International Atomic Energy Agency

OVERVIEW OF GLOBAL DEVELOPMENT OF ADVANCED NUCLEAR POWER PLANTS

John Cleveland and Juergen Kupitz
Division of Nuclear Power
Department of Nuclear Energy
IAEA

ICTP , Trieste
November 2005

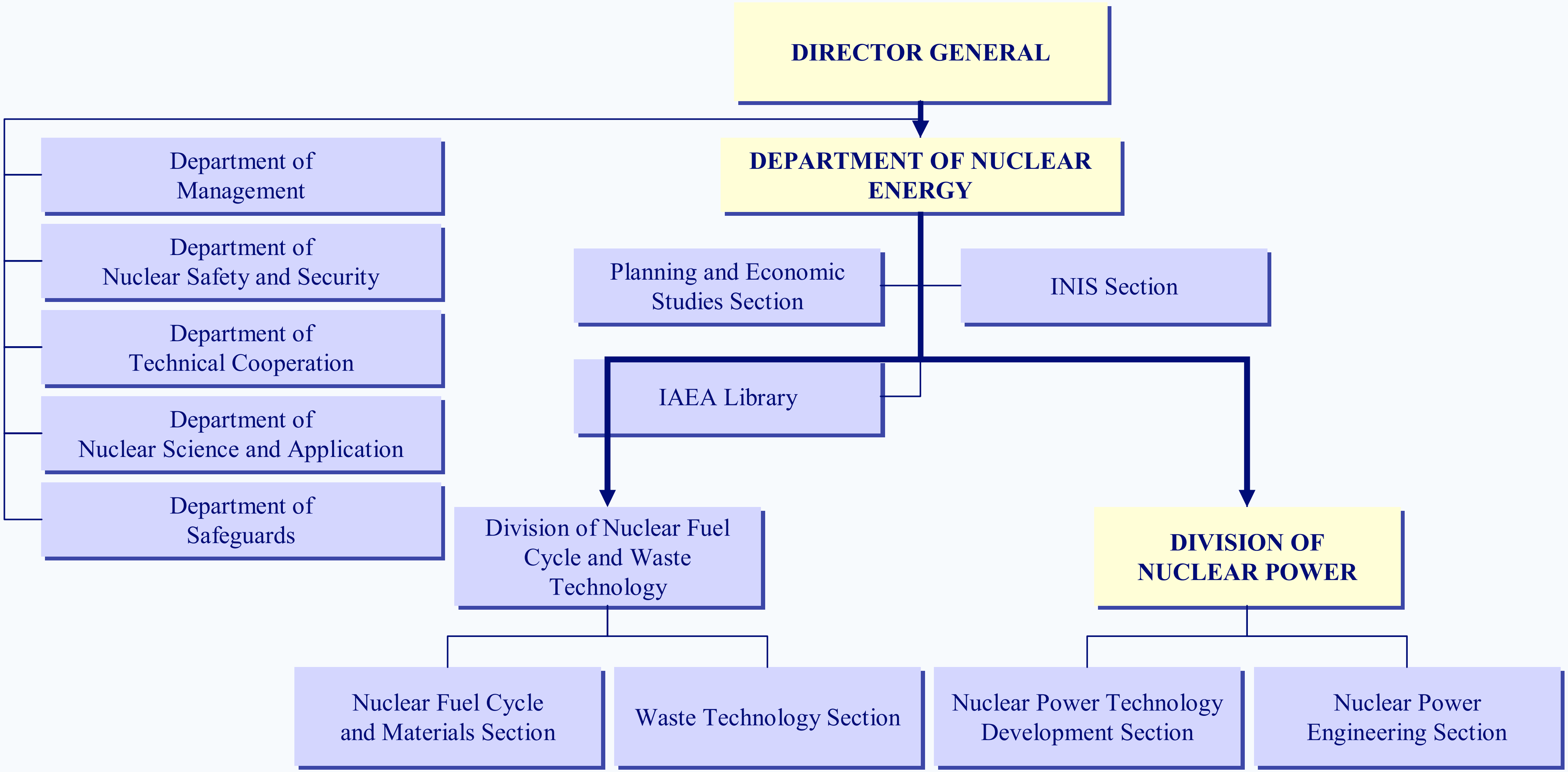
TOPICS

- **The IAEA at a glance**
- **OVERVIEW OF GLOBAL DEVELOPMENT OF ADVANCED NPPs**
  - **Status of nuclear power**
  - **Development of advanced designs**
    - **LWRs**
    - **HWRs**
    - **GCRs**
    - **FRs**
  - **International initiatives**
  - **Non-electric applications**
- **Brief summary of IAEA's Activities in Nuclear Power**

The IAEA at a glance

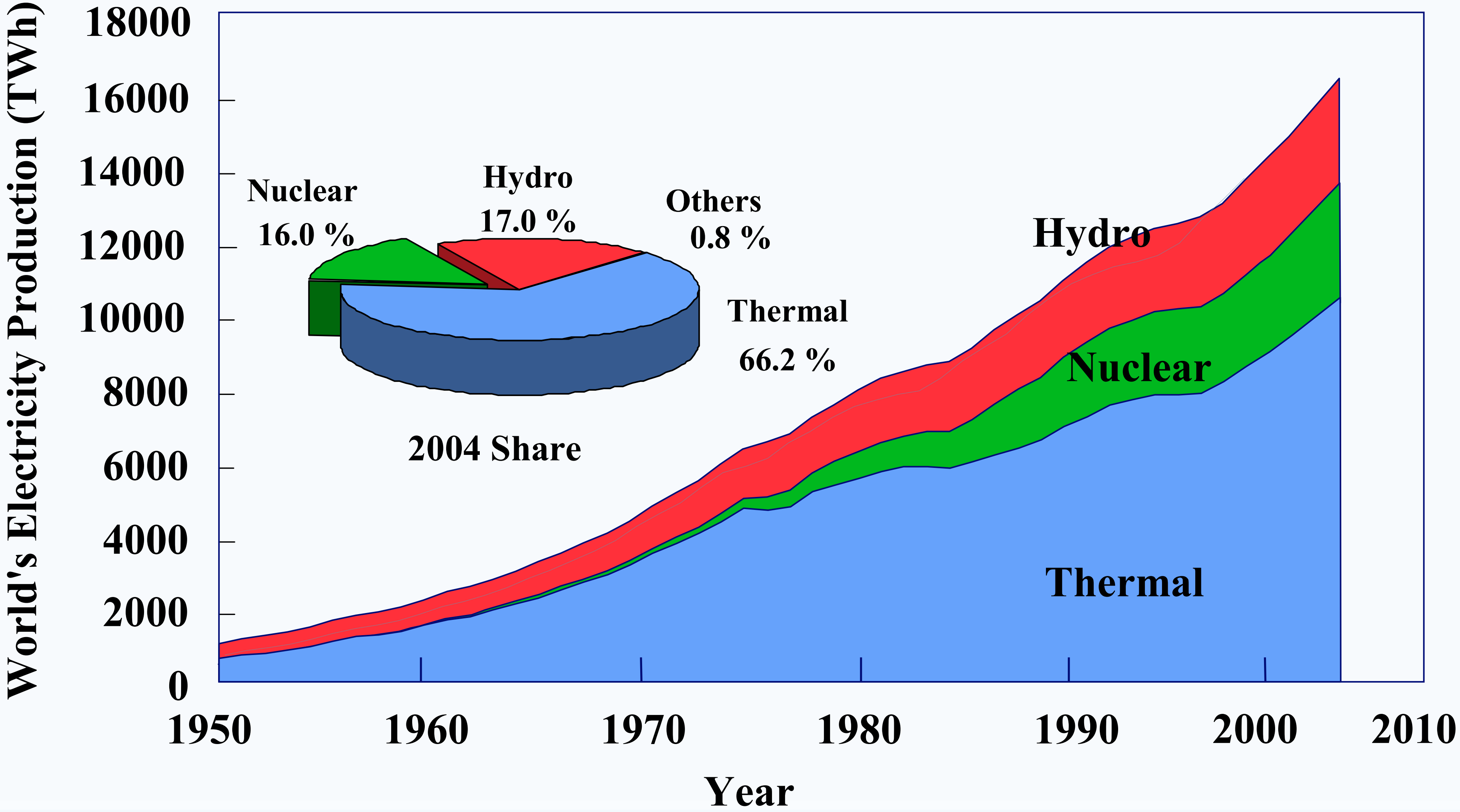
- Established in 1957 as world's "Atoms for Peace" organization in the UN family
- 138 Member States
- World's center for cooperation on safe, secure and peaceful uses of nuclear technologies
- Director General: Mohamed ElBaradei
- 2247 staff
- 268 M$ Regular Budget + 51 M$ Extra-budgetary + 75 M$ Technical Cooperation

