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WORKSHOP ON
NUCLEAR POWER PLANT SIMULATION

29 October - 9 November 2001

GLOBAL NUCLEAR POWER: CURRENT STATUS AND OVERVIEW OF NEW DEVELOPMENTS

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GLOBAL NUCLEAR POWER: CURRENT STATUS AND OVERVIEW OF NEW DEVELOPMENTS

November 2001
International Centre for Theoretical Physics
Trieste, Italy

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Vienna, Austria

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Outline

- The role of nuclear power today
- overview of development of new, advanced plants
- factors which influence decisions to build new plants
- what is needed for the future

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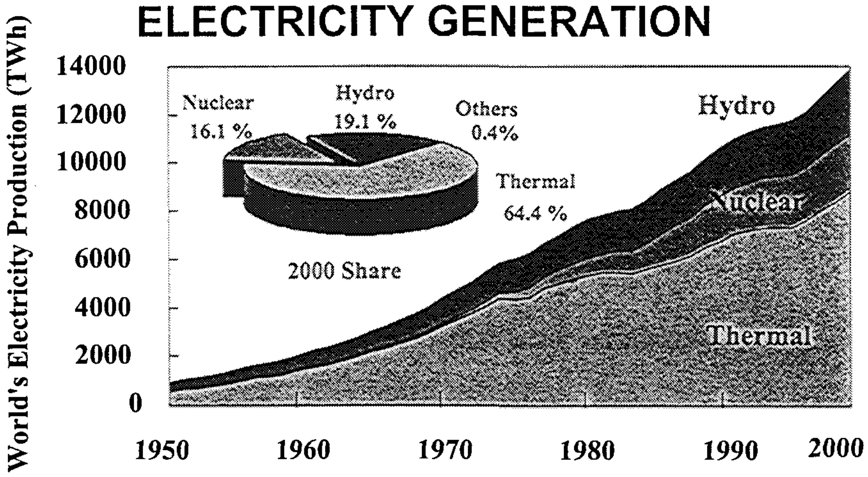
NUCLEAR CONTRIBUTION TO ELECTRICITY GENERATION



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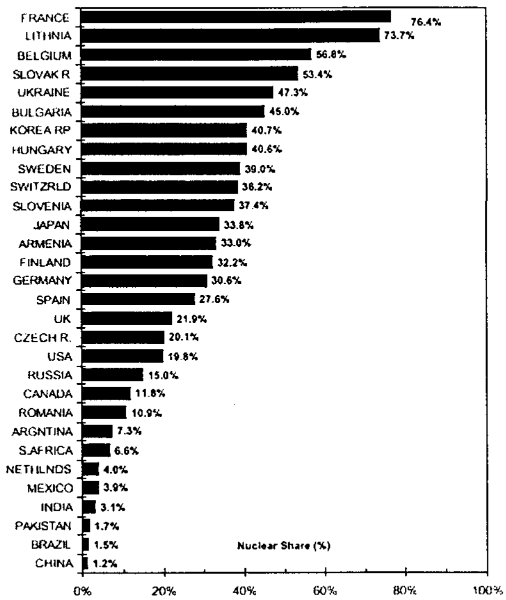

Note: The nuclear share of electricity supplied in Taiwan, China was 23.6% of the total.

NUCLEAR PLANTS GENERATE ELECTRICITY IN MANY COUNTRIES

Nuclear Share (%) of Electricity Generation in 2000

Global Nuclear Share:
~ 16%, 2450 TWh

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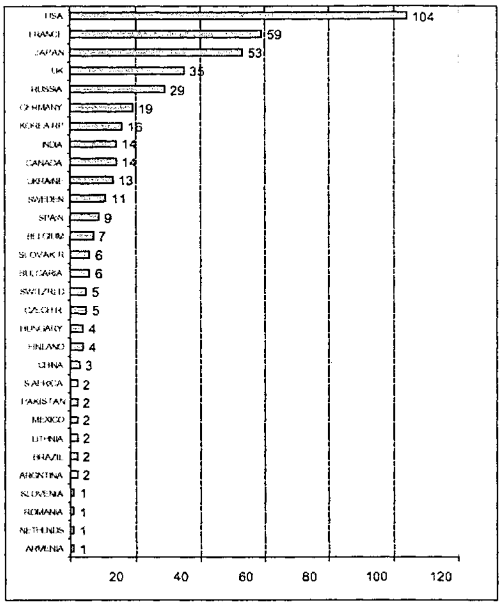

Note: Six reactors are in operation in Taiwan, China

MANY REACTORS ARE OPERATING IN THE WORLD

Number of Nuclear Reactors in Operation and under Construction in 2000

In Operation:	**438**
Total Capacity:	**351 GWe**
Under Construction:	**33**
Total Capacity:	**28.6 GWe**
Operating Experience:	**9819 RYs**
Number of Countries:	**31**
(Including Taiwan, China)	

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Six new plants were connected to the grid in 2000

- **Angra-2 (1309 MWe PWR in Brazil)**
- **Temelin-1 (981 MWe WWER in the Czech Rep.)**
- **Kaiga-1 and Rajasthan-3 & 4 (220 MWe HWRs in India)**
- **Chasnupp-1 (325 MWe PWR in Pakistan)**

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There were 5 construction starts in 2000

- Tianwan-2 (1060 MWe WWER in China)
- Tarapur-3 and –4 (500 MWe HWRs in India)
- Higashi Dori-1 (1100 MWe BWR in Japan)
- Hamaoka-5 (1380 MWe ABWR in Japan)

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The forecast is that nuclear power will probably grow, but its share of global electricity may fall

- some countries see no near term need for new nuclear capacity
- others see advantages in nuclear power expansion for security of energy supply
- some countries plan to increase their nuclear capacity (e.g. China, India, Japan, Republic of Korea)
- IAEA predicts probable growth (from 2000 value of 2450 TWh):
  - 2560 - 2910 TWh by 2010
  - 2110 - 3660 TWh by 2020
- however, IAEA predicts that the percentage of global electricity produced by nuclear power will decrease:
  - 14 % by 2010
  - 9.5-12 % by 2020

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To assure that nuclear power remains a viable option, considerable design and development is underway worldwide

- new designs are being developed for all major lines (LWRs, HWRs, HTGRs, LMRs)
- common goals
  - high availability
  - competitive economics
  - compliance with stringent safety objectives
- expenditures are more than US$ 2B / year - reflecting confidence in the future of nuclear power

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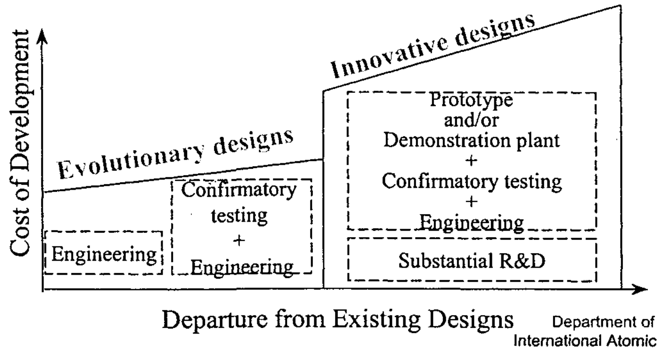
Advanced Designs

- Evolutionary designs **which aim to achieve improvements over existing designs through small to moderate modifications**
- Innovative designs **which incorporate radical conceptual changes in design approaches or system configuration and may require a prototype or demonstration plant as part of the development programme.**



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Safety objectives for nuclear plants have become more stringent

- INSAG-3: *Basic Safety Principles for Nuclear Power Plants*, IAEA, 1988
  - target for existing plants - likelihood of severe core damage <10^{-4} / plant year
  - target for future plants - likelihood of severe core damage < 10^{-5} / plant year, and severe accident management and mitigation measures should reduce by a factor of at least 10 the probability of a large off-site release requiring short term off-site response
- INSAG-5: *The Safety of Nuclear Power*, IAEA, 1992
  - confirmed this more stringent safety target for evolutionary LWRs and HWRs
- INSAG-3 (Rev 1), 1999
  - added an objective for future plants for the practical elimination of accident sequences that could lead to large early radioactive releases, with severe accidents that could imply late containment failure being considered in the design process (with best estimate analyses) so that their consequences would necessitate only protective measures limited in area and in time.

