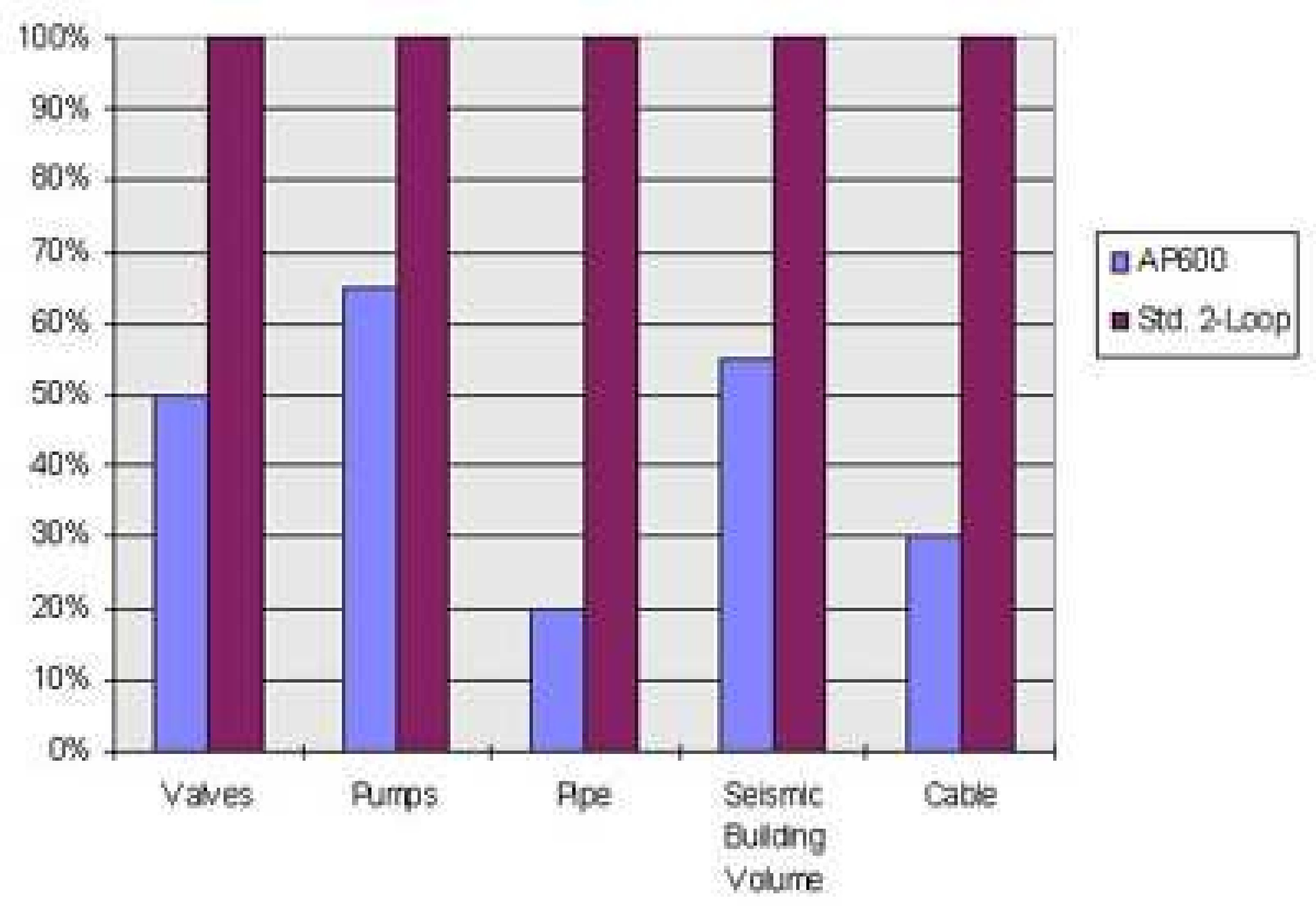
Four-train redundancy for main safeguard systems