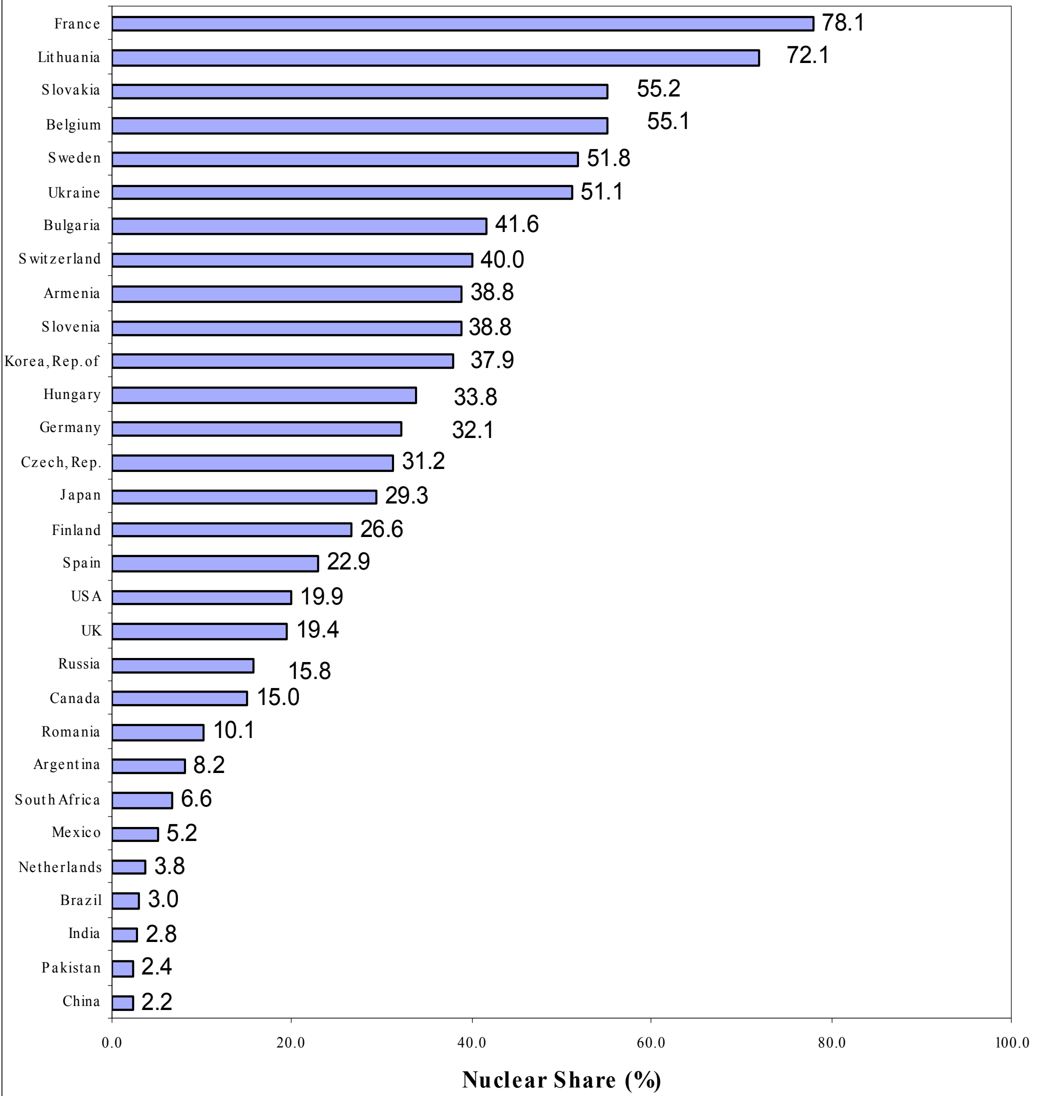
IAEA Departmental Organization



OVERVIEW OF GLOBAL DEVELOPMENT OF ADVANCED NPPs

NUCLEAR CONTRIBUTION TO ELECTRICITY GENERATION





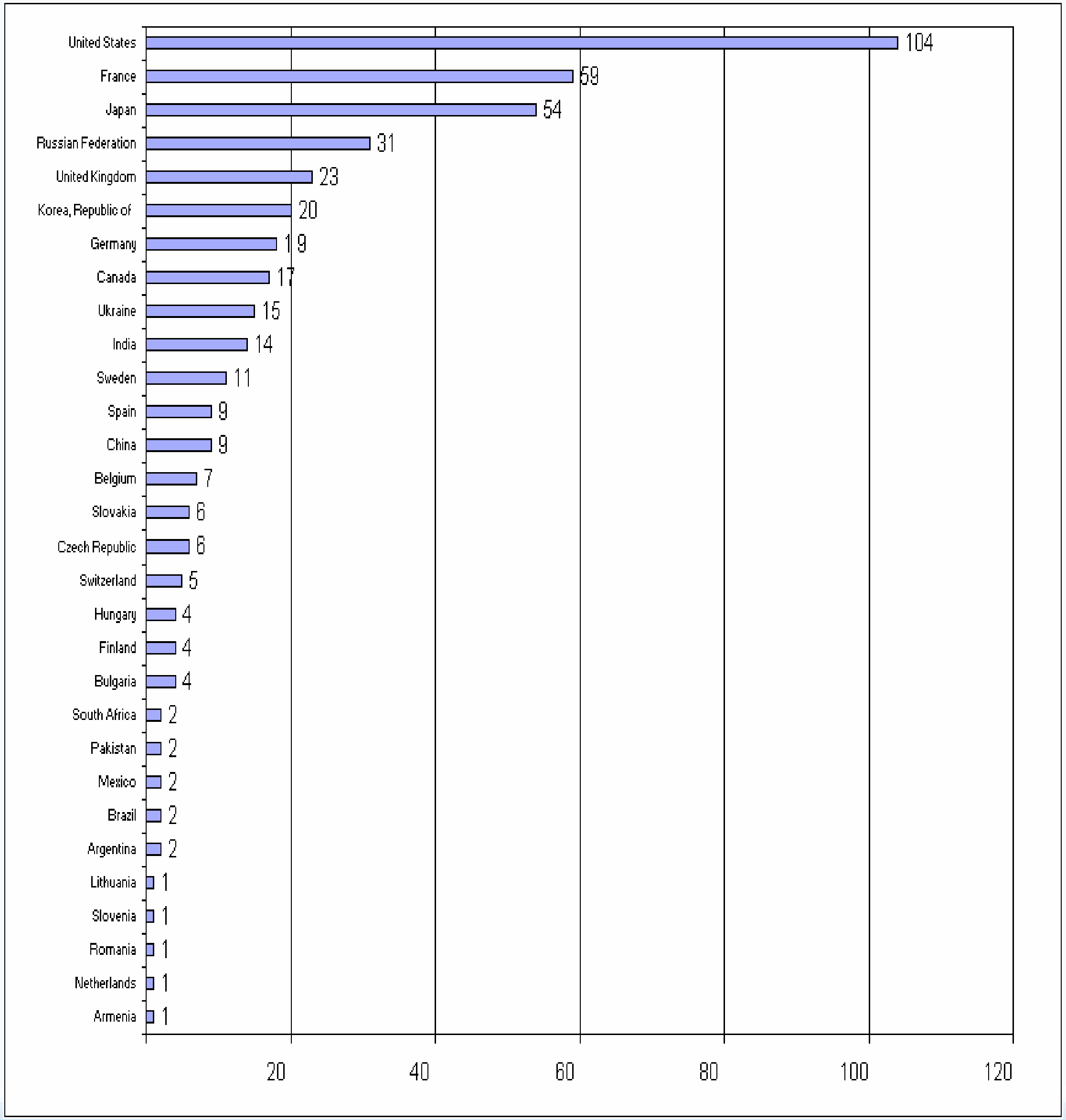
(note: The nuclear share in Taiwan, China was 21.5%)

MANY COUNTRIES HAVE NUCLEAR POWER

Nuclear Share (%) of Electricity Generation in 2004

Global Nuclear Share:

16.0%; 2619 TWh



MANY NUCLEAR PLANTS ARE OPERATING IN THE WORLD

In Operation:	**441**
Capacity:	**367.5 GWe**
Under Construction:	**26**
Capacity:	**20.8 GWe**
Operating Experience:	**11,600 RYs**
Number of Countries:	**31**
(including Taiwan, China)	

Note: data are as of 01.2005

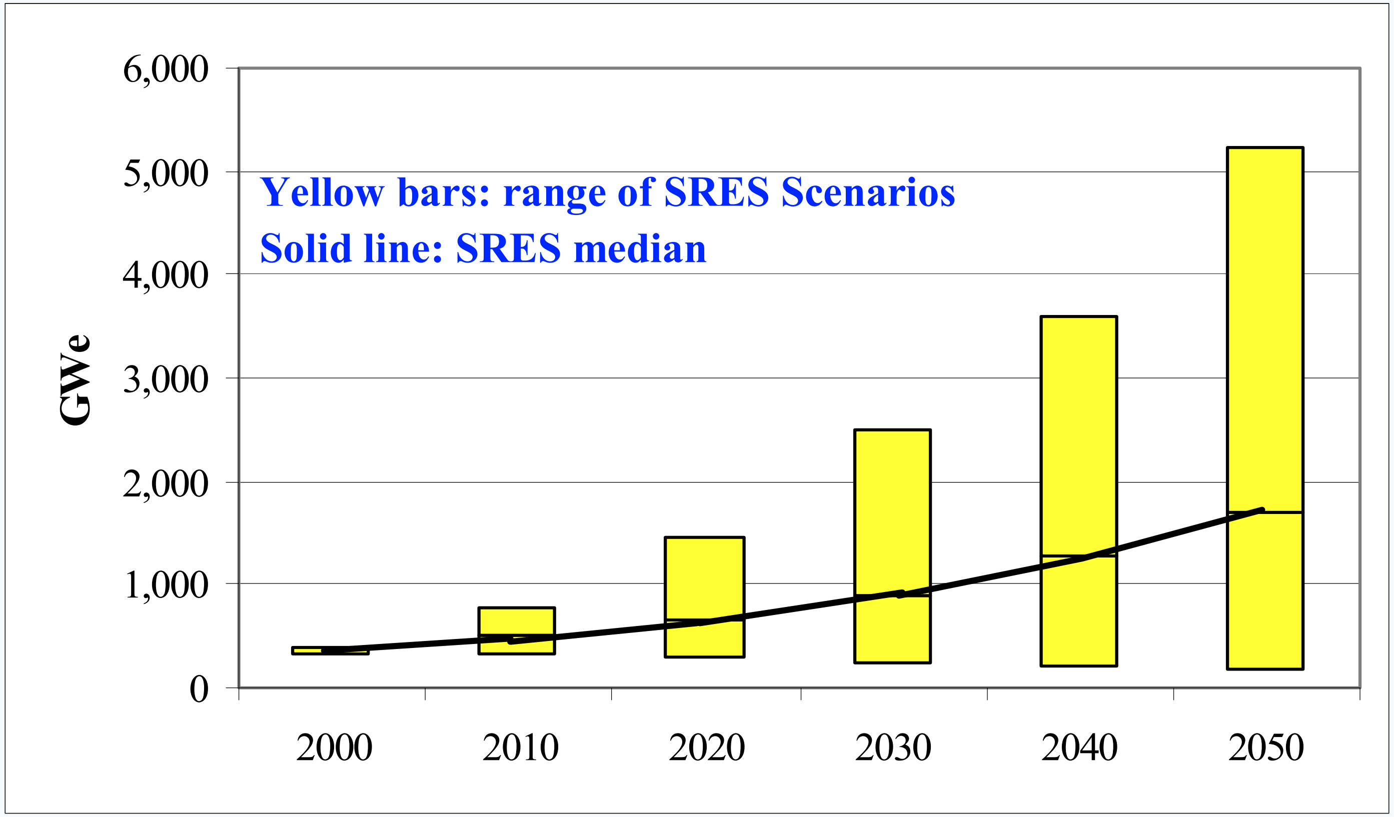
Note: Six reactors are in operation in Taiwan, China