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Safety objectives for nuclear plants have become more stringent

INSAG-10: *Defence in Depth in Nuclear Safety*, IAEA (1996)

- notes complementary means for advances in safety
  - further reduction in CDF - "as already indicated in INSAG-3,..figures below 10^{-5} ought to be achievable"
  - strengthening containment - noting that CDF below 10^{-5} ought to be achievable, but figures much smaller than that are difficult to validate with current methods and experience - so mitigation is essential
    - gives examples: protection of containment function such as ability to withstand H_2 deflagration or improved protection of basemat to prevent melt-through
- states the need to demonstrate that for accidents without core melt there will be no necessity for protective measures (evacuation or sheltering) for people living in the vicinity of the plant, and for severe accidents that are considered in the design, that only protective measures that are very limited in area and time would be needed (including restrictions in food consumption)

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SOME EVOLUTIONARY WATER COOLED REACTORS ARE STARTING OPERATION OR ARE UNDER CONSTRUCTION, OTHERS HAVE BEEN CERTIFIED BY REGULATORY AUTHORITIES, AND SOME ARE UNDER DEVELOPMENT...

- **Evolutionary LWRs**
  - **USA/Japan: 1360 MWe** ABWR **(GE-Hitachi-Toshiba) and 1700 MWe** ABWR-II **(Japanese utilities, GE-Hitachi-Toshiba); and 1530 MWe** APWR **(Mitsubishi-Westinghouse)**
  - **USA: 600 MWe** AP-600 **and 1350 MWe** System 80+ **(Westinghouse) and**
    1350 MWe ABWR **(General Electric);**
    also: 1000 MWe AP-1000 **(Westinghouse) and 1380 MWe** ESBWR
  - **France/Germany: 1545 MWe** EPR **and 1000 MWe** SWR-1000 **(Framatome ANP)**
  - **Rep. of Korea: 1000 MWe** KSNP+ **and 1400 MWe** APR-1400 **(KEPCO and Korean Industry)**
  - **Sweden: 1500 MWe** BWR90+ **(Westinghouse Atom)**
  - **Russia:** WWER-1000 **(V-392);** WWER-1500; **and** WWER-640 **(V-407) (Gidropress and Atomenergoprojekt)**
  - **China: 1000 MWe** CNP-1000 **(CNNC) and 600 MWe** AC-600 **(NPIC)**

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...SOME EVOLUTIONARY WATER COOLED REACTORS ARE STARTING OPERATION OR ARE UNDER CONSTRUCTION, OTHERS HAVE BEEN CERTIFIED BY REGULATORY AUTHORITIES, AND SOME ARE UNDER DEVELOPMENT

- **Evolutionary HWRs**
  - **Canada: AECL's evolutionary CANDU programme**
    - **700 MWe** CANDU-6
    - **935 MWe** CANDU-9
    - **400-650 MWe** Next Generation CANDU
  - **India: Nuclear Power Corporation of India, Ltd.**
    - **500 MWe** HWR

Designs are described in recent IAEA Status reports:
- **TECDOC-968** ***Status of Advanced LWR Designs*** **(IAEA, September 1997)**
- **TECDOC-984** ***Advances in HWR Technology*** **(IAEA, November, 1997)**

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Overview of Framatome ANP's European Pressurized Water Reactor (EPR)

- 1545 MWe design incorporating experience from latest series of PWRs operating in France (the N4 series) and Germany (the Konvoi series)
- designed to satisfy European Utility Requirements, and common safety requirements of German/French authorities
- basic design completed - end 1997
- relies primarily on well proven active systems to assure a high degree of safety

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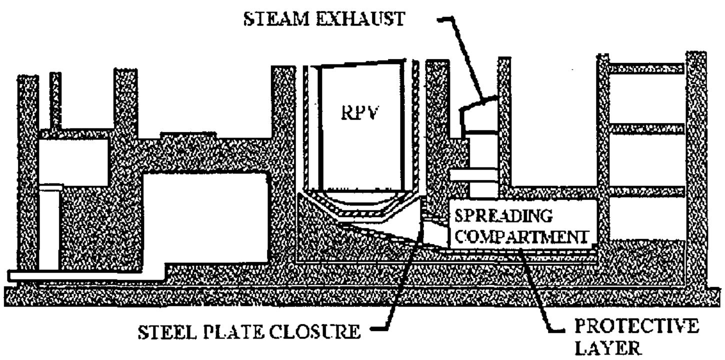
The EPR design has provision for spreading and cooling a molten core



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Overview of Framatome ANP's SWR-1000

- 1000 MWe BWR development activity with goal of using passive systems to further reduce SA probability --and achieve competitive cost
- designed to meet EUR, and safety requirements of the German / French authorities
- key features:
  - low power density
  - large water inventories
  - responds to accidents via passive systems - e.g.passive emergency condenser for core heat removal, passive containment condenser
- key passive systems tested at Juelich, PSI and Framatome ANP Germany
- review for compliance with EUR scheduled for completion in 2001
- expect to be commercially offered in 2002, upon completion of the Basic Design

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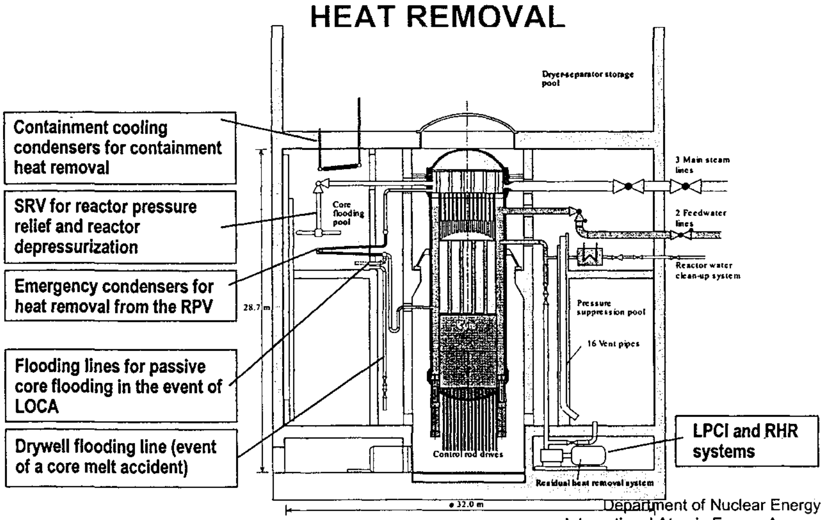
THE SWR-1000 HAS SEVERAL PASSIVE SYSTEMS FOR HEAT REMOVAL



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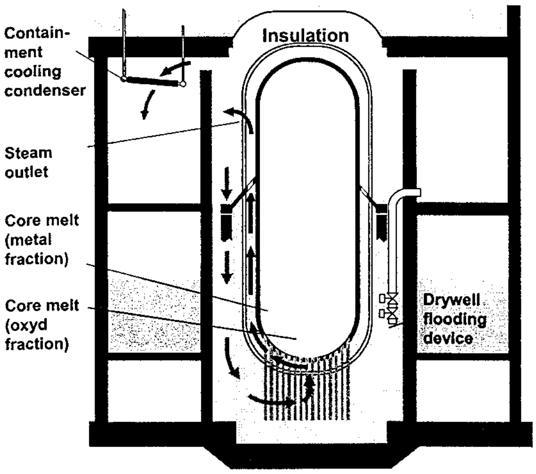
If the core were to melt, the SWR-1000 is designed to retain it inside the reactor pressure vessel



- External cooling of Reactor Pressure Vessel (RPV)
- Inerted containment
- Containment design pressure 7.5 bar
- Passive heat removal from containment