Inner refueling water storage tank

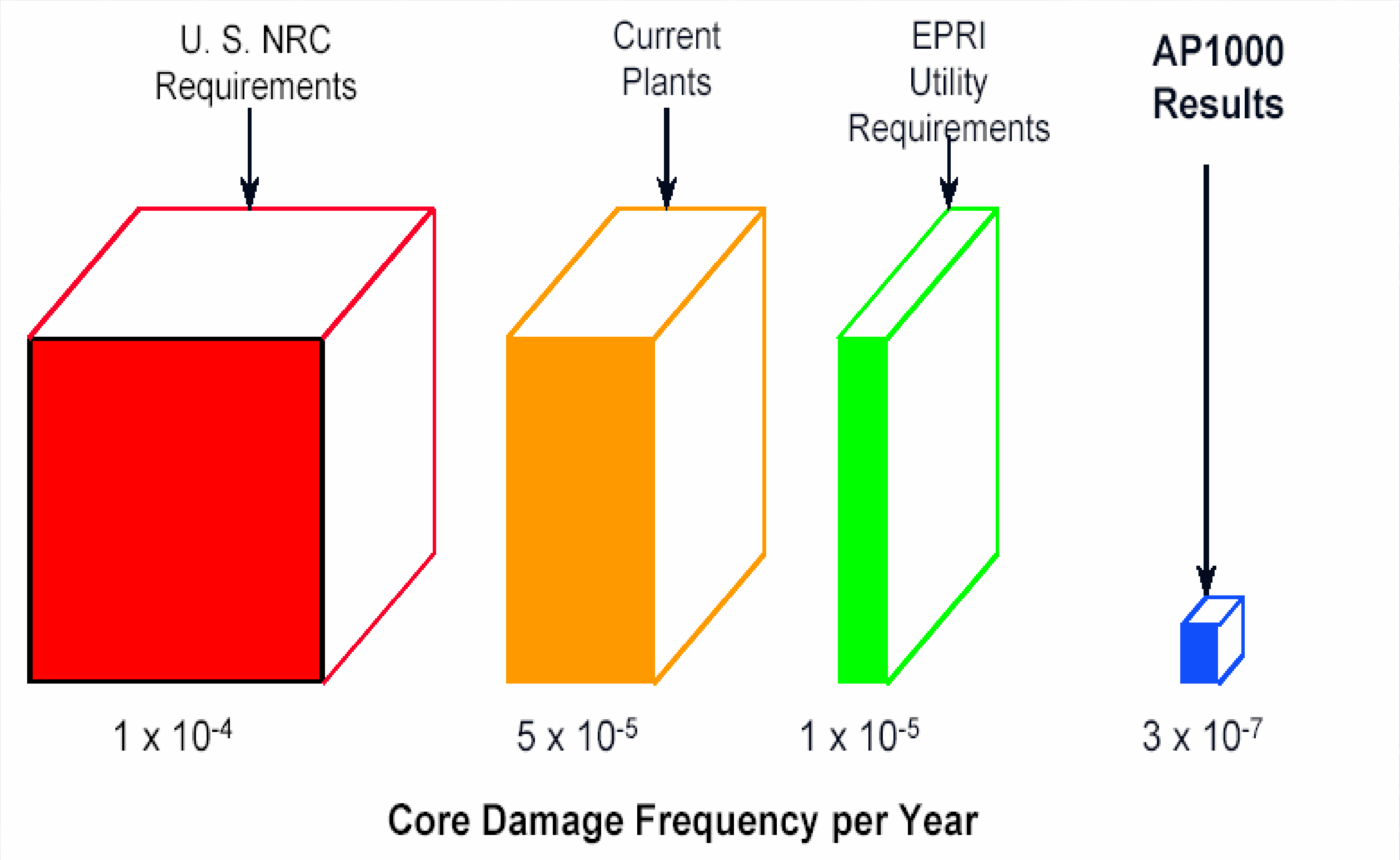
AP 600/ 1000


CONTAINMENT COOLING HEATED AIR DISCHARGE
PASSIVE CONTAINMENT COOLING SYSTEM WATER STORAGE TANK
CONTAINMENT COOLING AIR INLET
AIR BAFFLE
STEAM
WATER WITHIN THE RV
WATER OUTSIDE THE RV
Steel Containment Vessel
Sealed Test Section Volume
IN-CONTAINMENT REFUELING WATER STORAGE TANK
1. PRESSURIZER
2. STEAM GENERATOR
3. COLD LEG CONNECTION
4. PRESSURIZER CONNECTION
5. IRWST CONNECTION
6. CORE MAKEUP TANK
7. ACCUMULATOR
1
2
3
4
5
6
7

Simplicity


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Valves
Pumps
Pipe
Seismic Building Volume
Cable
AP600
Std. 2-Loop