IAEA PREDICTS THAT NUCLEAR POWER WILL GROW

- some countries have phase-out policies
- others see advantages for energy security, electricity price stability and greenhouse gas reduction
- some plan to increase nuclear capacity (e.g. China, India, Japan, Republic of Korea, Finland)
- IAEA predicts growth (from 2619 TWh in 2004):
  - 2776 - 2881 TWh by 2010
  - 3055 - 3769 TWh by 2020
  - 3115 - 4753 TWh by 2030

The Intergovernmental Panel on Climate Change (Scientific Advisory Body to the UN Framework Convention on Climate Change) also predicts that nuclear power will expand

Special Report on Emission Scenarios of the IPCC



predicted nuclear capacity vs. time

SEVERAL FACTORS WILL INFLUENCE NUCLEAR ENERGY'S FUTURE CONTRIBUTION

- The degree of global commitment to greenhouse gas reduction
- Continued vigilance in safety
- Continued vigilance in safeguards
- Technological maturity; economic competitiveness; and financing arrangements for new NPPs
- Implementation of high-level waste disposal
- Public perception, information and education

Fewer new plants are being built

Construction starts:

- The 1970s: average of 25 / year
- Recently:
  - 1998: 3 China (2), Japan (1)
  - 1999: 5 China (1), Rep. of Korea (2); Taiwan, China (2)
  - 2000: 5 China (1), India (2), Japan (2)
  - 2001: 1 Japan
  - 2002: 6 DPRK (1), India (5)
  - 2003: 1 India
  - 2004: 2 Japan (1), India (1)
  - to 8.'05 2 Pakistan (1), Finland (1)

For new plants, there are economic challenges

- **Market de-regulation and privatization change the criteria**
  - **Owners are no longer guaranteed cost recovery over long period of regulated rates**
  - **Private investors want high and rapid return on investments**
- **Nuclear plants have disadvantages with regard to financing, compared to fossil plants**
  - **Higher capital cost per kWe and generally larger sizes (e.g. 700 MWe and up)**
  - **Longer construction periods**
  - **Higher perceived risks (policy / regulatory,…)**

ADVANCED REACTOR DEVELOPMENT – Examples

DEVELOPMENT OF ADVANCED DESIGNS

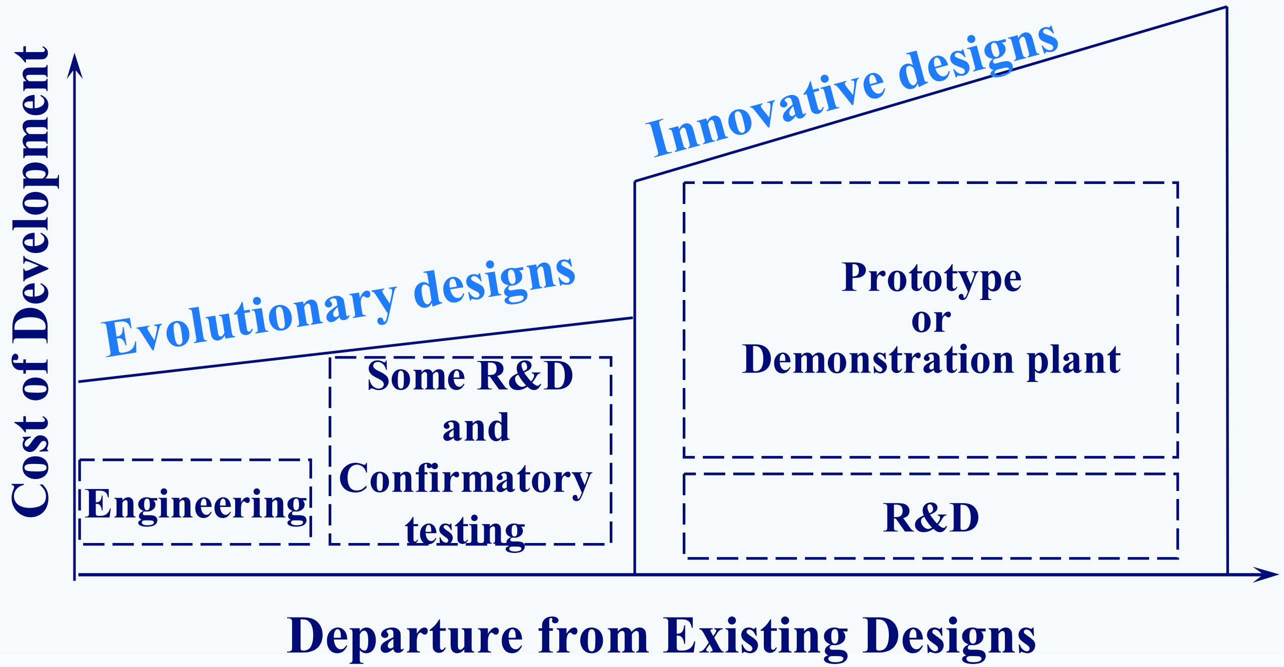
- proceeding for LWRs, HWRs, GCRs, FRs
- often guided by “Users Requirements Documents” (e.g. European Utility Requirements, …)
- incorporate
  - Experience from current plants
  - Technology advancements -- examples:
    - computer aided diagnostics - early indication of component or sensor degradation
    - improved corrosion resistant materials
    - design features for longer lifetime
    - extended use of information technology
    - better simulator training
    - advanced construction techniques
  - R&D results for new designs

Advanced Designs

(defined in IAEA-TECDOC-936)

- **Evolutionary designs** - achieve improvements over existing designs through small to moderate modifications

- **Innovative designs** - incorporate radical conceptual changes and may require a prototype or demonstration plant before commercialization



Safety approaches for new plants reflect stringent requirements

- reduction of the operator burden by improved man-machine interface and digital instrumentation and control;
- incorporation of highly reliable active safety systems or passive safety systems;
- a reduction in core damage frequency relative to current plants; and
- ensuring very low releases in the event of a severe accident to provide a technical basis to simplify emergency planning

THERE ARE SEVERAL EVOLUTIONARY WATER COOLED REACTOR DESIGNS (1/2)

- **Evolutionary LWRs**
  - **Japan: 1360 MWe ABWR (GE-Toshiba- Hitachi);**
    1700 MWe ABWR-II (Japanese utilities, GE-Hitachi-Toshiba);
    1540 MWe APWR (Japanese utilities, Mitsubishi and Westinghouse);
    1750 MWe APWR+ (Japanese utilities and Mitsubishi)
  - **USA: 600 MWe AP-600; 1100 MWe AP-1000; and 335 MWe IRIS (Westinghouse);**
    1350 MWe ABWR and 1330 MWe ESBWR (General Electric);
  - **France/Germany: 1545 MWe EPR and 1250 MWe SWR-1000 (Framatome ANP)**
  - **Rep. of Korea: 1000 MWe KSNP+ and 1400 MWe APR-1400 (KHNP and Korean Industry)**
  - **China: 1000 MWe CNP-1000 (CNNC) and 600 MWe AC-600 (NPIC)**
  - **Russia: WWER-1000 (V-392); WWER-1500; and WWER-640 (V-407) (Gidropress and Atomenergoprojekt)**

…. EVOLUTIONARY WATER COOLED REACTOR DESIGNS (2/2)

- **Evolutionary HWRs**
  - **Canada: AECL**
    - **Advanced CANDU reactor (light water cooled; heavy water moderated)**
  - **India: Nuclear Power Corporation of India, Ltd.**
    - **540 MWe HWR [evolution from current 220 MWe HWRs]**
      - **First unit: Tarapur-4 connected to grid (June 2005)**
    - **700 MWe HWR being developed**
- **Described in IAEA Reports:**
  - ***Status of Advanced LWR Designs: 2004* (TECDOC 1391)**
  - ***Heavy Water Reactors: Status and Projected Development (TRS Number 407, 2002)***

ABWR
[General Electric, Toshiba, Hitachi]

- Development started in 1970s
- strong application of “test before use”, even for features incorporated in BWRs outside of Japan
- Key developments: reactor internal pumps, improved control rod drives, re-inforced concrete containment, improved efficiency turbine, additional means of injecting water under accident conditions, advanced I&C and control room

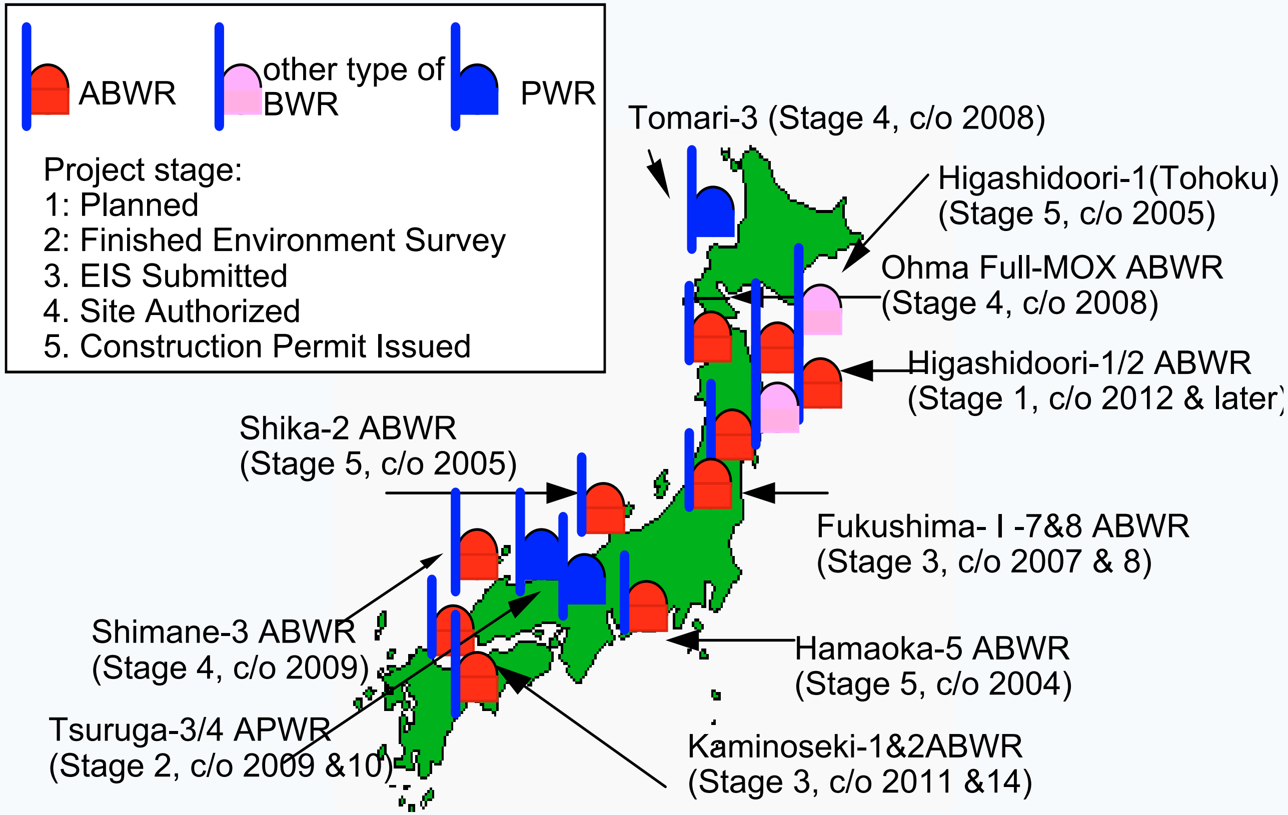
- U.S. version designed to meet EPRI URD received U.S.NRC Design Certification (1997)

