Defence-in-Depth Approach in the Design of Small & Medium Reactors

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Pakistan’s Nuclear Power Programme

- At present Pakistan has three operating nuclear power plants; another one is under construction; fifth to be constructed soon.
- 8800 MW(e) nuclear energy by 2030
- PWRs are the preferred choice
- Two-prong power units
  - 325 MW PWR SMR
  - 1000 MW PWR
Long Term Planning for NPPs

Long-Term Nuclear Power Plan (9 additional units of 8,325 MW by 2030)

- NPP3, C-2, 325 MW
- NPP4, K-2, 1000 MW
- NPP5, K-3, 1000 MW
- NPP6, 1000 MW
- NPP7, 1000 MW
- NPP8, 1000 MW
- NPP9, 1000 MW
- NPP10, 1000 MW
- NPP11, 1000 MW
Nuclear Power and Developing Countries
Nuclear Power and Developing Countries

• Two stimulants for growing share in world energy needs:
  Population growth and economic development

• Share of developing countries in NE is limited:
  ■ Insufficient infrastructure and small electricity grids.
  ■ Limited investment capability to invest in capital intensive nuclear projects. Loan difficulties.
  ■ Implementation of nuclear power has a longer timeline than most other commonly used electricity generation options.
  ■ Complex Nuclear Power Development Cycle required for sustainable nuclear power
Elements of NPDC for developing countries:

- National energy planning
- Comparative economic assessment of nuclear power
- Establishment of nuclear regulatory body, licensing regulations and applicable codes and standards
- Human resource development
- Nuclear technology selection
- Site selection and environmental assessment
- Preparation of URD, Bid Specification & Bids Evaluation
- Conclusion of commercial and financing contracts
- Plant construction and commissioning
- Operation and Maintenance
- Lifetime technical support to operating plants
• Centre of nuclear activity has shifted from North America and Western Europe to South and East Asia.

• Out of the last 40 nuclear plants connected to energy grids since 1995 around the world, 28 have been built in China, Japan, Korea, Russia, India and Pakistan.

• There are 133 nuclear plants in operation in East and South Asia with 25 more under construction and another 40 planned.

• A large no. of developing countries are eager to install NPPs.

SMR may provide a key to bridge the technology gap in developing countries
Small and Medium Reactors
Attractive Features of SMRs

- Well suited for small or localized grid.
- Provide power generation flexibility
- Modular design may provide incremental capacity increase.
- Minimal impact on population (EA and LPZ areas)
- Non-dependence on single large energy supply units. No massive electricity blackouts with plant trip
- RFOs of small distributed units may be arranged such that electricity is available to consumers the whole year around.
- Lesser dependence on geo-political situation
- Lower economic burden and lesser dependence on international loan agencies. (Lower interests on foreign loans)
# Large vs. Small & Medium Reactors (GEN-III/III+)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SMR (300-700 MW)</th>
<th>Large (&gt;= 1000 MW)</th>
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<tbody>
<tr>
<td>Cost Econom.</td>
<td>Medium</td>
<td>Good</td>
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<tr>
<td>Availability</td>
<td>limited</td>
<td>universal</td>
</tr>
<tr>
<td><strong>Infrastructure Requirement</strong></td>
<td>• Works with small or localized grid.</td>
<td>• Large/integrated grid</td>
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<tr>
<td></td>
<td>• Provide power generation flexibility</td>
<td>• Large cooling water requirement;</td>
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<tr>
<td></td>
<td>• Modular design may provide incremental capacity increase.</td>
<td>• Vast EA &amp; LPZ areas;</td>
</tr>
<tr>
<td></td>
<td>• Lesser dependence on geopolitical situation</td>
<td>• Safety &amp; Waste management issues</td>
</tr>
<tr>
<td></td>
<td>• No large blackouts with plant trip</td>
<td>• Technology dependence</td>
</tr>
<tr>
<td>Safety</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Human Resource</td>
<td>May work with limited manpower</td>
<td>A few hundred engineers/technicians required</td>
</tr>
<tr>
<td>Licensing Requirement</td>
<td>No substantial difference</td>
<td>Independent regulatory authority required</td>
</tr>
<tr>
<td>Proven Tech</td>
<td>Yes for Gen-II &amp; GEN-III</td>
<td>Yes for Gen-II &amp; GEN-III</td>
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</table>
Smaller capacity reactors have the following generic features