Probabilistic Safety Assesment



U. S. NRC Requirements

1×10^{-4}

Current Plants

5×10^{-5}

EPRI Utility Requirements

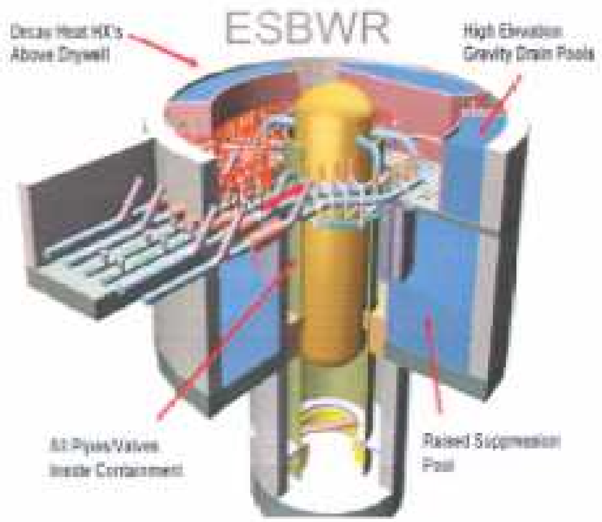
1×10^{-5}

AP1000 Results

3×10^{-7}

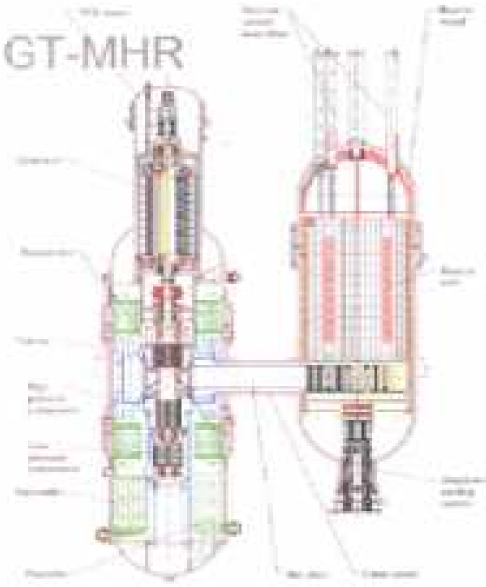
Core Damage Frequency per Year

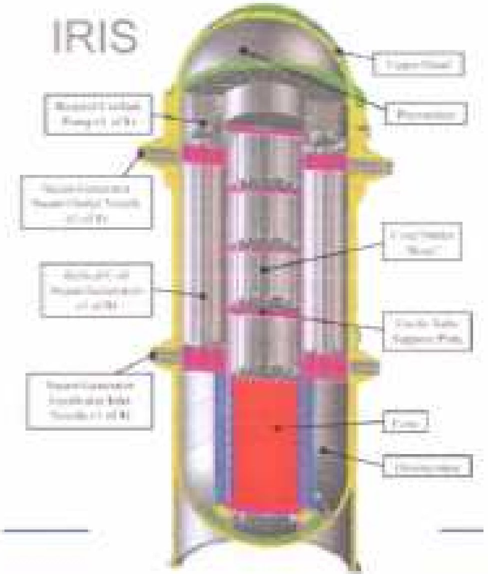
Designs in Pre-application Review

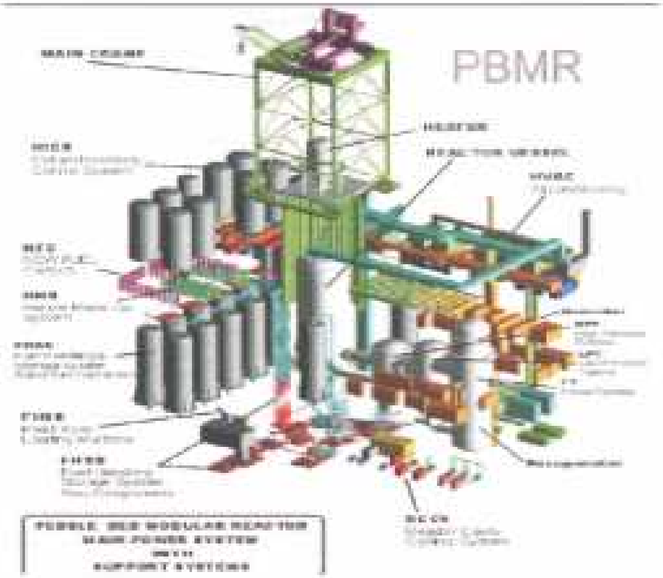

ESBWR


ACR-700

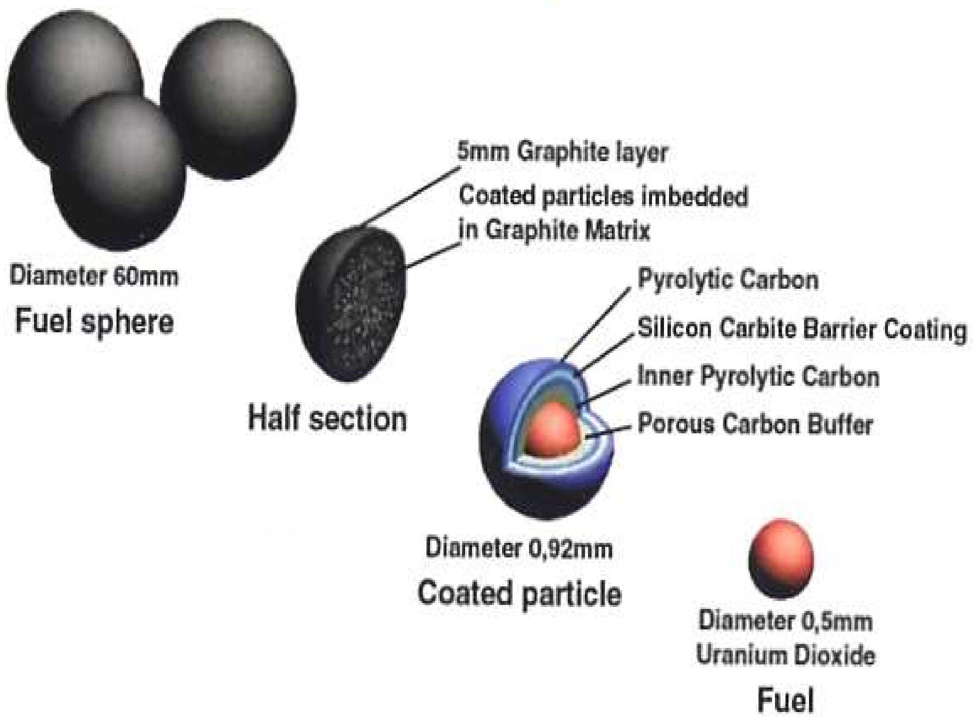

SWR-1000

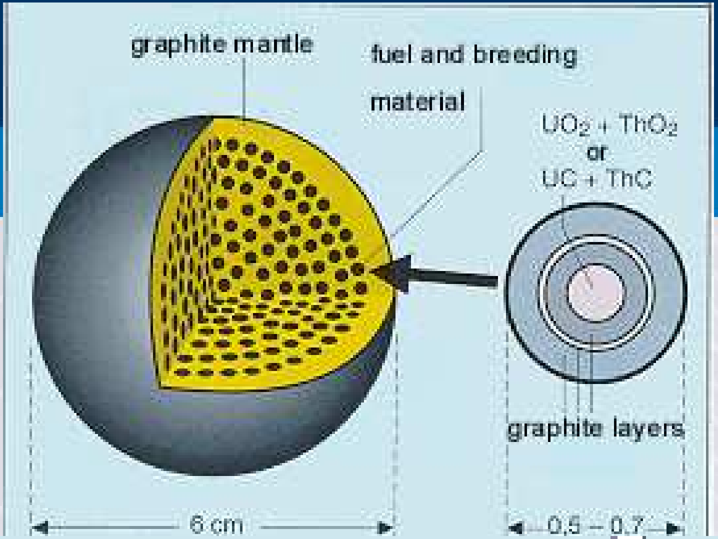

GT-MHR

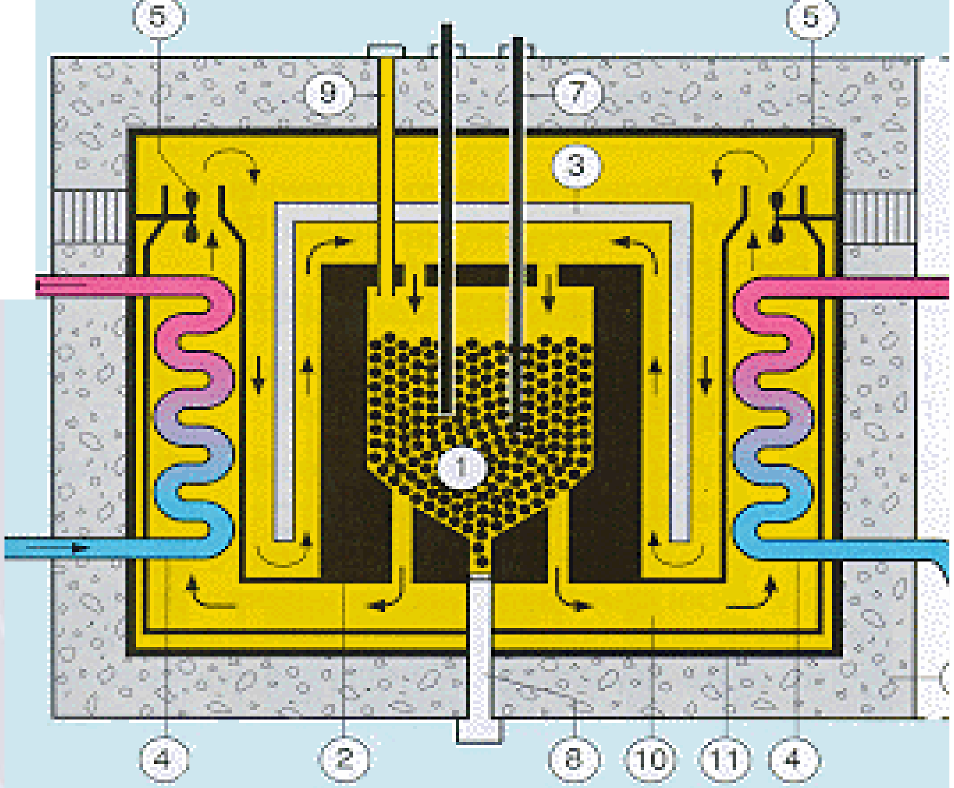

IRIS


PBMR

Fuel element design for PBMR







WHAT IS GENERATION IV ?

In short, "Generation IV" refers to the development and demonstration of one or more new nuclear energy systems

that offer advantages in the areas of

- sustainability,
- economics,
- safety and reliability,
- proliferation resistance and physical protection

Generation IV International Forum (GIF)

and could be deployed commercially by 2030

GENERATION IV SYSTEMS

Acronym		*Spectrum*	*Fuel cycle*
SFR	Sodium Cooled Fast R.	Fast	Closed