ABWRs are becoming a standardized series in Japan
[Kashiwazaki-Kariwa -6 & 7 and Hamaoka-5 are in commercial operation; Shika-2 was connected to the grid in July]

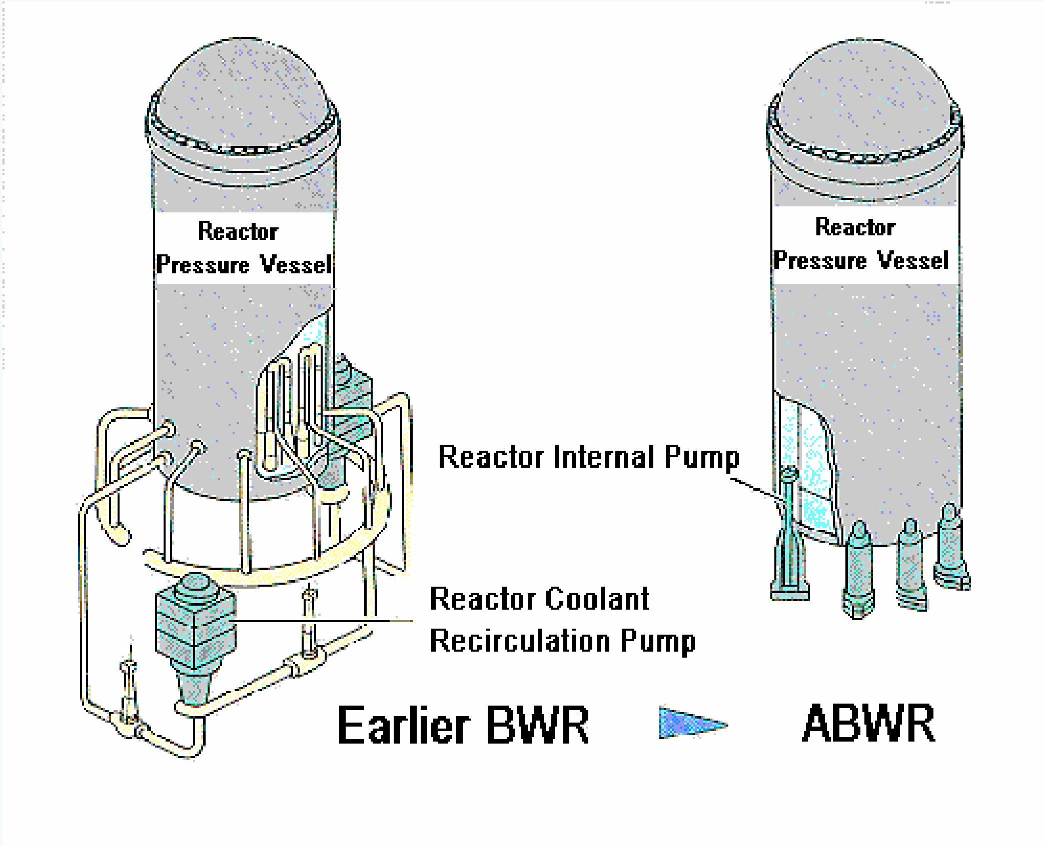
TEPCO's Kashiwazaki-Kariwa Units 6 and 7

More ABWR Projects are Underway

- **In Japan 8 more ABWR projects are in various stages**
- **In Taiwan, China 2 ABWRs are under construction**



The ABWR has less piping - a safety advancement



THE ABWR CONTROL ROOM IS MORE OPERATOR FRIENDLY

Older BWR

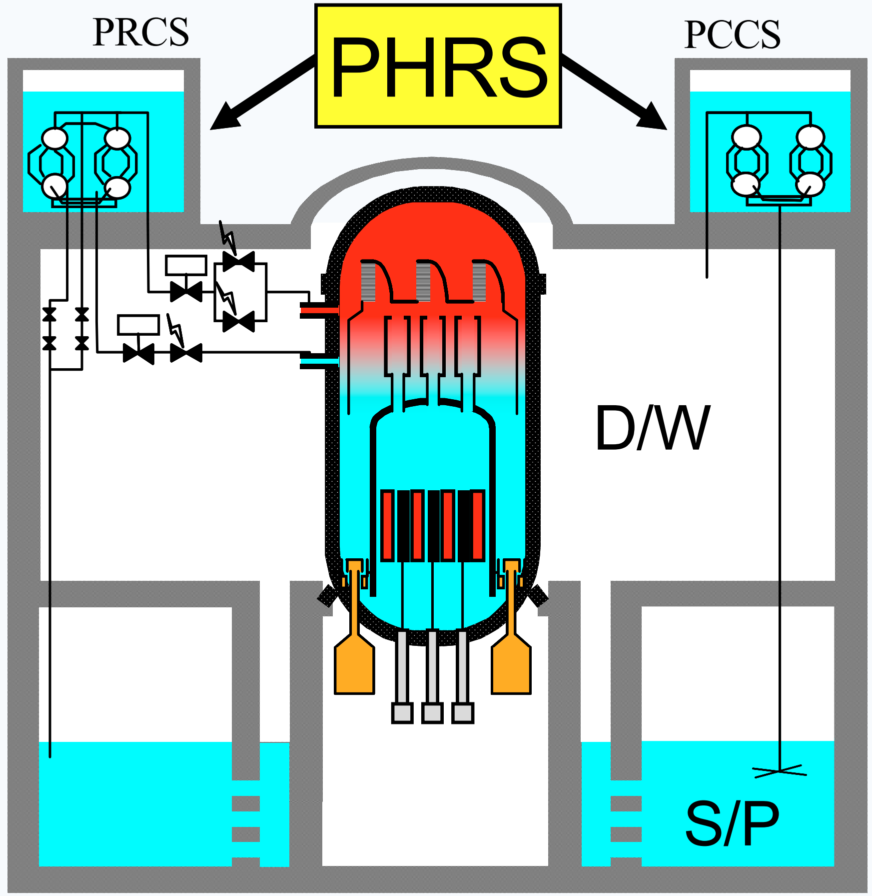
ABWR

The construction method shortened the construction time

ABWR-II

- TEPCO, 5 other utilities, GE, Hitachi and Toshiba began development in early 1990s
- 1700 MWe
- Goals (relative to standardized ABWR):
  - 30% capital cost reduction
  - reduced construction time
  - 20% power generation cost reduction
  - increased safety with active and passive systems
  - increased flexibility for future fuel cycles (high burn-up, MOX, high conversion)
- Commercial introduction – latter 2010s

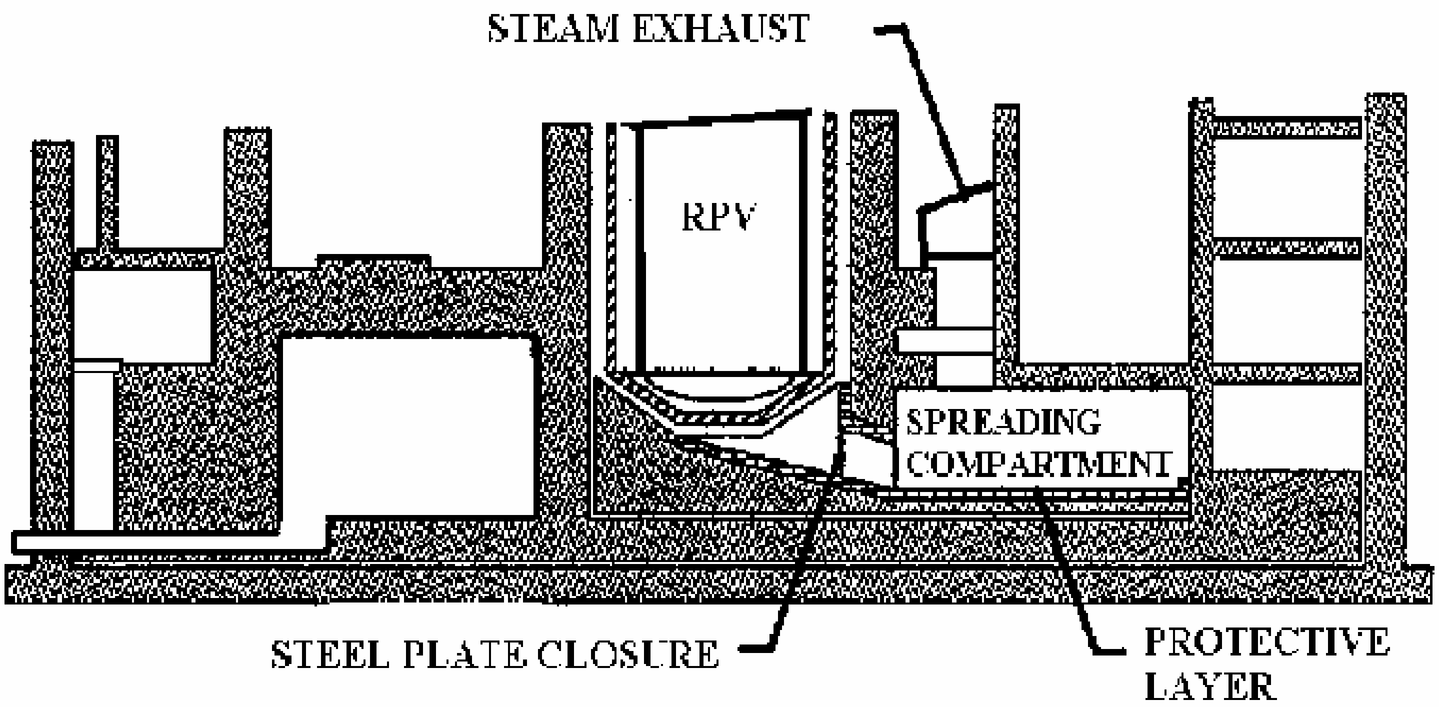
ABWR-II Has a Passive Core Heat Removal System and Containment Cooling System