- Larger surface-to-volume ratio, facilitating easier decay heat removal, specifically, with a single phase coolant
- An option to achieve compact primary coolant system design, e.g. integral pool type system for effective suppression
- Reduced core power density, facilitating easy use of many passive features and systems
- Lower potential hazard due to small source term; lower decay heat generation rate.
In near term, most new NPPs are likely to be evolutionary water cooled reactor designs building on proven systems while incorporating technological advances. Currently such designs range up to 1600 MW(e).

Innovative high temperature gas cooled reactors: PBMR-400 (ESCOM, South Africa), HTR-PM (INET, China), HTR-F/VHTR (AREVA-CEA, France), (FBR, India);

Small PWRs without on-site re-fuelling:

Lead-bismuth cooled small reactor without on-site refuelling
Scope of Innovative SMR Designs
Long – Term Perspective

- For the longer term,
- there is interest in innovative designs that promise improvements in safety,
- security, non-proliferation, waste management, resource utilization, economics,
- product variety (e.g. desalinated seawater, process heat, district heat and hydrogen) and flexibility in siting and fuel cycles.
In 2006, more than 50 innovative SMR concepts and designs had been, or were being, developed by national or international programmes. Innovative SMRs are under development for all principal reactor lines and for some non-conventional combinations. The target dates when they would be ready for deployment range from 2010 to 2030. Many of the designs share common design approaches (Important for standardization).
Common User Considerations (CUC)
Common consideratons or desired features provided by experts in developing countries with an interest and the potential for deploying new nuclear power plants in the next 40 years, together with the rationales, background information, and other supporting materials.

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No. NP-T-2.1
Desired Features by User Countries

- Economics and financing
- Infrastructure and implementation
- Nuclear Safety
- Environment
- Resources and waste management
- Proliferation resistance
- Physical protection
- Technical requirements
<table>
<thead>
<tr>
<th>Major issues/Sub-issues</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> Economics and financing</td>
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<tr>
<td>• Capital cost</td>
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<tr>
<td>• Electricity generating cost</td>
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<tr>
<td>• O &amp; m cost</td>
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<tr>
<td>• Fuel cycle cost</td>
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<tr>
<td><strong>2</strong> Infrastructure and implementation</td>
</tr>
<tr>
<td><strong>3</strong> Nuclear safety</td>
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<tr>
<td>• Licensing and regulatory considerations</td>
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<tr>
<td>• Safety analysis approach</td>
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<td>• Safety systems</td>
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<tr>
<td>• External events</td>
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<tr>
<td>• Occupational radiation exposure</td>
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<tr>
<td>• Dose to the general public</td>
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<td>• Accident frequencies</td>
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## Structure of User Considerations

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<th><strong>Technical considerations</strong></th>
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<tr>
<td>•</td>
<td>Proven technology</td>
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<tr>
<td>•</td>
<td>Standardization</td>
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<tr>
<td>•</td>
<td>Constructability</td>
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<td>•</td>
<td>Unit size</td>
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<td>•</td>
<td>Plant life</td>
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<td>•</td>
<td>Simplification</td>
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<tr>
<td>•</td>
<td>Design margins</td>
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<td>•</td>
<td>Ease of operation and maintenance</td>
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<td>•</td>
<td>Plant performance</td>
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<td>•</td>
<td>Maneuverability</td>
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<td>•</td>
<td>Operation cycle</td>
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<td>•</td>
<td>Flexibility in the use of fuel</td>
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<td>•</td>
<td>Man-machine interface</td>
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<td>•</td>
<td>Siting</td>
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<tr>
<td>•</td>
<td>Non electrical applications</td>
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<td></td>
<td>Major issues/Sub-issues</td>
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<td>------------------------------------------------------------</td>
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<tr>
<td>5</td>
<td>Environment, resources and waste management</td>
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<tr>
<td></td>
<td>• Environmental impacts</td>
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<td></td>
<td>• Long term availability of fissile materials</td>
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<td></td>
<td>• Amount of waste</td>
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<td></td>
<td>• Waste management</td>
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<td></td>
<td>• Spent fuel management</td>
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<td></td>
<td>• Decommissioning</td>
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<tr>
<td>6</td>
<td>Proliferation resistance</td>
</tr>
<tr>
<td></td>
<td>• Safeguards regime</td>
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Expectation form SMR: Users Requirements