LFR	Lead Alloy Cooled R.	Fast	Closed
GFR	Gas Cooled Fast R.	Fast	Closed
VHTR	Very High Temperature R.	Thermal	Once-through
SCWR	Supercritical Water Cooled	Th. & F.	Once-t. & Cl.
MSR	Molten Salt R.	Thermal	Closed

Goals for Gen IV Nuclear Energy Systems (1)

- **Economics**
  - ➢ Competitive fuel cycle
  - ➢ Energy production costs
  - ➢ Financial risk

- **Sustainability**
  - ➢ clean air objectives, long term availability of systems and effective fuel utilization
  - ➢ minimization and management of nuclear waste
    - ▪ increased levels of protection for public health and the environment
    - ▪ reduced long term stewardship burden in the future

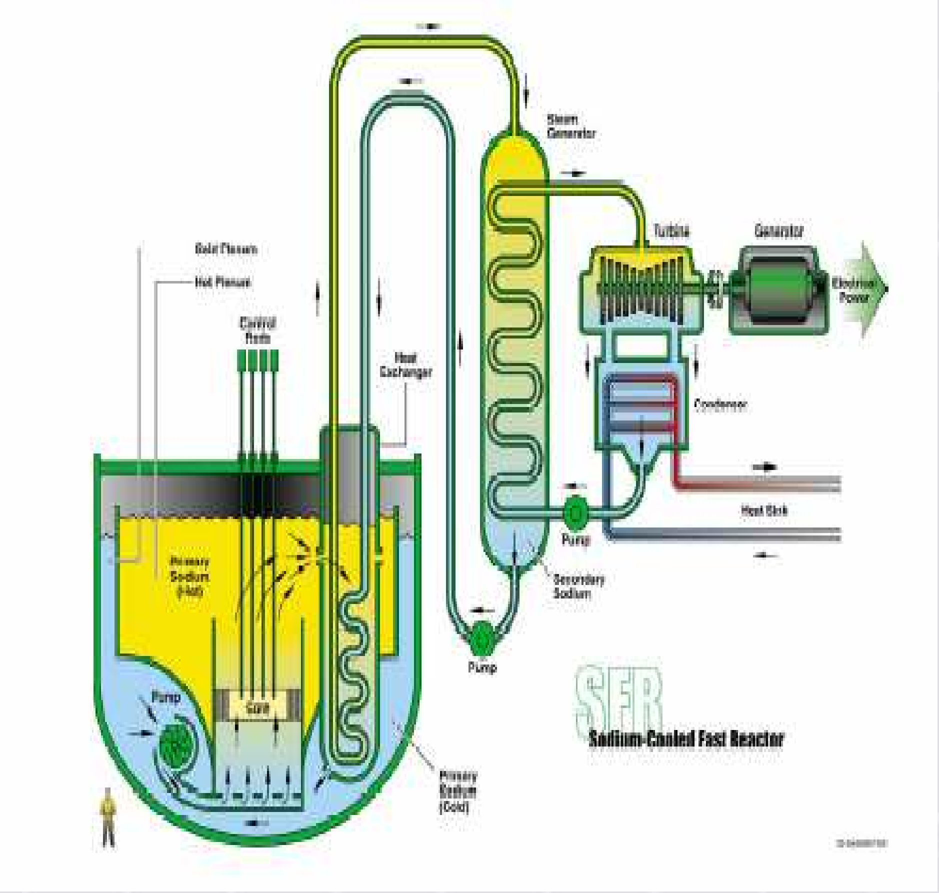
Goals for Gen IV Nuclear Energy Systems (2)

- **Proliferation resistance & Physical Protection**
  - Controlling and securing nuclear materials and nuclear installations
- **Safety and Reliability**
  - excellence in safety and reliability
  - reduction of the likelihood and severity of reactor core damage, and rapid return to plant operation
  - elimination of the need for off-site emergency response