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Overview of Toshiba, Hitachi and General Electric ABWR

- Development started in 1970s (by design organizations and utilities, with support from government of Japan)
- strong application of "test before use", even if features had been 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
- 2 ABWRs (1356 MWe) are operating: Kashiwazaki-Kariwa Unit 6 (construction: 11/92-12/96); Unit 7 (construction: 7/93-7/97)
- 2 ABWRs are under construction (Hamaoka-5 and Shika-2) in Japan, and 8 more are planned
- U.S. version was designed to meet EPRI URD and received U.S.NRC Design Certification (5/97)
- 2 units under construction in Taiwan, China

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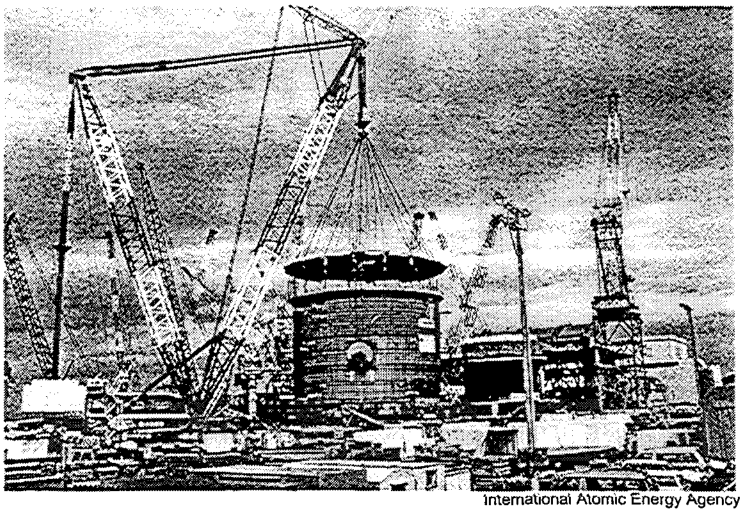
Large Block Construction Method: Installation of Containment Vessel Liner Module (at K-7 Plant, Japan)



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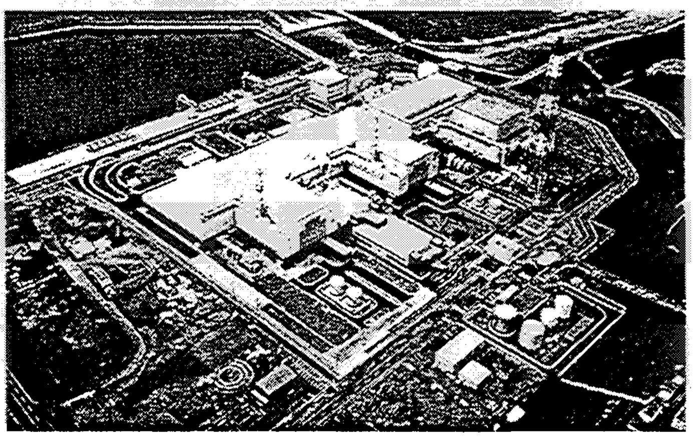
The First Two ABWRs in the World Are Operating in Japan



TEPCO's Kashiwazaki-Kariwa Units 6 and 7

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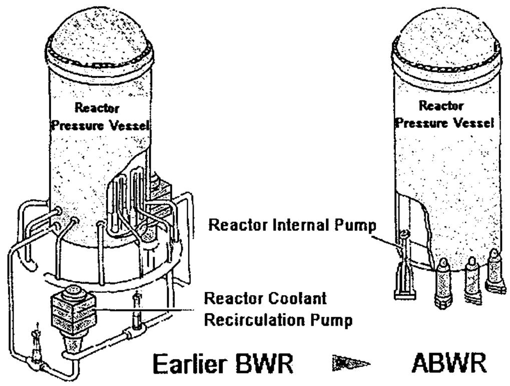
The ABWR reactor coolant re-circulation pumping system is simpler



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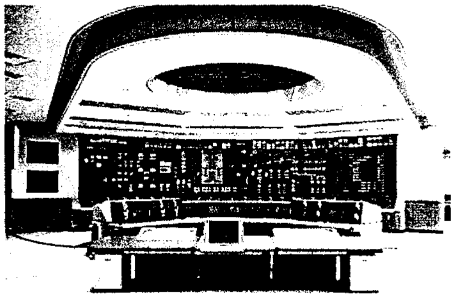
The ABWR control room incorporates advances in I&C and man-machine interface



Earlier BWR ABWR

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Overview of APR-1400 (Rep. of Korea)

- advanced PWR (formerly called Korean Next Generation Reactor) – development started in 1992
- based on 1000 MWe KSNP experience [the first KSNPs are Ulchin 3 and 4 which started operation in 1998]
- 1400 MWe selected to capture economies of scale
- included in Korean Government's "fourth electricity supply development plan" for electricity supply for completion by 2010
- relies primarily on well proven active systems for safety
- In March 2001, KEPCO started the Shin-kori 3,4 project for the APR1400

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Overview of Westinghouse AP-600 and AP-1000

- AP-600:
  - developed under U.S. ALWR programme and designed to meet EPRI URD
  - received Design Certification (12/99)
  - key developments:
    - passive core cooling system (depressurization, safety injection, residual heat removal); passive containment cooling system
    - in-vessel retention
    - passive systems well verified by test
- AP-1000
  - 1090 MWe plant being designed in co-operation with Mitsubishi
  - the goal is reduction of capital costs through economy-of-scale
  - applying the passive safety technology developed for the AP-600
  - design being prepared for certification application (hope for certification by end of 2004)
  - design of European version (EP-1000) to meet EUR has been underway since 1994 by a group of European utilities, Westinghouse, Ansaldo and Fiat
    - goals: 60 year life, 90% availability, passive systems to back-up active systems, in-vessel retention, CDF below 10^{-5}

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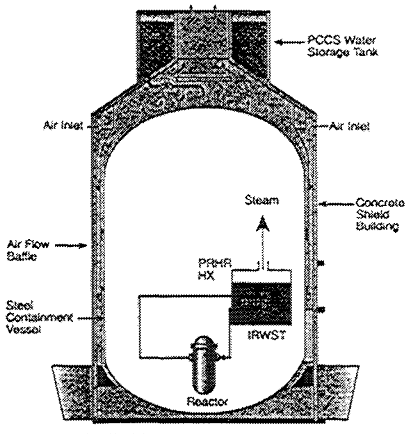
AP-600 PLANT HEAT SINK



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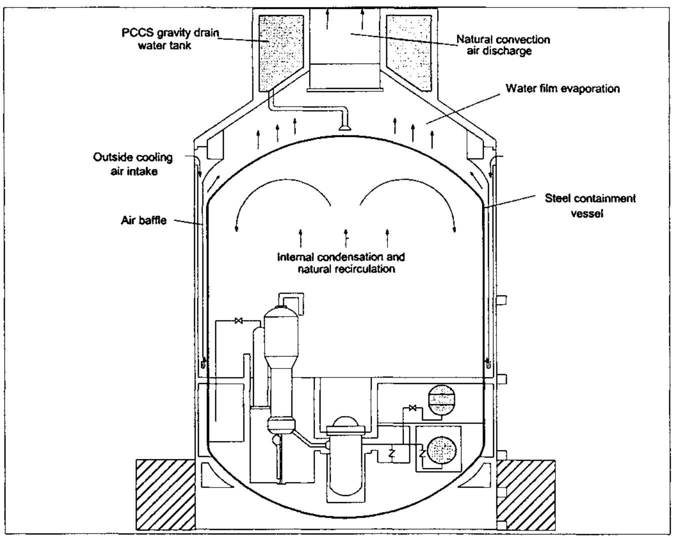

AP-600 Passive Containment Cooling System

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Overview of Atomenergoproject / Gidropress WWER-640