Framatome ANP's EPR

- 1545 MWe PWR
- Incorporates experience from France's N4 series and Germany's Konvoi series
- Meets European Utility Requirements
- Relies primarily on well proven active safety systems
  - 4 independent 100% capacity safety injection trains
- Provision for cooling molten core
- Received design approval from French safety authority in October 2004

The EPR design has provision for spreading and cooling a molten core



In Europe, new nuclear plants are becoming a reality

site excavation for Olkiluoto-3 EPR in Finland;
construction start: 7.2005

Artist's concept of completed unit

TVO has stated the arguments that supported purchase of the new NPP

The new NPP

- covers partly the additional electricity demand and replaces old power plants
- enables, together with renewables, the fulfilment of the Kyoto commitments
- secures stable and predictable electricity price
- reduces the dependence on electricity import

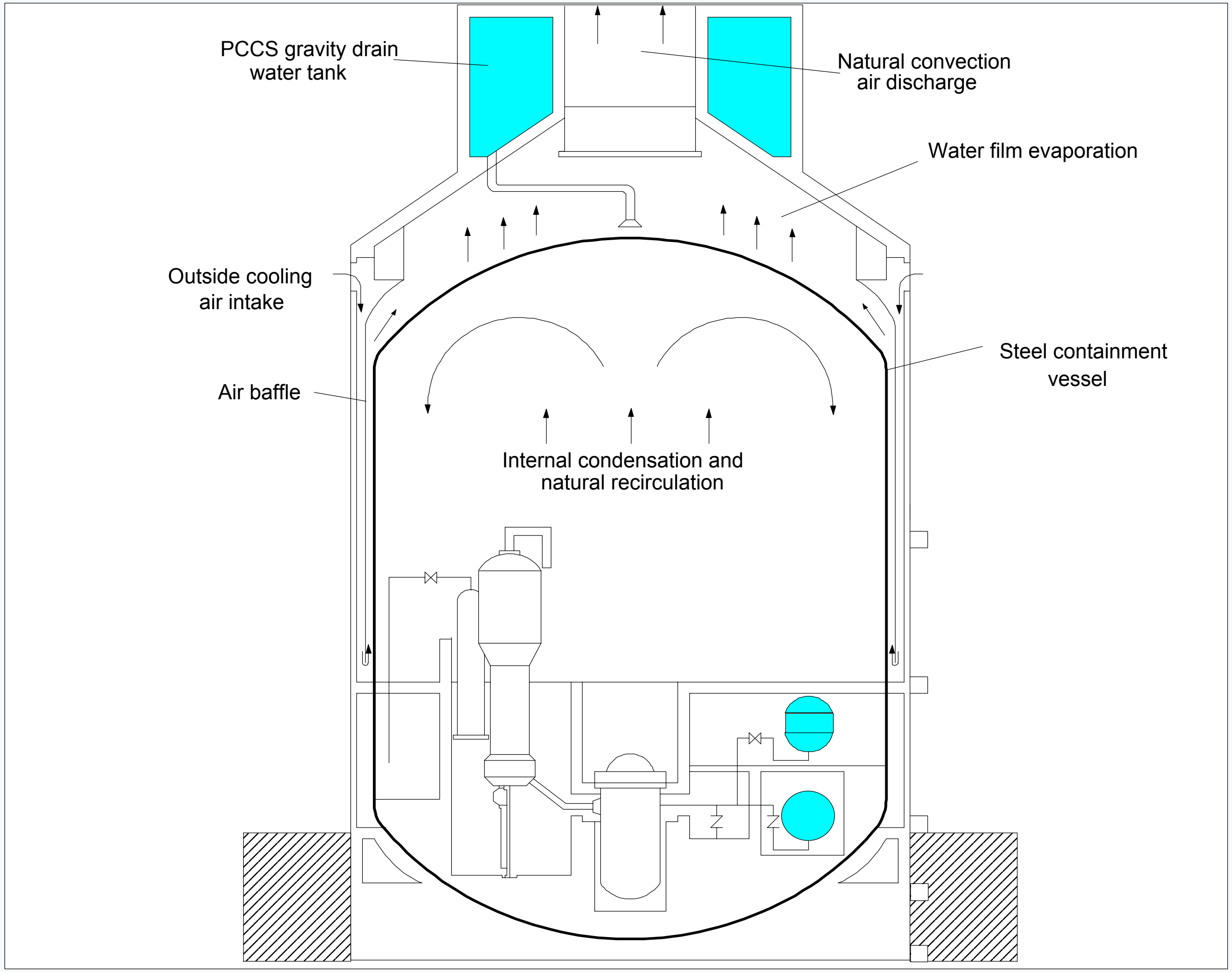
Rep. of Korea's APR-1400

- development started in 1992
- 1400 MWe - for economies of scale
- Incorporates experience with 1000 MWe KSNPs
- relies primarily on well proven active safety systems
- first units will be Shin-kori 3,4
- design Certified by Korean Regulatory Agency in 2002

Westinghouse's AP-600 and AP-1000

- **AP-600:**
  - **developed in U.S. DOE ALWR programme to meet EPRI URD**
  - **Certified by U.S.NRC (1999)**
  - **Key developments:**
    - **passive systems for depressurization, safety injection, residual heat removal, containment cooling**
    - **in-vessel retention**
    - **new systems verified by test**
- **AP-1000:**
  - **1090 MWe**
  - **pursues reduced capital costs by economy-of-scale**
  - **applies the AP-600 passive system technology**
  - **Received Final Design Approval from U.S.NRC (9/2004); anticipate Design Certification by 12/2005**

AP-1000 Passive Containment Cooling System



INNOVATIVE DESIGNS ARE BEING DEVELOPED IN SEVERAL COUNTRIES

- **gas, water and liquid metal cooled designs**
- **several are small and medium size reactors (SMRs)**
  - **APPROPRIATE FOR MODEST DEMAND GROWTH AND SMALLER ELECTRICITY GRIDS**
  - **EASIER TO FINANCE**
  - **SIMPLER DESIGN**
  - **PASSIVE SAFETY SYSTEMS**
  - **GOOD FIT FOR NON-ELECTRIC APPLICATIONS**

EXAMPLES OF INNOVATIVE WATER-COOLED REACTORS (1/2)

- Designs for conversion of Th^{232} or U^{238} (addressing sustainability goals)
  - India's Advanced HWR
    - fuel with ThO_2 to produce U^{233}
    - vertical pressure tube design
    - natural circulation
  - Japan's high conversion LWR concepts
    - for U^{238} conversion with Pu fuel (tight lattice; low moderation)
    - build on ABWR technology
      - RMWR (JAERI et.al.)
        Concepts range from 300 – 1300 MWe
      - RBWR (Hitachi) – 1300 MWe

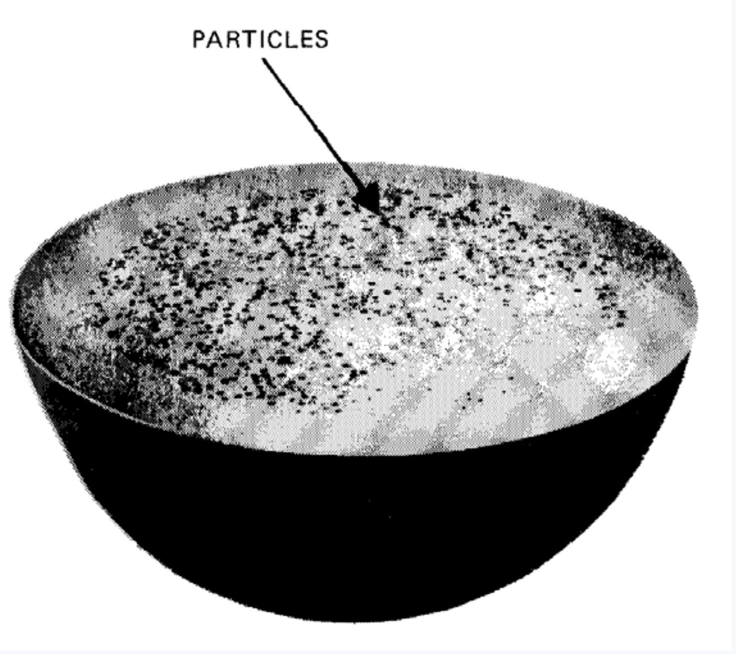
EXAMPLES OF INNOVATIVE WATER-COOLED REACTORS (2/2)

- **Some integral primary system PWRs**
  - **Core and steam generators are in same vessel – eliminates piping**
    - **CAREM (CNEA) Argentina**
    - **SMART (KAERI) Rep. of Korea [1/5th scale prototype; 2008]**
    - **IMR (Mitsubishi et.al) and PSRD (JAERI) Japan**
    - **VBER and KLT-40 (OKBM) Russia**
  - **Generally "small" - below 300 MWe**
  - **Often for electricity and seawater desalination**
- **Thermo-dynamically supercritical reactors**
  - **Operate above critical point (22.1 MPa; 374 C) – thermal efficiency of 44-45 % vs. 33-35% for current LWR**
  - **Selected for development by GIF**