Phases

- Viability: *pre-conceptual design*
- Performance: *conceptual design*
- Demonstration: *preliminary design*
- Industrial : *engineering design*
- Final project
- Construction

SFR (Sodium Fast Reactor)



- electricity production (with high efficiency, close to 40 %)
- Cogeneration
- actinide management
- modules of 50 MWe or large plant of 1500 MWe
- chair = Japan and USA / members = France, South Korea, UK and (Euratom)

Sodium-cooled fast reactors (SFR)
case deployment year 2020

- best experienced system in France, USA and Japan

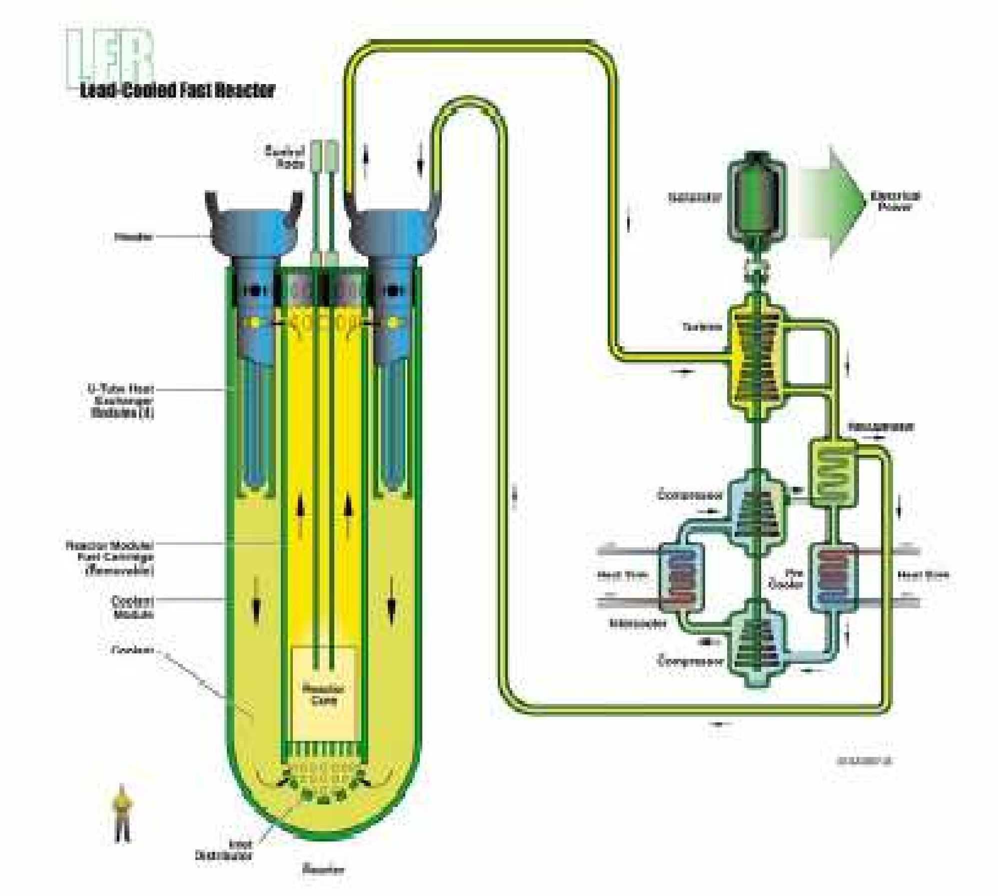
- efficient management of U resources

- demonstration reactors:
  France: 250 – 600 MWe – start up of operations by 2020.
  Advanced Burner Reactor (ABR in the USA – deployment by 2022
  Japanese Sodium Fast Reactor (JSFR)
  Chinese Experimental Fast Reactor (CEFR)

- "EISOFAR": *Roadmap for a European Innovative Sodium Cooled Fast Reactor* / initiated in February 2007, co-ordinated by CEA Cadarache.

- European roadmap: confirmation of key technologies and design options in 2012

LFR (Lead-Cooled Fast Reactor)



- electricity production (with high efficiency, close to 45 %)
- Cogeneration
- actinide management
- reference power = small modules of 20 MWe and moderated-size system of 600 MWe
- Euratom, USA, South Korea and Japan

Lead-cooled fast reactors (LFR) case deployment year 2025

- **experience from Russian NIKIET development of the lead-cooled 300 MWe reactor BREST (Beloyarsk, with an on-site fuel cycle, completion of the project by 2020)**

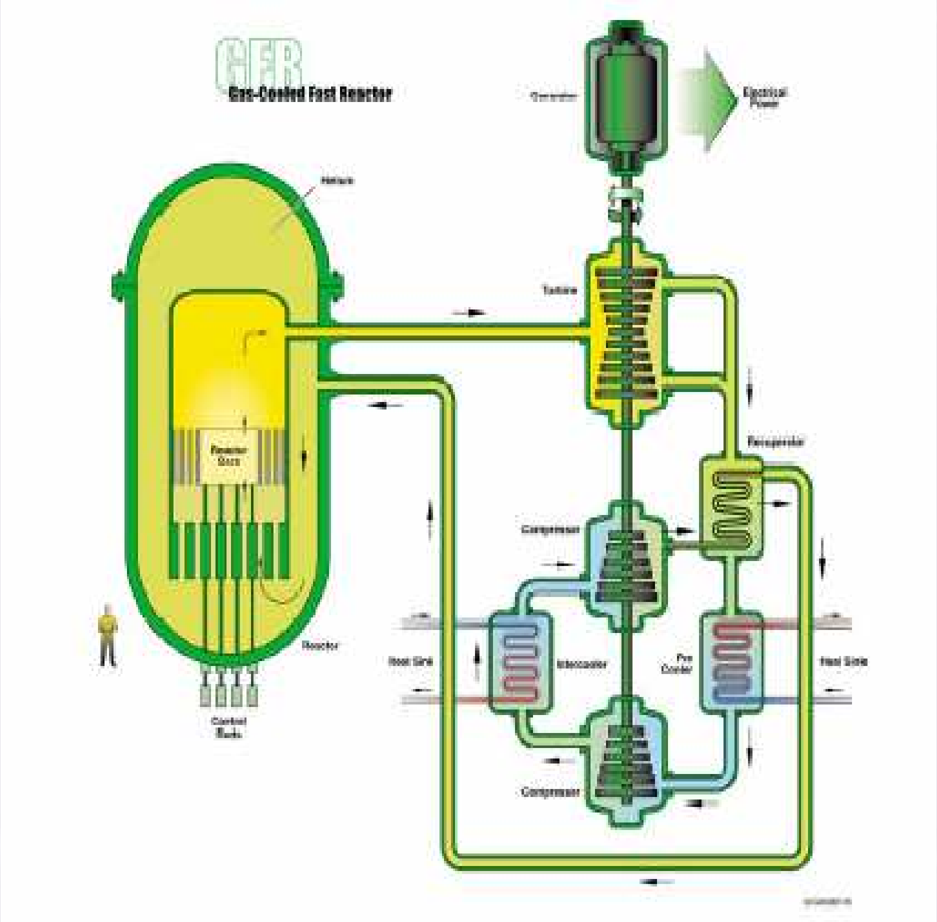
- **proliferation resistance due to core design and long refuelling intervals (up to 20 years)**