- designed to meet Russian regulatory req'ts & IAEA safety guides
- relies on passive safety systems
- key features:
  - low power density, large water inventories
  - passive ECCS (accumulator, gravity driven water tank), and RHR (via natural convection in secondary circuit to HX in large water tank)
  - in-vessel retention for SA
  - double containment (inner:steel, outer: concrete)
- construction licenses have been issued for WWER-640 units at 2 sites

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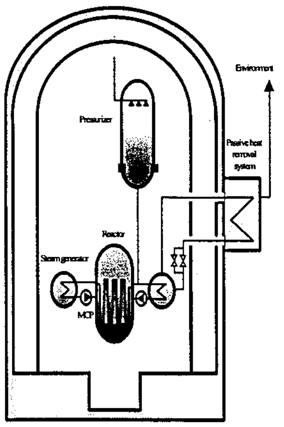
WWER-640 - The operation of passive heat removal systems under non-LOCA conditions



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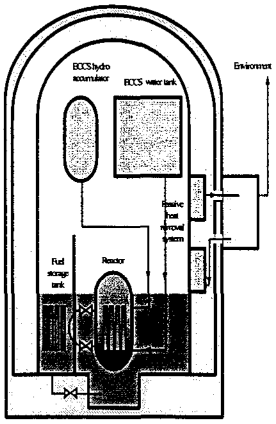
WWER-640 - the operation of passive heat removal systems under LOCA conditions



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Overview of AECL CANDU-9 and -6E

- **CANDU-9: 935 MWe PHWR; CANDU-6E: 700 MWe - evolutionary version of operating CANDU-6s**
- **key improvements (both):**
  - **improved pressure tube materials**
  - **advanced I&C and control room design**
  - **passive systems to backup active systems: passive residual heat removal and containment cooling - using large water tank at high elevation**
- **CANDU-9 has received positive licensing review by AECB**

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Overview of AECL CANDU-NG

- 400 – 1200 MWe [650 MWe reference size]
- Currently in concept definition phase
- More compact core design
- Light water coolant, heavy water moderated
- ~1.6 % SEU; 20,000 MWd / t burnup
- Use of SEU with thicker pressure tubes allows higher pressure and temperature – higher thermal efficiency
- Advanced fuel element design (“CANFLEX”)
- Plan CNSC licensability review to begin in 2003

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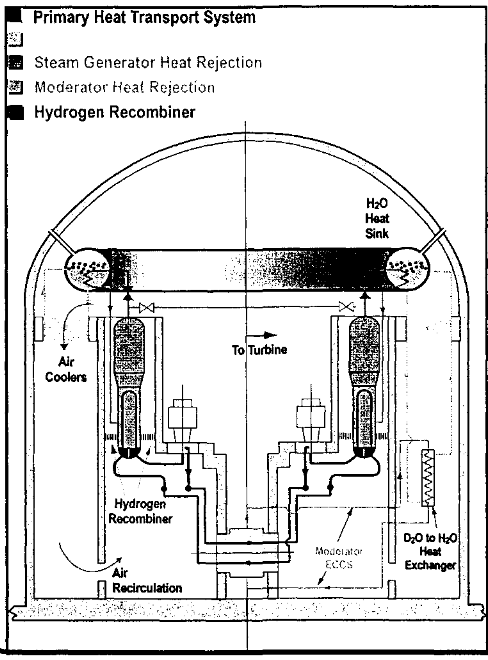

Next Generation CANDU plants will utilize passive safety systems

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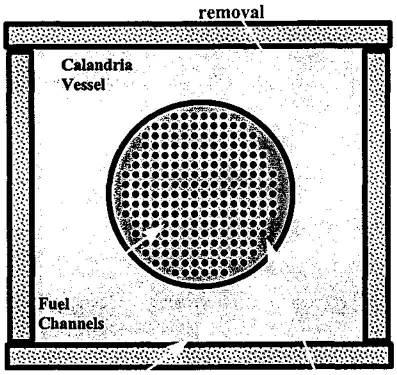

CANDU severe accident mitigation features

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Overview of Bhabha Atomic Research Centre AHWR

- 235 MWe, vertical pressure tube reactor design :
  - heavy water moderator
  - boiling light water coolant - natural circulation in normal operation
- Th fuel cycle (PuO_2-ThO_2 and ThO_2-$U^{233}O_2$ in different fuel pins)
- passive safety systems:
  - core heat removal
  - ECCS injection
  - containment cooling

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SUMMARY OF GAS COOLED REACTOR DEVELOPMENT

- experience base is 1360 reactor years
- 34 gas cooled reactors (Magnox and AGRs, cooled by CO_2) are operating in UK generating most of its nuclear electricity; CO_2 cooled reactors have also operated in France, Japan, Italy and Spain
- HTGRs (cooled by helium) have operated in UK (1), Germany (2) and the USA (2)
- The 30 MW(th) HTTR test reactor in Japan (at Oarai) achieved criticality in November, 1998
- In China, the 10MW(th) pebble bed High Temperature Reactor (HTR-10) at Tsinghua University achieved criticality in December 2000.
- A 115 MWe Pebble Bed HTR is being designed by ESKOM (South Africa) for highly efficient generation of electricity
- The US, Russia, France and Japan are working on the preliminary design of a GT-MHR for Pu consumption and electricity and process heat production

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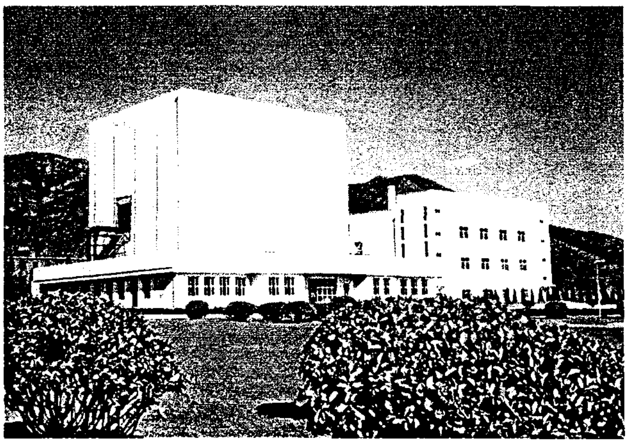
China's HTR-10



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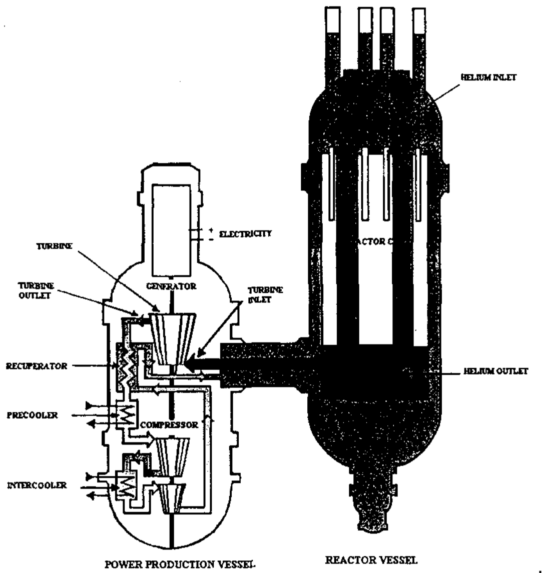

A direct cycle gas turbine HTGR offers high thermal efficiency

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CONSIDERABLE EXPERIENCE HAS BEEN ACHIEVED WITH LMRs

- **Development started in USA, USSR, the UK and France in late 1940s and early 1950s with test reactors such as EBR-1 [produced world's first nuclear electricity] in the USA, and BR-2 in the USSR**
- Experimental reactors **such as EBR-2, Fermi and FFTF (USA), BR-10 and BOR-60 (USSR), Rapsodie (France), KNK-II (Germany), JOYO (Japan), FBTR (India), and DFR (UK) were constructed from the 1950s - 1970s,** *leading to*
- demonstration or prototype fast reactors **such as Phénix (France), PFR (UK), BN-350 (USSR-Kazakhstan), BN-600 (USSR-Russia), MONJU (Japan) and PFBR (India), and**
- **the 1200 MWe full-scale Superphénix (France) -- (shut down at end of 1998).**
- **Total experience base with LMRs is 141 reactor-yrs**