SUMMARY OF GAS-COOLED REACTOR DEVELOPMENT

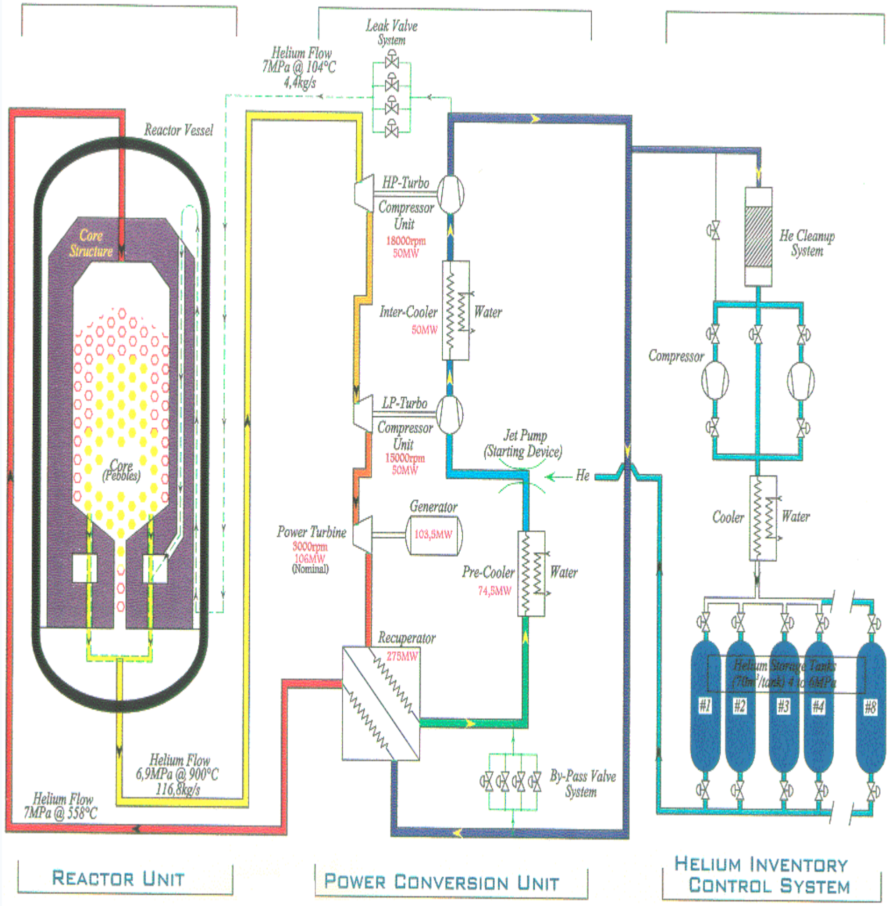
- 1565 reactor-years experience
- CO_2 cooled
  - 26 reactors (Magnox and AGRs) generate most of the UK's nuclear electricity
  - also operated in France, Japan, Italy and Spain
- Helium cooled
  - operated in UK (1), Germany (2) and the USA (2)
  - current test reactors:
    - 30 MW(th) HTTR (JAERI, Japan)
    - 10 MW(th) HTR-10 (Tsinghua University, China)
  - In South Africa a ~ 165 MWe plant is being designed
  - Design and development activities underway in China, Rep. of Korea, Russia, France, Japan and the USA

In helium cooled “pebble bed reactors”, fuel particles are contained in graphite pebbles (d= 6 cm)



- ~ 15000 coated fuel particles / pebble
- ~ 800,000 pebbles / core (~ 1/3 without fuel) for a 165 MWe reactor
- on-line re-fueling

The South African "Pebble Bed Modular Reactor" (PBMR) promises high thermal efficiency and safety



- being developed by Eskom, SA's Industrial Development Corporation, and BNFL
- a direct cycle helium turbine (η ~ 41- 43%)
- inherent features provide a high safety level

THERE IS CONSIDERABLE OPERATING EXPERIENCE WITH FAST REACTORS

- Test and experimental LMRs - operated in Russia, France, Germany, India, Japan, United Kingdom, USA, *leading to*
- Demonstration and prototype LMRs in France (250 MWe Phénix), UK (250 MWe PFR), Kazakhstan (750 MWt BN-350[1]), Russia (600 MWe BN-600), Japan (280 MWe MONJU); and the full scale 1200 MWe Superphénix plant in France (shut down in 1998)
- Development continues in France, Japan, India, Russia, China, the Republic of Korea, and the USA
- Various coolants are investigated (e.g. Na, Pb, Pb-Bi, He)

[1] 150 MWt for desalination; + 130 MWe

FAST REACTOR DEVELOPMENT IS CONTINUING

- **France:** **Phénix re-started in 2003 to study transmutation of long lived waste & use of Pu fuels; investigating He cooled FR in Gen-IV**
- **Japan:** **MONJU - shut down in 1995 due to sodium leak – restart planned 2008; feasibility study on commercial FR – Fuel Cycle systems; operating JOYO experimental LMR (recently upgraded to harder spectrum and higher flux); investigating Na cooled FR in Gen-IV**
- **India:** **40 MWth FBTR is in operation; constructing 500 MWe Prototype Fast Breeder Reactor**
- **Russia:** **operating BN-600; initial construction work on a BN-800 is ongoing (for start-up 2010); developing large Na, Pb, and Pb-Bi cooled systems**
- **China:** **constructing 25 MWe Experimental Fast Reactor [CEFR]; planning 600 MWe Prototype FR**
- **Rep. of Korea:** **designing 150 MWe Kalimer plant -- construction foreseen after 2010; investigating Na cooled FR in Gen-IV**
- **USA:** **Gen-IV Technology Roadmap includes FRs; Advanced Fuel Cycle Initiative is developing recycle technologies for FRs**

VARIOUS FUTURE ROLES FOR FAST REACTORS ARE FORESEEN

- fissile material (Pu, U^{233}) breeding
- Pu incineration
- transmutation of long-lived nuclear waste (fission products and actinides)
  - in reactors, or
  - in sub-critical cores driven by particle accelerators (Accelerator Driven Systems)

THE BN-600 LMR PROVIDES 25 R-Y EXPERIENCE FOR FUTURE COMMERCIAL PLANTS

BN-600, Beloyarsk, Russia

SOME COUNTRIES ARE CONSTRUCTING NEW LMRs

China's 25 MWe experimental FBR

Construction site - India's 500 MWe Prototype FBR

FUTURE NUCLEAR ENERGY SYSTEMS ARE BEING ADDRESSED THROUGH INTERNATIONAL COOPERATION (1/2)

The GENERATION IV International Forum (GIF)

- ✓ Started - Jan 2000; USA, UK, Switzerland, Rep. of Korea, South Africa, Japan, France, Canada, Brazil, Argentina, European Union
- ✓ Development is guided goals in 4 areas
  - Sustainability (resources; waste)
  - Safety and reliability (excellence; core damage; emergency response)
  - Economics (life cycle cost, risk to capital)
  - Proliferation resistance and physical protection (material diversion and protection against terrorism)
- ✓ Selected 6 systems for development – to be ready by 2030:
  - Gas-cooled Fast Reactor
  - Pb or Pb-Bi Cooled LMR
  - Sodium Cooled LMR
  - Super-critical Water-cooled Reactor
  - Very High Temperature Reactor
  - Molten Salt Reactor

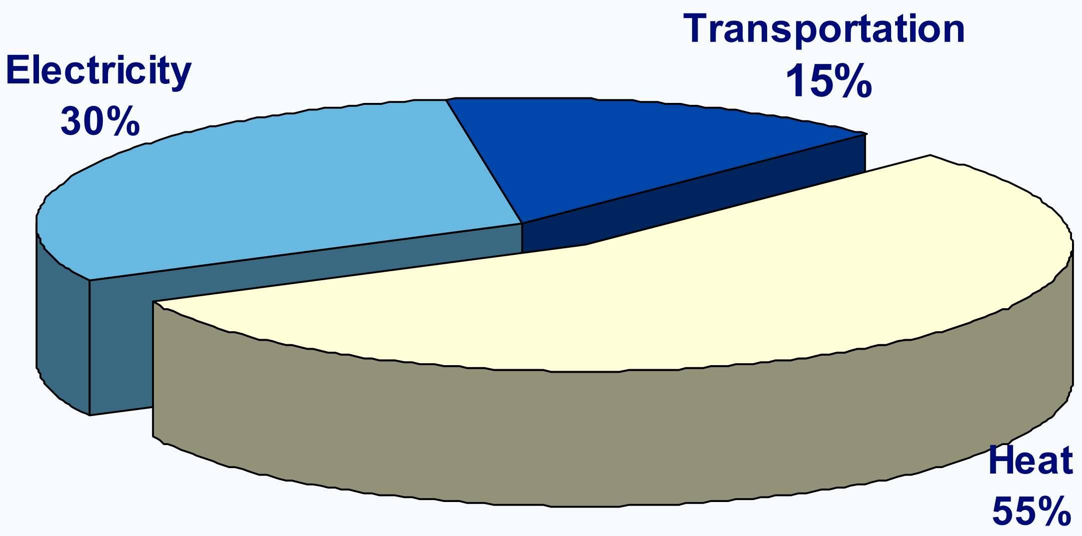
FUTURE NUCLEAR ENERGY SYSTEMS ARE BEING ADDRESSED THROUGH INTERNATIONAL COOPERATION (2/2)

IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

- Started in 2000 in response to IAEA General Conference Resolution
- 22 Member States plus the European Commission
- Goals
  - To help ensure that nuclear energy is available to contribute in fulfilling 21st century energy needs in a sustainable manner;
  - To bring together technology holders and users to consider jointly the actions required to achieve desired innovations in nuclear reactors and fuel cycles
- Developed a methodology for Member State assessment of innovative reactors and fuel cycles (in the areas of economics, safety, environment, waste management, proliferation resistance and infrastructure)
- Methodology currently being applied by several Member States to examine innovative systems