- **demonstration reactor (if selected as second type of FR system in Europe) - start up by 2020**

- **Euratom FP-6 project “ELSY”: European Lead-cooled / Specific Targeted Research Project funded for 3 years, initiated in October 2006, co-ordinated by Ansaldo**

- **European roadmap: confirmation of design options in 2012 (back up solution, after SFR)**

GFR (Gas-Cooled Fast Reactor)

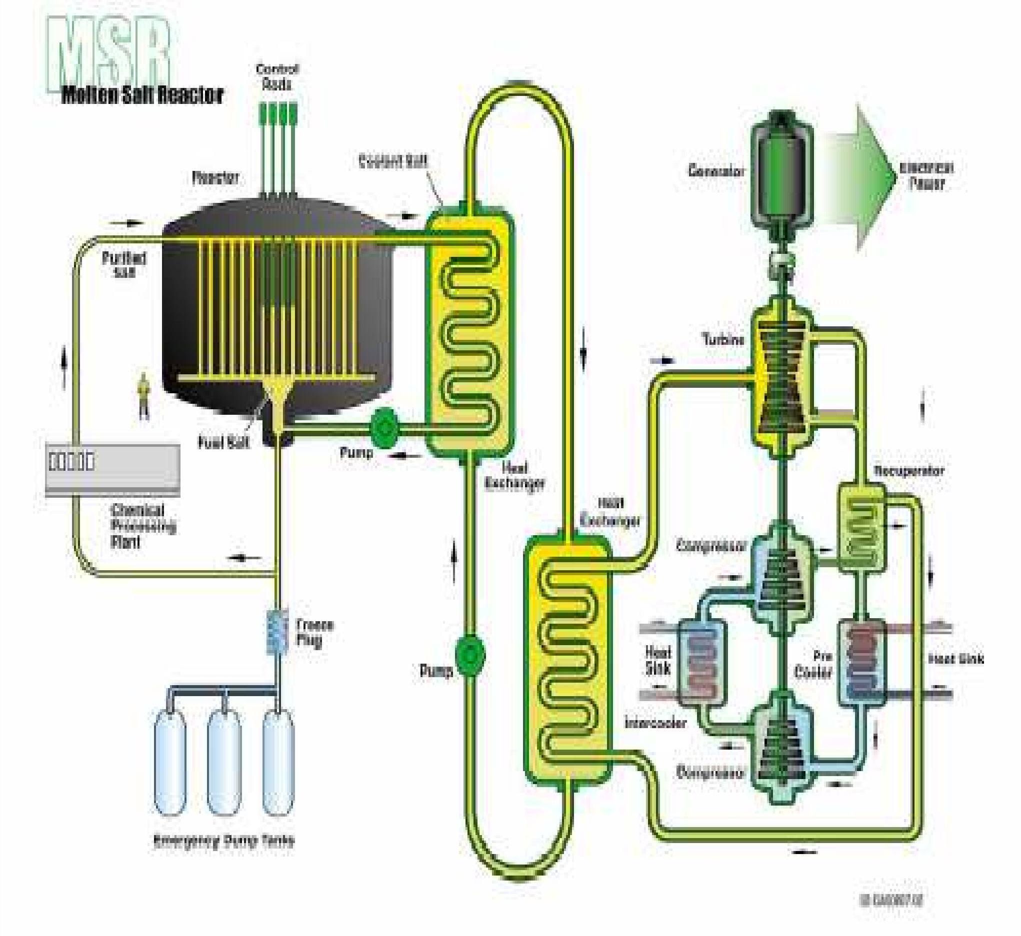


- mainly electricity production (high efficiency, higher than 45 %)
- Cogeneration
- actinide management
- reference power = 300 - 1500 MWe
- chair = France and USA members = Euratom, Japan, South Africa, South Korea, Switzerland and UK

Gas-cooled fast reactors (GFR) case deployment year 2025

- efficient management of U resources
- demonstration reactor (if selected as second type of FR system in Europe) : Experimental Technology Demonstration Reactor (ETDR in Europe, 50 – 100 MWth) – start up by 2020
- Euratom FP-6 project : “GCFR”: Gas Cooled Fast Reactor / Specific Targeted Research Project funded for 4 years, co-ordinated by AMEC-NNC Knutsford
- European roadmap: confirmation of design options in 2012 (back up solution after SFR)

MSR (Molten Salt Reactor)



- Electricity production
- Cogeneration
- full actinide management
- reference power = 1000 MWe
- Euratom, France and USA.