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Various roles are foreseen for LMRs

- LMRs can contribute by
  - traditional breeding of fissile material (Pu, U^{233})
  - Pu incineration
  - transmutation / utilization of long lived nuclear waste (fission products and actinides)
    - in reactors, or
    - in sub-critical cores driven by spallation neutron source (ADS)

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LMR development is continuing in some countries

- France: **transmutation of long lived nuclear waste and incineration of Pu is investigated [CAPRA and CADRA projects], and demonstration in Phénix is planned**
- Japan: **MONJU was shut down indefinitely in 1995 due to sodium leak in secondary circuit; design of 660 MWe demonstration FBR is ongoing; operation of JOYO experimental LMR continues for irradiation tests**
- India: **FBTR is in operation; construction scheduled to begin in 2001 for the 500 MWe Prototype Fast Breeder Reactor**
- Russia: **operation of BN-600 continues very successfully; work on one BN-800 unit is ongoing; incineration of Pu in BN-800 is possible; development continues on large sodium cooled designs, and on lead cooled BREST-300 reactor with passive safety**
- China: **construction is underway for a 25 MWe experimental fast reactor [CEFR]**
- Rep. of Korea: **150 MWe Kalimer plant is being designed -- construction foreseen after 2010**

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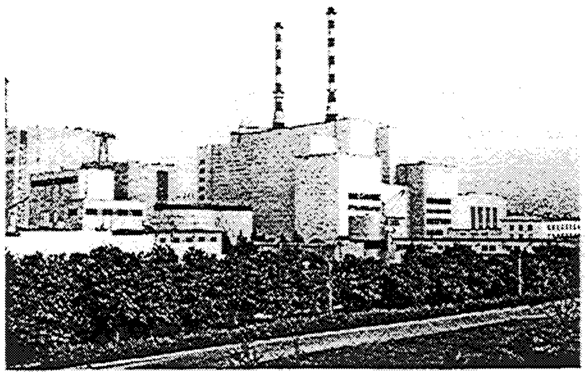
The BN-600 LMR has been operating since 1980 very successfully (LF = 72%), providing an experience base for future commercial plants



BN-600, Beloyarsk, Russia

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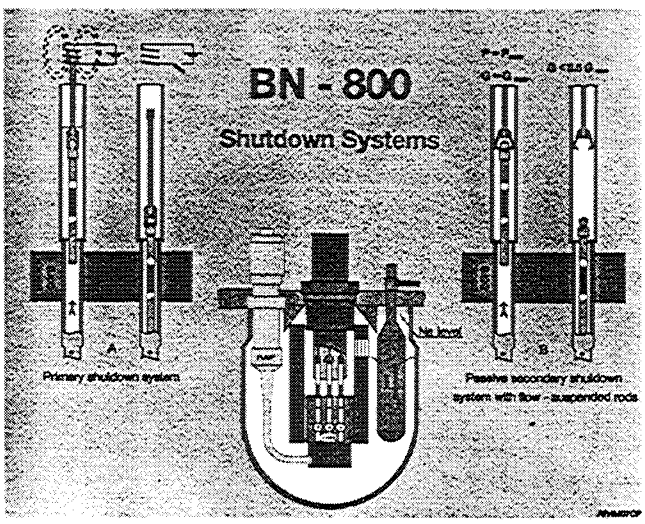

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Means are being examined to reduce the quantity of long lived nuclear waste

- transmutation / utilization of actinides and long lived fission products by coupling a particle accelerator with a sub-critical nuclear reactor
- reduced generation of actinides by introduction of the thorium cycle
- studies and R&D are underway in several countries, including China, India, Japan, the Republic of Korea, Russia, Europe and the U.S.A.

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INTEREST IN SMALL AND MEDIUM SIZED REACTORS IS INCREASING

- BETTER MATCH TO MODEST DEMAND GROWTH
- BETTER FIT TO SMALLER ELECTRICITY GRIDS
- SIMPLER DESIGN
- PASSIVE SAFETY SYSTEMS
- EASIER TO FINANCE
- GOOD FIT FOR SEVERAL NON-ELECTRIC APPLICATIONS

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The Institute of Nuclear Energy Technology (Tsinghua Univ., Beijing) is developing a Nuclear Heating Reactor (NHR)

- a 5 MWt NHR operates at INET providing heating; a test facility for desalination is also operating at INET
- 2 units of NHR-200 are proposed for district heating in Shenyang city. Currently, the site assessment and technical and economic feasibility study are underway.
- the Yantai Municipal Government and the Tsinghua University have initiated a joint project for a Nuclear Seawater Desalination Plant (160,000 m^3/d) using an NHR-200 coupled with a desalination system, and a pre-feasibility study will be conducted.
- Morocco is considering using a 10MWt NHR from INET in demonstration project for sea-water desalination (8000 m^3/day)

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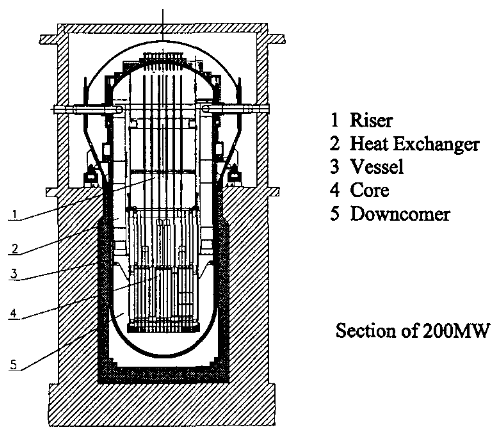
INET's NHR is an integral PWR design with natural circulation in the primary circuit



Section of 200MW heating reactor

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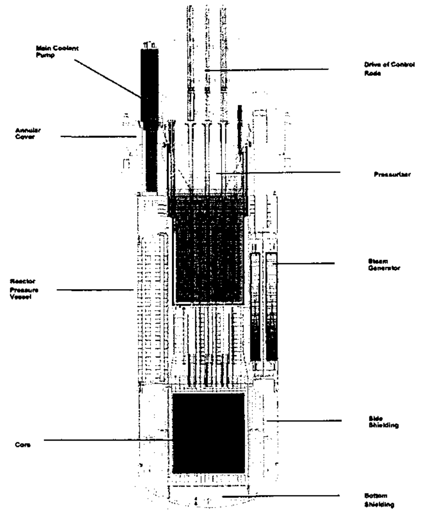
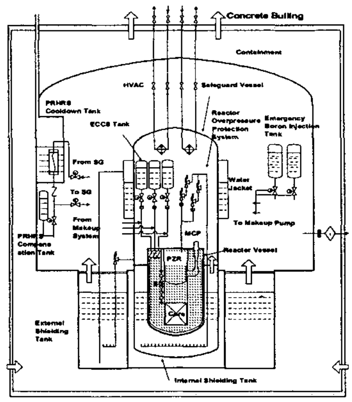
The SMART design, being developed by KAERI, is an integral PWR



SMART Safety Systems



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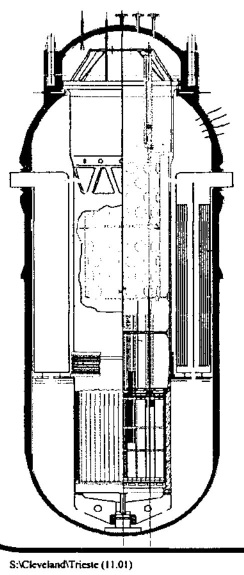
AN INTEGRAL PWR, "CAREM", IS BEING DEVELOPED BY CNEA, ARGENTINA



Main features
- Thermal power: 100 MWth
- Electric power: 25 MWe
- Simple, modular and safe design
- Integrated primary circuit
- Natural convection cooling
- Self-pressurization
- Passive shut-down and emergency cooling systems
- Fuel: Enriched uranium
- Moderator: Light water

Applications
- Electric power generation.
- Stepping stone from a research reactor to a nuclear power plant.
- Water desalinization.