- A design life of 60 years;
- High plant availability; short RFOs; 18 M operating cycles
- Increased margins to reduce sensitivity to disturbances
- Improved automation and HMI and increased margins to provide time for operator to act in accident/Incident cond.
- Core damage frequency < 10^-5 per reactor-year
- Cumulative frequency of large releases <10^-6 per reactor-year
- Design measures to cope with severe accidents.

(IAEA Report on Common User Considerations by Developing Countries for Future Nuclear Energy Systems, 2009)
CUC of SMR Safety
Defense-in-Depth Concept
Safety of Nuclear Installations

- No. of NPPs expected to operate in next 50 years will increase considerably over the present number.

- If safety of NES \( \approx \) safety of operating systems today, there is an overall increase in the numerical risk of nuclear accidents.

- **INPRO methodology objective:** Increase in calculated risk would be compensated by increased safety level of NES on lessons learned from systems in operation.
Defense-in-Depth Concept

Level 1 - Prevention of abnormal operation and failure;
Level 2 - Control of abnormal operation and detection of failure;
Level 3 - Control of accidents within design basis;
Level 4 - Control of severe plant conditions, including prevention of accident progression and mitigation of consequences of severe accidents;
Level 5 - Mitigation of radiological consequences of significant release of radioactive materials.
Strategy of Defense-in-Depth

Physical Barriers

Shield Building

Steel Liner

Pressure Vessel

Fuel Cladding

Fuel Pellet
Strategy of Defense-in-Depth

Systematic Barriers

Inherent Safety

Precaution

Prevention

Mitigation

Beyond DBA

Negative Reactivity Feedback +
Reactor Control System +
Reactor Protection System +
Engineered Safety Features +
Severe Accident Precaution/Coping +

Event Frequency CDF
Design Features of Pressurized Water SMR to Level 1 of Defence in Depth

- Negative reactivity coefficients
- Elimination of liquid boron reactivity control system
- Relatively low core power density
- Integral design of primary circuit with in-vessel location of steam generators and (hydraulic) control rod drive mechanisms
- Compact modular design of the reactor unit
- Primary pressure boundary in pressurized, low enthalpy containment
- Leaktight reactor coolant system with internally immersed pumps
- A single, small diameter double connecting line between the primary coolant pressure boundary and auxiliary systems
- Natural circulation based heat removal from the core in normal operation
Design Features of Pressurized Water SMR to Level 2 of Defence in Depth

- Active systems of instrumentation and control
- Negative reactivity coefficients over the whole cycle
- A relatively large coolant inventory in the primary circuit, resulting in large thermal inertia
- High heat capacity of nuclear installation as a whole
- Favourable conditions for implementation of the leak before break concept, through design of the primary circuit
- Little coolant flow in the low temperature pressurized water containment enclosing the primary pressure boundary
- Redundant and diverse passive or active shutdown systems
Design Features of Level 3 of Defence in Depth

- Negative reactivity coefficients over the whole cycle
- Relatively low core power density and primary coolant temperature
- Large thermal inertia with large coolant inventory in primary circuit
- High heat capacity of nuclear installation as a whole
- Primary pipelines being connected to the hot part of the reactor
- Use of once-through steam generators
- A dedicated steam dump pool located in the containment building
- Self-pressurization, large pressurizer volume, elimination of sprinklers, etc.
- Limitation of inadvertent control rod movement by an overrunning clutch and by the limiters
Design Features of Level 3 of Defence in Depth