Molten salt reactors (MSR)

case deployment year 2030

- non-conventional technology closely linked to P&T (quasi-continuous recycling of fuel in a closed fuel cycle with continuous extraction of fission products)

- breeder in thermal / fast spectrum (Thorium cycle possible), or burner for spent fuel recycling

- Euratom FP-6 project : "ALISIA": Assessment of liquid salts for innovative applications, funded for 1 year initiated in February 2007, co-ordinated by CEA Saclay

SCWR (Super-Critical Water Cooled Reactor)

electricity production (efficiency, close to 45 %)

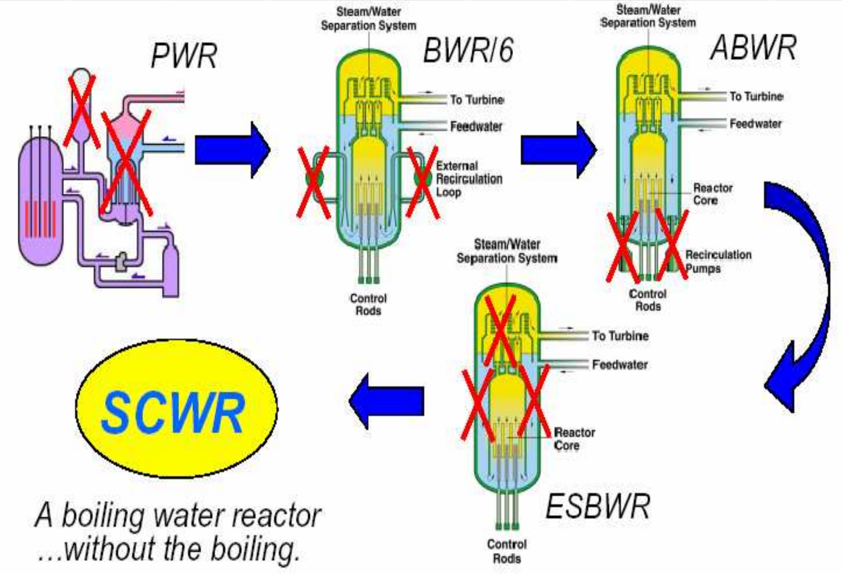
cogeneration

actinide management in the fast version

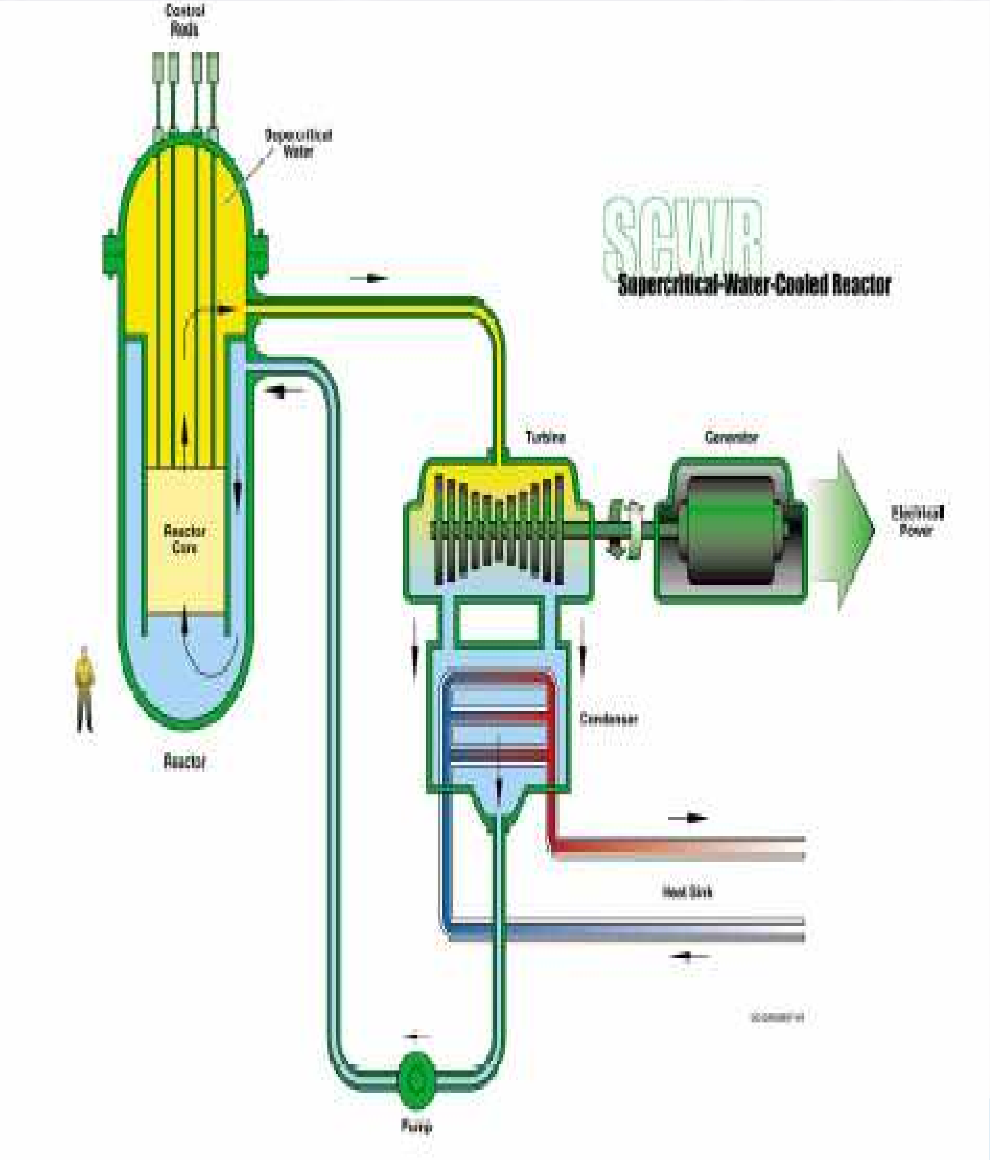
power = 1700 MWe

chair = Canada and USA /

members = Euratom, Japan, France and South Korea



A boiling water reactor
…without the boiling.