Present stage: Engineering and tests at ad-hoc facilities

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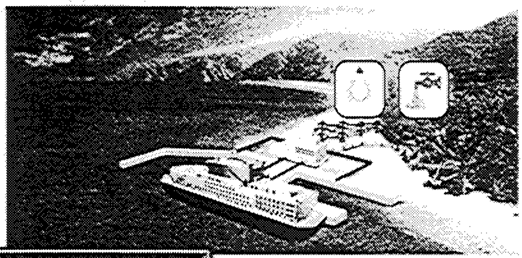
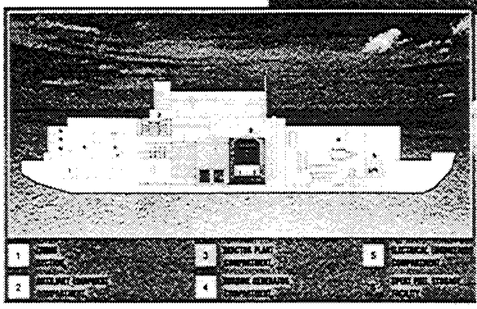
An alternative electricity / heat delivery strategy involves barge mounted reactors (Russia)





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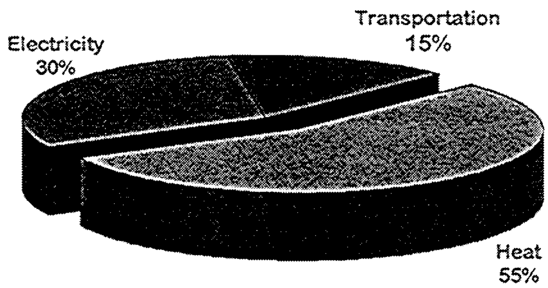
The potential for non-electric applications of nuclear energy is quite large



Primary energy consumption by application

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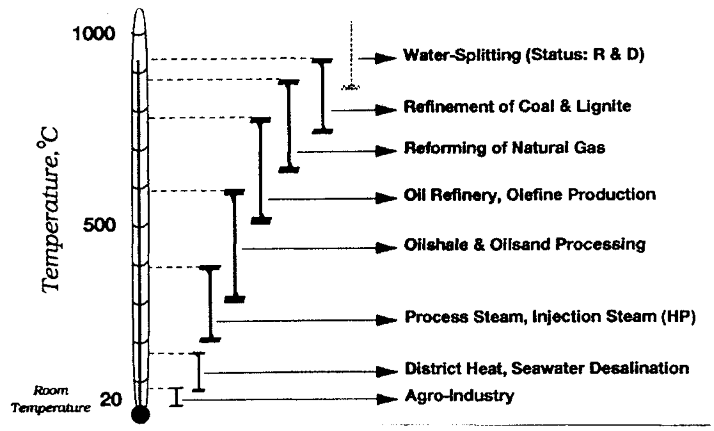
Temperature regions of heat consumption: typical examples of industrial processes



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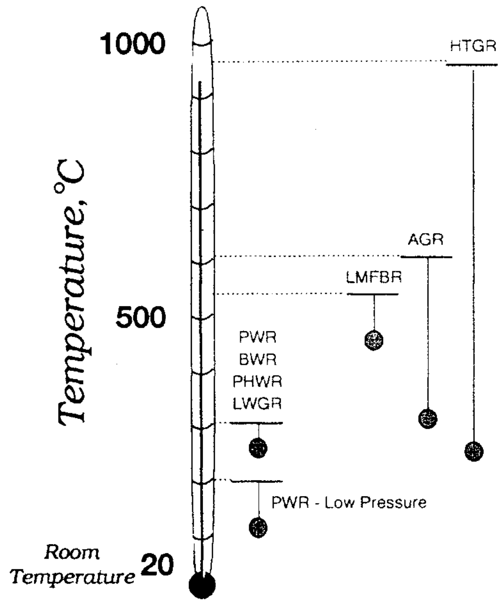
Temperature capabilities of reactor types

Maximum Temperature of Primary Coolant



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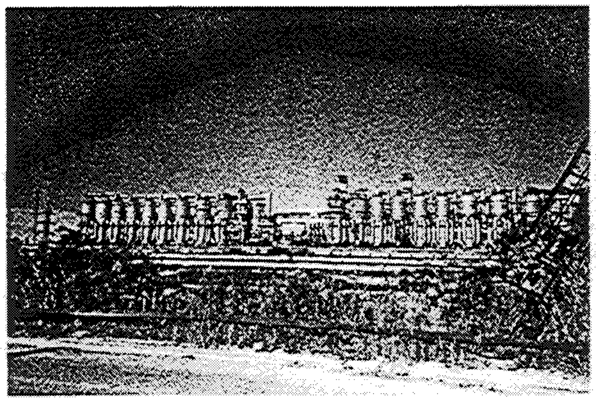
Nuclear energy was used for for seawater desalination in Kazakhstan



Evaporators connected to BN-350 reactor at Aktau, Kazakhstan

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Several countries have experience in desalination of seawater with nuclear energy

- Kazakhstan: **the BN-350 began operating in 1973, and produced electricity + heat for desalination (approx. 80,000 m³ / day) until 1999**
- Japan: **several NPPs produce both electricity and desalinated water (Ikata1-3, Ohi 1-4, Genkai-3 and 4, and Takahama-3 and -4)**
- Pakistan: ***A small desalination facility*** **has been in service since 2000 at the Karachi Nuclear Power Plant**
- India: **since 2000 has operated a desalination facility connected to a 100 MWt research reactor; is constructing desalination units (commissioning expected in 2002) connected to two existing Kalpakkam HWRs**

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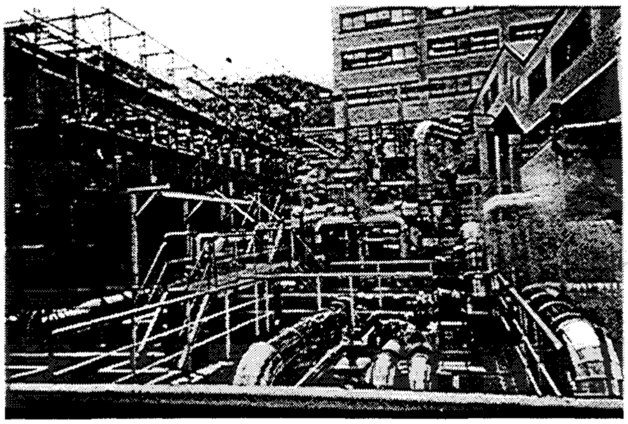
Nuclear desalination is carried out at the Ohi site of Kansai Electric Power Company



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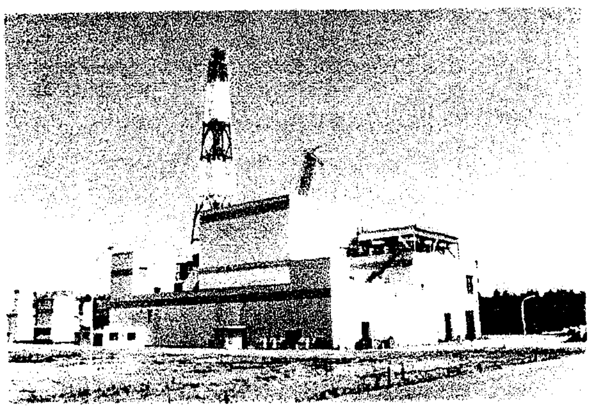
The HTTR will be used to demonstrate high temperature heat applications with nuclear energy



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Several factors will influence decisions to build new plants