- Low heat-up rate of fuel elements predicted in a hypothetical event of core uncovering, owing to design features
- Passive emergency core cooling, often with increased redundancy and grace period
- Passive system of reactor vessel bottom cooling
- Natural convection of water in flooded reactor cavity following small LOCA
- Dedicated pool for steam condensation under a steam generator tube rupture
- Low enthalpy pressurized water containment embedding the primary pressure boundary or double containment
Design Features of Level 4 of Defence in Depth

- Very low leakage containment; elimination or reduction of containment vessel penetrations
- Reasonably oversized reactor building with passive cooling system
- Relatively small, inert, pressure suppression containment
- Reduction of hydrogen concentration in the containment by catalytic recombiners and selectively located igniters
- Sufficient floor space for cooling of molten debris; extra layers of concrete to avoid containment basement exposure directly to such debris
Design Features of Level 5 of Defence in Depth

- Mainly administrative measures
- Relatively small fuel inventory, less nonnuclear energy stored in the reactor, and lower integral decay heat rate
- Design features of Levels 1–4 could be sufficient to achieve defence in depth Level 5
Hierarchy of plant procedures for various operating conditions should be well planned.
Adopt Passive Safety Features

- No reliance on AC power
- Automatic response to accident condition assures safety
- Long term plant safety assured without active components (natural forces only)
- Containment reliability greatly increased by passive cooling
- In severe accidents, reactor vessel cooling keeps core debris in vessel
- Large margin to safety limits
- Defense in depth -active non-safety systems provide additional first line of defense
## Incorporation of Inherent and Passive Safety Design Features into SMRs

<table>
<thead>
<tr>
<th>Design feature</th>
<th>Positive effects</th>
<th>Negative effects</th>
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<tbody>
<tr>
<td>Elimination of liquid boron reactivity control system</td>
<td>• Decrease in capital and operation costs; plant simplification; • Relaxed concerns of human actions of a malevolent character</td>
<td>Certain deterioration of fuel cycle characteristics</td>
</tr>
<tr>
<td>Integral primary circuit with internal steam generators and control rod drives</td>
<td>• Reduced CDF and large early release frequency (LERF), allowing economy of multiunit plants. Positive economic effects from reduced or eliminated emergency planning; • Decreased plant costs: compact primary circuit &amp; steel containment, and reduced siting area; • Reduced O &amp; M costs: Simplified operation and maintenance;</td>
<td>Increased cost owing to the limited power of a single module. Increased cost of a larger reactor pressure vessel</td>
</tr>
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## Incorporation of Inherent and Passive Safety Design Features into SMRs

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<thead>
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<tr>
<td>Natural convection of the coolant</td>
<td>Reduced operation and maintenance costs owing to design simplification and elimination of main coolant pumps</td>
<td>Increased specific cost of RPV; increased complex reactor operation</td>
</tr>
<tr>
<td>Relatively low core power density and coolant temperature facilitating the use of a passive emergency core cooling system with an infinite grace period, actuated upon flow rate decrease</td>
<td>Essential simplification of design, with cost savings</td>
<td>Increased plant costs owing to limited reactor power and energy conversion efficiency</td>
</tr>
</tbody>
</table>
Passive containment cooling system
Enhanced Safety Features in Chasnupp- Unit 2

- IVR by External Reactor Vessel Cooling
- Cavity Flooding System
- Passive Auto-catalytic Recombiners (PAR’s) for hydrogen control
- Loose Parts Monitoring System for pressure boundary integrity monitoring
- Motorized throttle valve at pressurizer to avoid high pressure melt ejection (HPME)
- Anti-dilution Protection signal (ADP) as counter measure for heterogeneous boron dilution
IVR by External Reactor Vessel Cooling

- Also adopted in some advanced PWRs, e.g. AP600, AP1000, APR1400
- Protection of the integrity of the reactor vessel containing the molten corium by cooling its external surface
- Lower part of the reactor vessel should be submerged with cooling water
Thank You