NON-ELECTRIC APPLICATIONS OF NUCLEAR ENERGY

The potential for non-electric applications of nuclear energy is large

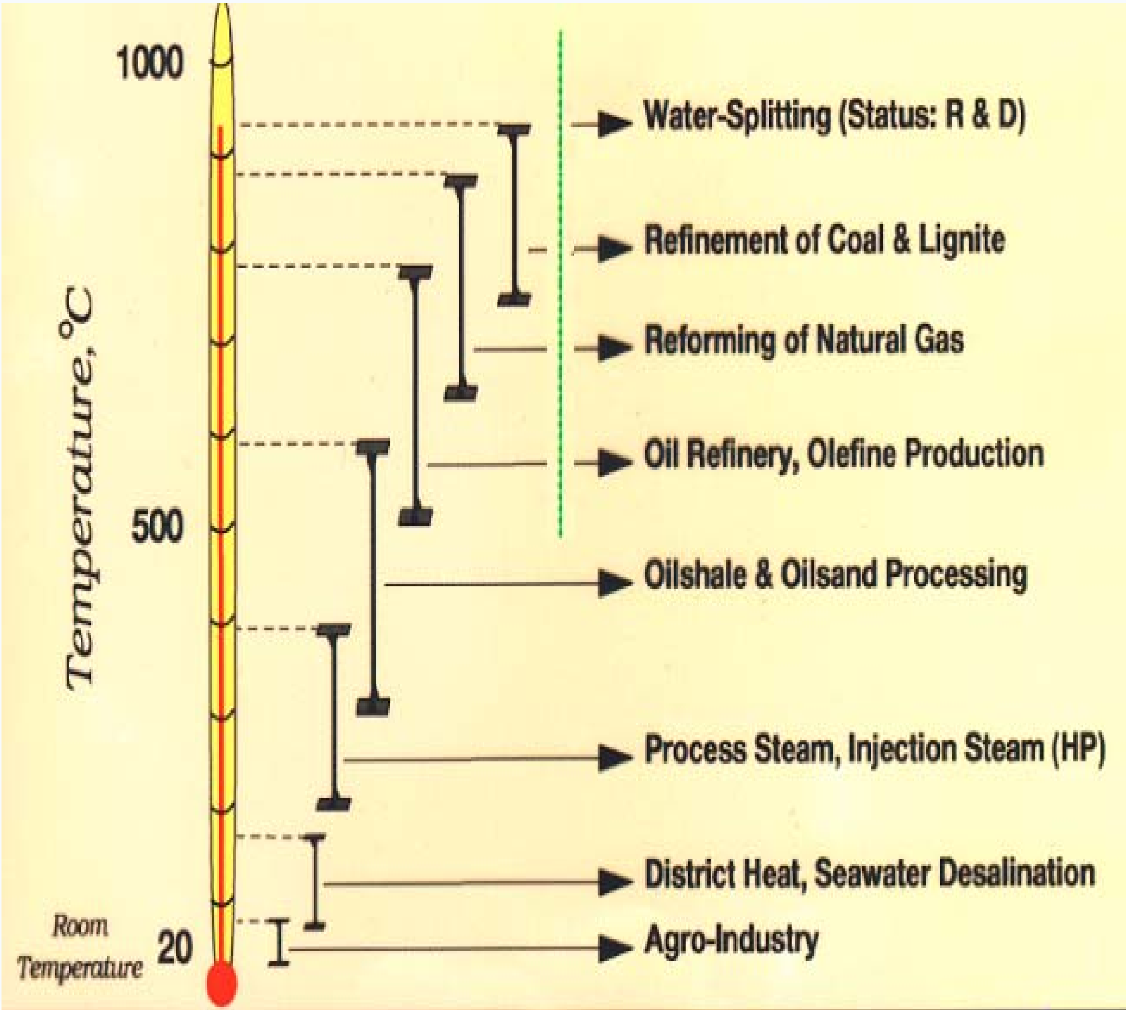


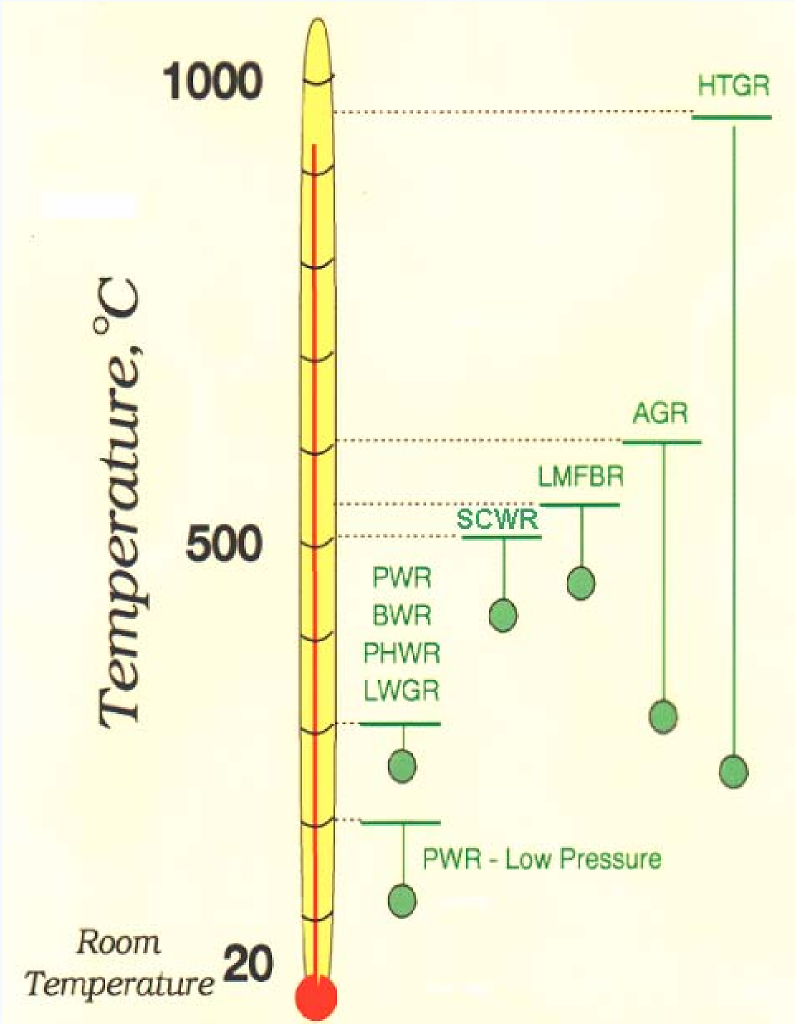
Energy consumption by application

EXAMPLES OF APPLICATIONS OF NUCLEAR ENERGY

- Sea-water desalination
- District heating
- Heat for industrial processes
- Hydrogen production (e.g. for transportation)
  - At “fuelling stations” by electrolysis of water using nuclear electricity
  - At central nuclear stations by
    - steam reforming of methane
    - high temperature electrolysis
    - thermo-chemical processes
    - hybrid electro-chemical / thermo-chemical processes

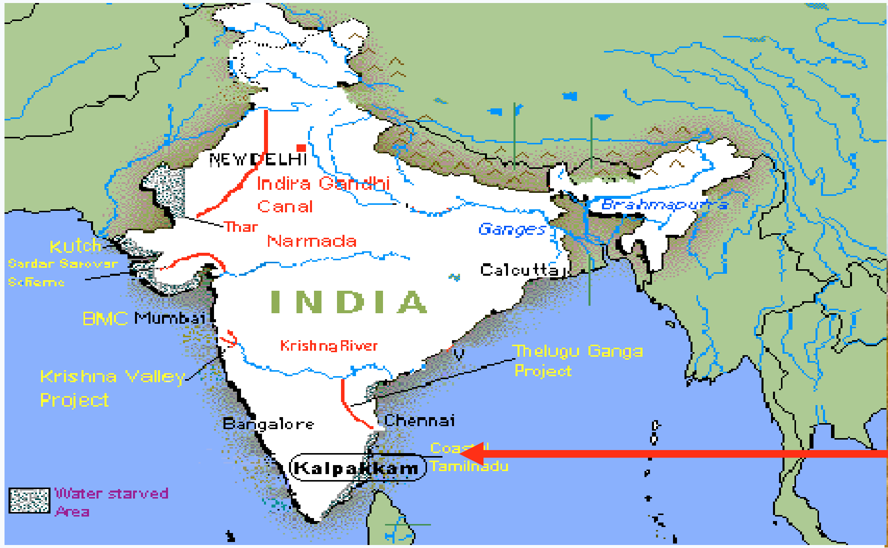
NUCLEAR PLANTS CAN PROVIDE THE HEAT REQUIRED FOR MANY PROCESSES



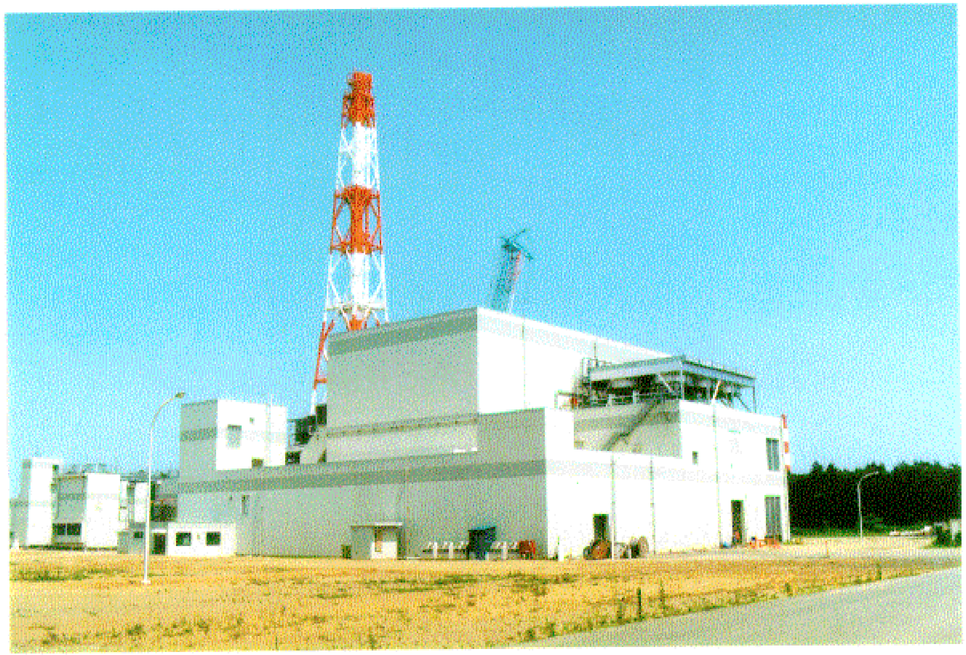


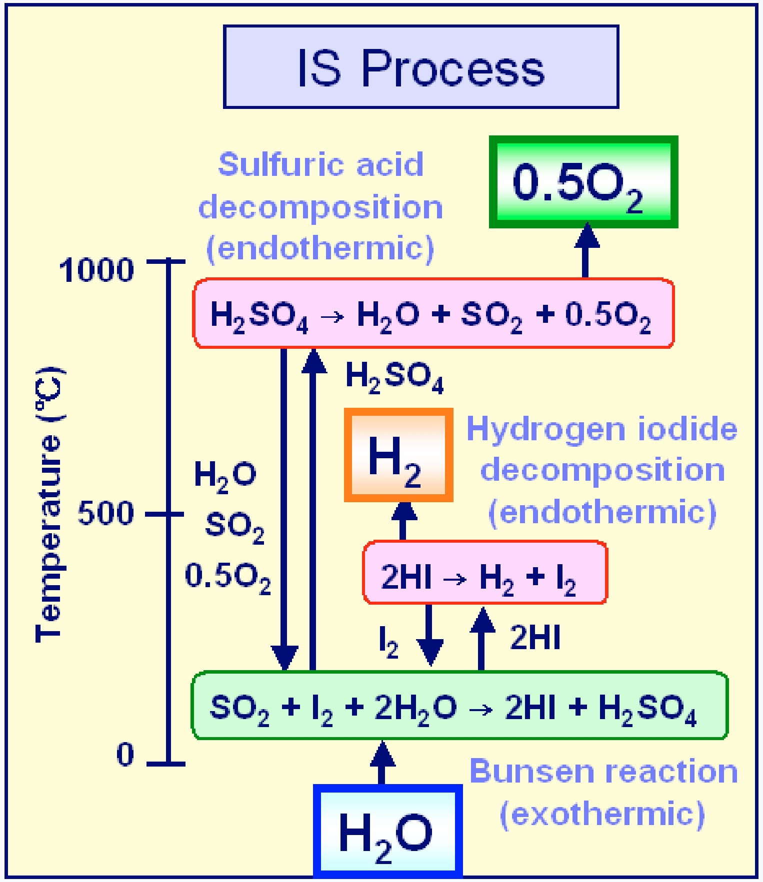
Desalination of seawater with nuclear energy