(1) economics

(2) financial arrangements

(3) social, political and institutional factors

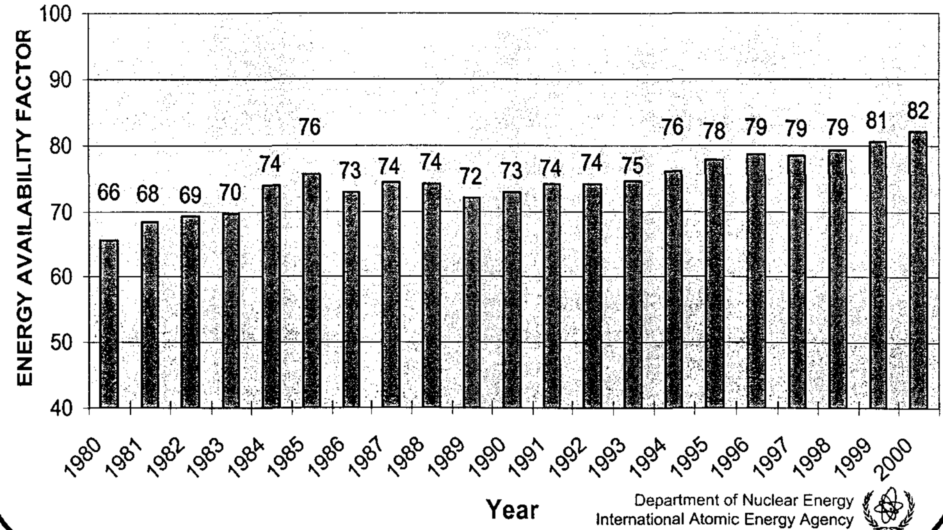
(4) technological readiness of new plant designs

...Several factors will influence decisions to build new plants...

(1) economics [cont.]

- Achieving high plant availability is a key factor for economic competitiveness
  - World-wide, the average availability factor of NPPs has increased from about 66% in 1980 to 82% in 2000, with some utilities achieving significantly higher values.
- Further increase in availability factor for current plants can be achieved with application of, for example:
  - longer fuel cycle length using high burn-up fuel
  - simpler systems for control of hydrogen in the event of an accident (requiring less testing thereby shortening the outage)
  - improved I&C and man-machine interface

NPP OPERATORS HAVE ACHIEVED SIGNIFICANT INCREASES IN AVAILABILITY



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Several factors will influence decisions to build new plants...

(2) financial arrangements

- factors typically considered by financial institutions
  - **large investment**
  - **relatively long construction time**
  - **complex technology**
  - **licensing**
- factors which "help"
  - **precondition: national policy favorable to nuclear**
  - **reliance on proven technology**
  - **stable regulatory environment**
  - **assurance of revenues**
  - **creditworthiness of owner**
- for imported plant -
  - **typically invite financed bids - based on export credits**
  - **domestic portion of work needs to be locally financed, or incorporated into financing package**

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Several factors will influence decisions to build new plants...

(3) social - political, and institutional

- energy security
- public opinion
  - negative in some countries
    - influenced by Chernobyl and TMI
    - influenced by news media
  - what needs to be done
    - assure safety of operating plants [WANO, IAEA]
    - implement high level waste disposal
    - further develop technologies to provide high degree of safety
    - clarify effects of low levels of radiation
    - improve dialogue with public (simple, clear terms)
- institutional preparedness

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Several factors will influence decisions to build new plants...

(4) technological readiness of new designs [cont.]

- development of new plants is guided by the large experience base and R&D results: e.g. EPRI URD, European Utility Requirements, Korean Utility Requirements Document
- some advancements being applied at current plants will be incorporated into future plants -- examples:
  - computer aided diagnostics - early indication of component or sensor degradation
  - improved corrosion resistant materials (e.g. Inconel-690)
  - advanced I&C systems
  - better simulator training
  - advanced construction techniques (e.g. all weather, large block,..)

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Several factors will influence decisions to build new plants...

(4) technological readiness of new designs - [cont.]

- **for** new plants, **technologies for high performance and enhanced economics are included in design phase, e.g.:**
  - **design for on-line maintenance**
  - **widened design margins for longer lifetime, like 60 yrs**
  - **improved neutron reflector (lower fluence for longer vessel life)**
  - **extended use of information technology**
  - **greater plant standardization and system modularization**

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Several factors will influence decisions to build new plants...

(4) technological readiness of new designs - [cont.]

- **technologies for** enhanced safety
  - **improved accident <u>prevention</u>**
    - **increased margins**
    - **active systems of proven high reliability with increased redundancy and diversity; improved physical separation -"bunkerization"**
    - **"passive" cooling and condensing systems which operate without external input**
      - **rely on gravity, natural circulation, compressed gas as driving force**

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Several factors will influence decisions to build new plants...

(4) technology readiness of new designs - [cont.]

- **technologies for enhanced safety:**
  - improved accident mitigation

    - common approaches
      - design of highly reliable depressurization systems
      - large containment volumes and enhanced measures for containment protection - e.g. ignitors and/or recombiners to prevent hydrogen combustion (PWRs); containment inerting with N_2 (BWRs)

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Several factors will influence decisions to build new plants...

(4) technology readiness of new designs [cont.]

- **technologies for enhanced safety:**
  - improved accident mitigation
    - differing approaches (examples)
      - in-vessel retention (below 1000 MWe?), or
      - measures, below the reactor vessel, to spread and cool molten core
      - designing for "dry" reactor cavity to prevent steam explosion in event of vessel melt-through, or
      - demonstrating cavity design can withstand steam explosion

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Economics of nuclear power

There is good news about existing plants...

- **many existing plants**
  - **are nearly or fully depreciated;**
  - **are achieving high availability;**
  - **are achieving low and competitive production costs (fuel + O&M)**
- **lifetime extension and power up-ratings are attractive options**

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Economics of nuclear power

- Current plants compete well with alternative technologies
  - **1999 US nuclear power production costs (fuel plus operation and maintenance costs) dropped to an average of 1.83 US cents/kWh, compared to 2.07 cents/kWh for coal-fired plants, 3.18 cents/kWh for oil-fired plants, and 3.52 cents/kWh for natural gas-fired plants [Ref: *Nucleonics Week*, Jan. 11, 2001, p.3]. In 1999 the most efficient nuclear plants in the USA achieved production costs of 1.1 cents per kilowatt-hour.**
  - **Information provided by the EC based on experience of Bayernwerk AG (Germany) shows that in 1998 production costs from largely depreciated nuclear and hard coal plants were 1.57 to 1.88 €cents /kWh for nuclear and 2.08 to 2.38 €cents /kWh for coal; and representative costs for new gas-fired plants were 2.49 to 2.69 €cents /kWh.**

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Economics of nuclear power

Current plants compete well with alternative technologies

- generation costs in France in 1997 (before the recent price increases in fossil fuels) reported by Framatome at ICONE-9, based on information from the French Ministry of Industry, for a base production of 6000 hr/year, and a discount rate of 8%, were:
  - nuclear: 20.8 French centimes (fuel: 4.5; O&M: 3.37; investment: 12.7)
  - coal: 23.5 French centimes (fuel: 10.1; O&M: 4.5; investment: 8.9)
  - gas: 22.6 French centimes (fuel: 15.5; O&M: 2.2; investment: 4.9)
  - wind: 30 - 50 French centimes (investment: 25-40; O&M: 5-10)
  - solar: 200 - 300 French centimes
- the cost of a kilowatt-hour (including amortization, fuel and operation and maintenance costs) generated with nuclear power by Electricité de France in 2000 was between 15 and 18 French centimes depending on site. This is a decrease of 7% since 1998. [Ref: *Nucleonics Week*, April 5, 2001, p.6].

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Economics of nuclear power

IN MANY COUNTRIES NUCLEAR IS NOT THE ECONOMIC CHOICE FOR NEW CAPACITY...