Supercritical water-cooled reactors (SCWR) deployment year 2025

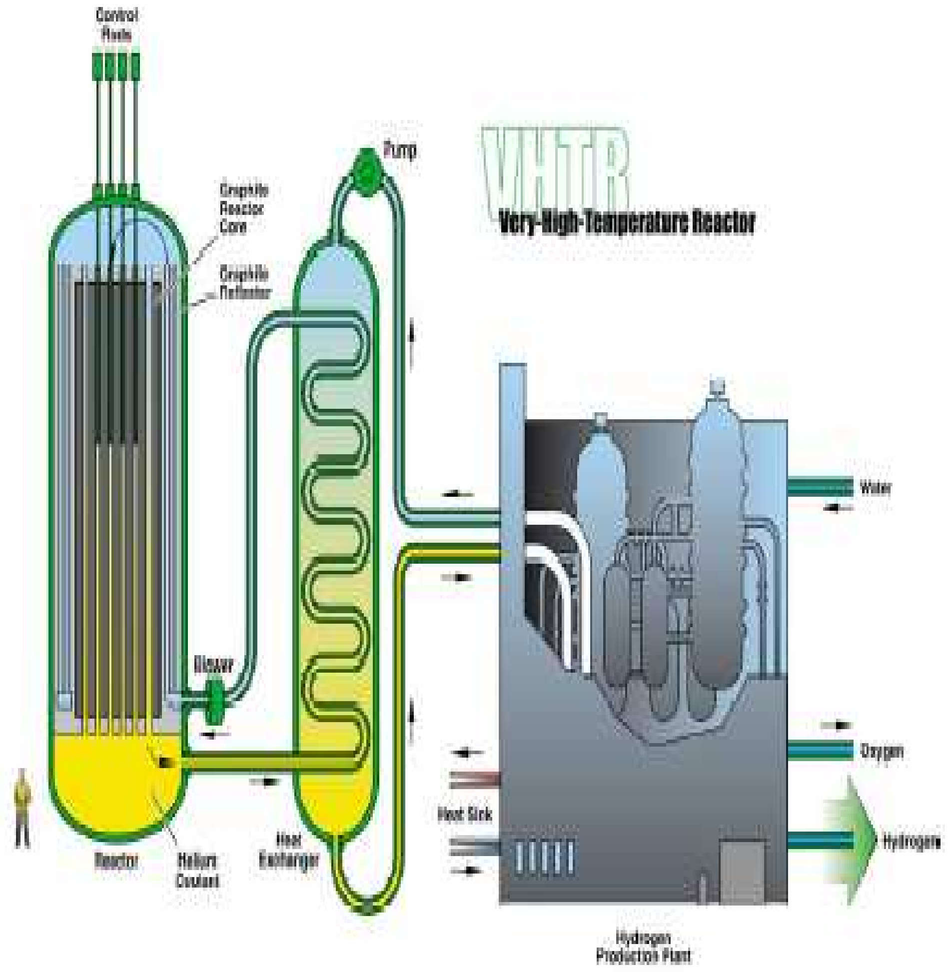
- **excellent economy (no steam generator, no recirculation pump, no steam separator) / existing technology in commercial supercritical-water-cooled fossil-fired power plants**

- **passive safety systems similar to the boiling water reactor SWR-1000 (Generation III)**

- **Euratom FP-6 project: “HPLWR”: High Performance Light Water Reactor funded for 3.5 years, initiated in Sept. 2006, co-ordinated by FZK Karlsruhe**

- **European roadmap: confirmation of design options (viability) in 2012**

VHTR (Very High Temperature Reactor)



- Cogeneration
- maybe only electricity production (with high efficiency, in the order of 40 - 45 %)
- no actinide management - once through cycle
- power = 600 MWth / 300 MWe
- chair = Japan and France members = Euratom, Canada, South Korea, South Africa, Switzerland and UK

Very high-temperature gas reactors (VHTR) case deployment year 2020

- fuel can resist fast neutron fluences , with specific burnups reaching 200 GWd/ton of fuel and temperatures of 1600 ° C in accident conditions
- demonstration reactors for nuclear cogeneration = Next Generation Nuclear Plant (NGNP) planned in the USA by 2021 and European demo planned by 2015 – 2020
- Euratom FP-6 project : “RAPHAEL”: ReActor for Process heat, Hydrogen And ELectricity generation . funded for 4 years, initiated in April 2005, co-ordinated by AREVA NP
- European roadmap: confirmation of design options (including cogeneration) in 2012

INTERNATIONAL PROJECT ON INNOVATIVE NUCLEAR REACTORS AND FUEL CYCLES: INPRO

- ❑ "To provide a Forum for Discussion of Experts and Policy Makers from Industrialized and Developing Countries on all aspects of Nuclear Energy Planning as well as on the Development and Deployment of INS in the 21st century".

- ❑ "To develop the Methodology to analyze INS on a global, regional and national basis and establish it as an Agency's recommendation".

- ❑ "To facilitate Coordinating and Collaboration among member states for planning of INS development and deployment".

- ❑ "To pay particular attention to the needs of developing countries interested in INS".

The Global Nuclear Energy Partnership (GNEP)

- **Expand use of nuclear power**
- **Minimize nuclear waste**
- **Demonstrate Advanced Burner Reactors**
- **Demonstrate Small , exportable reactors**
- **Enhanced nuclear safeguards technology**

21st Century Strategies

❖**Short Term (-2025)**

Existing fleet 40-year plant life

Plant life extension beyond 40 years

Construction of new NPP´s with technology of GEN III

❖**Near Term (2030- 2050)**

Construction of NPP´s with technology: Gen 3+ and GEN IV

Transmutation

❖**Long Term (2050-)**

NPP´s with GEN IV technology
Fusion reactors

Nuclear power must be part of our future