- **Japan: Several NPPs produce both electricity and desalinated water for plant use**
- **Kazakhstan: BN-350 produced electricity + 80,000 m^3 desalinated water / day) 1973 - 1999**
- **Pakistan: Has designed a facility (4800 m^3 / day) for the KANUPP plant**
- **India: An experimental facility is operating and a larger facility (6300 m^3 / day) is in commissioning at Kalpakkam**

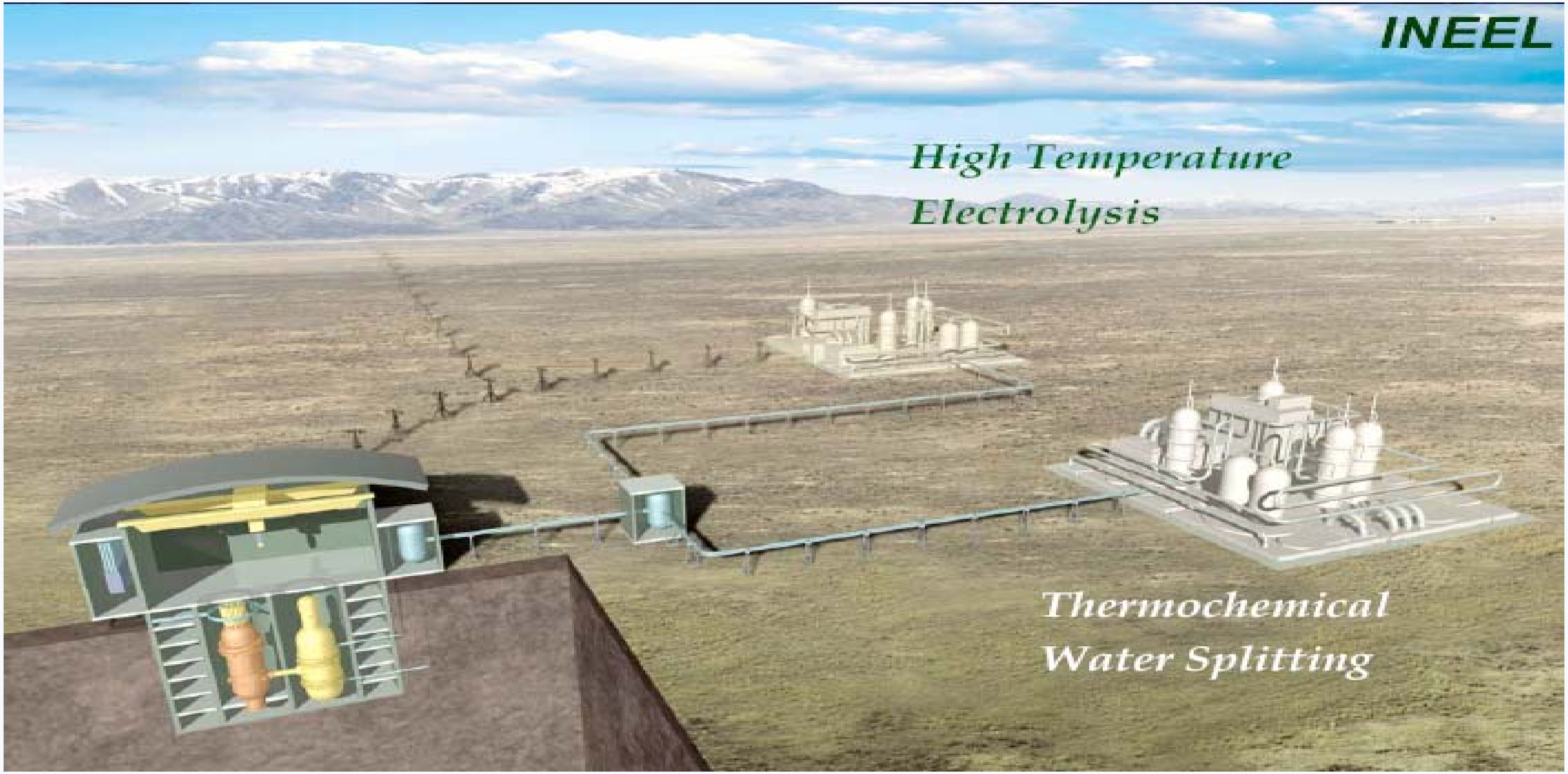


JAERI's HTTR can be used to demonstrate hydrogen production





A “Next Generation Nuclear Plant” for production of H_2 and electricity is planned in the USA



IAEA ACTIVITIES IN NUCLEAR POWER

With regard to nuclear power, IAEA's STATUTE authorizes the agency, *inter alia*, to

- "encourage and assist research on, and development and practical application of, atomic energy for peaceful uses throughout the world"; and
- "foster the exchange of scientific and technical information on peaceful uses of atomic energy"
- "encourage the exchange and training of scientists and experts in the field of peaceful uses of atomic energy"

IAEA works toward Nuclear Power's Renaissance for ensuring clean and sustainable energy

Objective - Foster the efficient and safe use of Nuclear Power

Actions:

- ✓ Maintain balanced and objective information
- ✓ Foster collaboration in advanced NPP development
- ✓ Catalyse innovation
- ✓ Improve training and human performance
- ✓ Contribute to NPP management improvements
- ✓ Assist in infrastructure establishment
- ✓ …many others….

Expected Results

- ✓ Efficient operation of current plants
- ✓ Advanced NPPs with very competitive economics and high level of safety
- ✓ Clean and sustainable energy source
- ✓ Improved living standards in developing countries
- ✓ …others...

IAEA's Nuclear Power Division fosters international collaboration for current and advanced NPPs

See: www.iaea.org

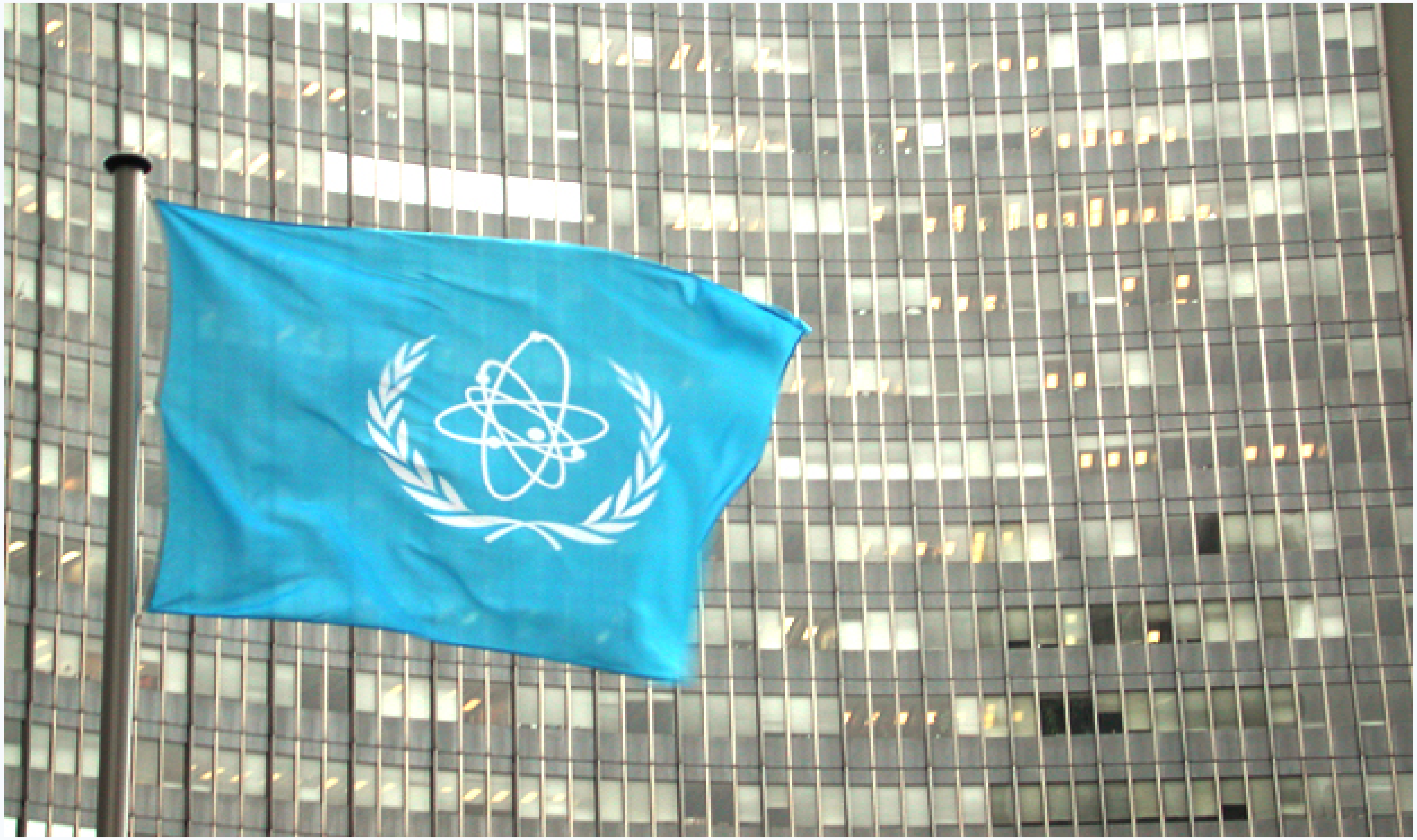
Science and Technology / Nuclear Energy Programme

- Improving NPP Operating Performance
- NPP Quality Assurance and Quality Management Principles
- Training for Excellence in Performance of NPP Personal
- Strengthening National and Regional Nuclear Power Infrastructures
- NPP Life Management Including Databases
- Modern NPP Control and Instrumentation

- Requirements and Prospects for Small and Medium Size Reactors
- High-Temperature Gas-Cooled Reactor Technology
- Advanced Technologies for LWRs and HWRs
- Advances in Fast Reactors and Accelerator Driven Systems
- Nuclear Desalination
- User Friendly Education with Nuclear Reactor Simulators
- Fast Reactor Data Retrieval and Knowledge Preservation

- International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

IAEA



…atoms for peace