- Higher capital cost per kWe, and generally larger sizes compared to fossil alternatives, result in large financing burden
- Market de-regulation and privatization change criteria
  - Owners are no longer guaranteed cost recovery over long period of regulated rates
  - Private investors want rapid return on investments

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Illustrative projected capital costs and construction times are highest for NPPs, and because NPPs are generally of larger size, they require large amounts of up-front capital

	Cost per kWe installed[1] US $ 80% of cases (total range from the OECD-NEA report[3])	Base cost[2] per kWe US $ 80% of cases	Construction period Years	Typical unit size MWe
Nuclear Water-cooled reactors	2,070 - 2670 (1690 - 3150)	1440 - 2260	5 - 8	600 – 1,500
Coal	1160 - 2020 (1050 –2930)	840 - 1550	4– 5	400 – 1,000
Natural gas CCGT	510 – 970 (450 – 1770)	420 - 810	1.5 - 3	250 — 750

[1] Includes interest during construction (IDC), contingency and cost of major refurbishment
[2] "overnight cost" without IDC, contingency and cost of major refurbishment
[3] Projected Costs of Generating Electricity - Update 1998 (OECD Nuclear Energy Agency)

Economics of nuclear power

- Generating cost comparisons (nuclear, coal and gas) are country specific, and depend strongly on assumptions, e.g.
  - cost of gas
  - level of pollution abatement required for coal plants
  - plant lifetime, amortization period
  - capacity factor,...
- OECD/NEA-IEA report (in cooperation with IAEA) projects that new nuclear would not have the lowest generation costs in most countries, even at low discount rates
- Recent examinations in Finland by TVO show nuclear provides lower generating costs than coal, gas or peat. Study assumed 91% CF (justified by experience with Olkiluoto units) and 5% discount rate

Economics of nuclear power

Where nuclear faces strong competition, base "overnight" capital costs need to be reduced by approx 30%, to range of about U.S. $ 1000-1400 / kWe

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Economics of nuclear power

High capital costs are a challenge to the nuclear industry

- **In 1998, there were only** 4 **construction starts [China (2), Japan (1) and Taiwan, China (1)]; in** 1999 **there were only** 7 **[China (1), Japan (2), Rep. of Korea (2) and Taiwan, China (2)]; and in 2000, there were 5 construction starts [China (1), India (2), Japan (2)]**
- **Compare to the 1970s - with 251 NPP construction starts in that decade**
- The design organizations are challenged **to develop advanced reactors with**
  - **drastically lower capital costs and short construction times**
  - **sizes (including small and medium sizes) appropriate to grid capacity and owner investment capability**
  - **high levels of standardization and modularization**

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Economics of nuclear power

- Proven means for cost reduction need to be fully utilized
  - as described in OECD-NEA report, EPRI-URD, TECDOC-682,...
    - **Economies of scale;**
    - **Economies of series replication;**
    - **Standardization;**
    - **Streamlined construction methods to reduce construction schedule;**
    - **Multiple unit construction**
    - **Efficient project management;**
    - **[in developing countries] furthering self reliance and enhancing local participation**
    - **Close co-ordination with regulators;**
    - **......others**
  - Benefits are being experienced, and pursued, e.g.
    - **in Rep. of Korea with KSNP and APR-1400**
    - **in Japan with ABWR and ABWR-II**
    - **By Canada with CANDU-6**
  - Benefits are pursued, e.g.
    - **In Europe with the EPR, the SWR-1000; the BWR-90+; in Russia with WWER-1500; In the USA with AP-1000; in Argentina with CAREM; in China with CNP-1000; and many others**

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Economics of nuclear power

- New approaches should be developed and implemented; e.g.
  - Development of "smart" components / systems **(instrumented and monitored)** and methods **for detecting incipient failures to improve reliability – to reduce dependence on costly redundancy and diversity practices**
  - Further development of probabilistic risk analysis methods (and data bases) for evaluating safety benefit of design features **leading to simplified designs without compromising reliability and safety**
  - Development of passive safety systems (and associated reliability models) **where the safety function can be met more cheaply than with active systems**
  - Improvement of the technology base for eliminating over-design **(better codes and data bases)**
  - Development of international consensus regarding commonly acceptable safety requirements **that would facilitate development of standardized designs which can be built in many countries without requiring significant re-design efforts**

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Making new NPPs competitive presents a challenge to designers, regulators and potential plant buyers, working together

- **Challenge to designers – mentioned earlier**
- **Challenge to regulators**
  - **move to more risk informed safety requirements for new plants,**
  - **establish design certification procedures which don't take too long, and have sufficient flexibility to accommodate**
    - **technology advances**
    - **design changes which maintain safety level at reduced cost; and**
    - **a variety of users needs (e.g. needs for a variety of plant sizes).**
- **Challenge to plant buyers – set "user requirements" that result in the most cost effective solutions while meeting safety requirements**

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Generation-IV: The U.S. DoE's Office of Nuclear Energy, Science, and Technology is conducting a wide-ranging discussion on the development of next-generation nuclear energy systems

- The activity is engaging governments, industry, and the research community of several countries.
- The work is being conducted on an international basis to identify, assess, and develop sustainable nuclear energy technologies that can be deployed over the next 30 years to help meet energy needs of the 21^{st} century
- **A first step is the development of a "Technology Roadmap" to guide research and development**

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Generation-IV Goals
for nuclear energy systems and fuel cycles

- Sustainability
  - ..provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization
  - ..minimize and manage nuclear waste and notably reduce the long-term stewardship burden
  - ..increase the assurance that they are very unattractive, and the least desirable route, for diversion or theft of weapons-usable materials
- Safety and Reliability
  - ..excel in safety and reliability
  - ..have a very low likelihood and degree of reactor core damage
  - ..eliminate the need for offsite emergency response.
- Economics
  - ..have a clear life cycle cost advantage over other energy sources
  - ..have a level of financial risk comparable to other energy projects

INPRO – International Project on Innovative Nuclear Reactors and Fuel Cycles

- IAEA's General Conference (2000) invited all interested Member States (MSs)to combine efforts, under the aegis of the Agency, in considering issues of the nuclear fuel cycle, in particular by examining innovative and proliferation-resistant nuclear technology
- INPRO Objectives
  - help insure that nuclear energy is available to contribute to the global energy supply in a sustainable manner in the 21st century
  - to bring together all interested MSs (both technology holders and users) to consider the actions necessary to achieve desired innovations
  - to create a process that will have an impact on and complement ...ongoing initiatives at the national and international level

INPRO (cont.)

- Considering views both from technology developers and users
- Considering views both from industrialized and developing countries
- Work is being implemented by group of international experts assigned to the team in Vienna
- Utilizing IAEA's expertise in safeguards, safety and technology development
- Time horizon is 50 years
- Addressing new applications (e.g. hydrogen production and sea water desalination)

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INPRO (cont.)

- Phase 1
  - Select criteria, develop methodologies for concept comparisons and determine user requirements for:
    - Resources, demand and economics
    - Safety
    - Spent fuel and waste
    - Non-proliferation
    - Environment
  - Examine technologies against criteria and requirements
- Phase 2
  - With approval of participating MSs
    - Examine feasibility of starting an international project
    - Identify technologies which might be appropriate for implementation by MSs in an international project

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Conclusions

- nuclear power will expand, especially in Asia, and could contribute to sustainable energy strategies
- new designs are being developed to meet high performance and safety goals - some have been certified by licensing authorities
- together with simplification, standardization, and short construction time [which are in general being pursued by all design organizations], different approaches are being taken to achieve economic plants:
  - increase electric rating to get benefit of economy of scale, or develop SMRs to benefit from economies of series replication of modular, factory fabricated systems
  - rely on well proven highly reliable active systems or rely on passive safety systems which do not require active support systems such as AC power and cooling water
- many technological developments incorporated into new designs have been tested to demonstrate readiness

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Conclusions [cont.]

- the challenges facing nuclear power are to:
  - continue to achieve the highest level of safety at current plants
  - implement high level waste disposal
  - achieve further technical advances to assure economic competitiveness and very high levels of safety
  - develop innovative and evolutionary reactors
  - establish a sound basis for defining the potential of nuclear power to contribute to sustainable development

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