Safety Design Criteria of Indian Sodium Cooled Fast Reactors: Current Status

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FBR Program in India

- FBR program started with Fast Breeder Test Reactor (FBTR) – Design ratings attained - power level raised to 30 MWt recently
- Prototype and industrial scale reactor: PFBR 500 MWe - Techno Economic Demonstration – Under commissioning at Kalpakkam
- FBR program – closed fuel cycle – Co-located fuel cycle facility with PFBR
- Operating experience from FBTR & Design, construction experience from PFBR – input for future FBR design
- Future FBR Design: Improved economy & enhanced safety with twin unit layout (*paper on reference design in FR-17*)
- Two FBRs in Kalpakkam + 4 FBRs at some other site
- Metal fuel FBR in the long run to be preceded by a metal fuel test reactor
Consolidation of experience with metal fuel through comprehensive and graded approach

- Pin level irradiation program in FBTR
- Experience with Industrial scale subassembly in test reactor
- Experience with fuel behavior, fuel performance and related data, Closed fuel cycle etc
Road Map for Metal Fuel Reactor & Fuel Cycle Technology

- Pin level irradiation in FBTR
- Assembly Level Irradiation in FBTR
- Loading as part of driver core in FBTR - planned

- Development of pyro-processing technology in lab & pilot scale
- Feasibility of aqueous reprocessing of metal fuels
- Demonstration of closed fuel cycle technology

- Metal Fuel Test Reactor
  - Demonstration of fuel cycle closure along with metal fuel reactor technology

- Metal Fuel Power Reactor
Improved Major Safety Features
Envisaged in FBR 1&2

- Homogeneous core with sodium upper plenum - SVCR < 1 $
- Stroke Limiting Device in CSR (1st SDS)
- Temp Sensitive Magnetic Switch in DSR (2nd SDS)
- Hydraulic rod to address LOFA
- Vessel cooling system (under study)
- 3 primary pumps and - 6 primary pipes – reduction in severity due to primary pipe guillotine rupture
- Redundant CSS support
- Reduced SWR probability with lesser SG modules
Background to New SDC for Future Indian SFRs

- The safety criteria specifies the requirements and it is intended to ensure “the highest standards of safety that can reasonably be achieved”
- First version was issued in 1990 by AERB with respect to design of 500 MWe PFBR
- It is being re-formulated by AERB towards enhancing the safety of sodium cooled fast reactors further (*AERB/NPP-FBR/SC/D*) – discussions are currently in progress
- The new criteria will form the basis for the design of future SFRs in India
- Rationalization among the safety design criteria of other nuclear power plants licensed in India, viz., PHWR and LWR plants is also attempted
- The safety code establishes:
  - (i) design requirements for the structures, systems and components (SSCs) for safe operation and for preventing events that could compromise safety, or for mitigating the consequences of such events, if they do occur and
  - (ii) organisational processes important to safety, that are required to be met.
- The safety criteria tries to establish relationship between the safety objective and safety principles, and relationship between requirements for nuclear safety functions and design criteria for safety
- Scope: Applicable for SFRs using MOX or Metal fuel
Basis for deriving the safety criteria

• The safety criteria for design of SFR are derived based on the following

  – Safety criteria for design of PFBR, released in 1990
  – Relevant IAEA documents under the Nuclear Safety Standards program
    • SSR-2/1 (Rev.1) of July 17, 2014
    • Safety design criteria for Generation IV sodium cooled fast reactor system, SDC-TF/2013/01, May 01, 2013
    • Lessons learned from Fukushima accident
### Existing AERB Design Code for PHWRs

<table>
<thead>
<tr>
<th>Operational states</th>
<th>Accident conditions</th>
<th>Beyond design basis accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AOO</td>
<td>(a) DBAs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(b) Severe Accidents</td>
<td></td>
</tr>
<tr>
<td>Included in the design basis</td>
<td>Beyond design basis</td>
<td></td>
</tr>
</tbody>
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### New AERB Design Code for LWRs

<table>
<thead>
<tr>
<th>Operational states</th>
<th>Accident conditions</th>
<th>Cond. practically eliminated</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO AOO</td>
<td>DBAs Design Extension Conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Design Extension Conditions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No core melt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Severe Accidents (core melt)</td>
<td></td>
</tr>
<tr>
<td>Included in the design basis</td>
<td>Beyond design basis</td>
<td></td>
</tr>
</tbody>
</table>
### Plant States (Considered in Design)

#### Existing code for PFBR

<table>
<thead>
<tr>
<th>Operational States</th>
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<tbody>
<tr>
<td>Normal Operations</td>
<td>Anticipated Operational Occurrences</td>
</tr>
<tr>
<td></td>
<td>Design Basis Accidents</td>
</tr>
<tr>
<td></td>
<td>Beyond design Basis Accidents</td>
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#### New code for SFRs

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<td>Design Extension Conditions</td>
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<tr>
<td></td>
<td>Accidents without Core melt</td>
</tr>
<tr>
<td></td>
<td>Accidents with Core melt</td>
</tr>
</tbody>
</table>
Major requirements specified in the safety criteria are basically derived from the following safety principles (IAEA)

- Responsibility for safety
- Leadership and management for safety
- Optimization of protection
- Limitation of risks to individuals
- Protection of present and future generations
- Prevention of accidents
- Emergency preparedness and response
Safety Requirements

- Design safety requirements are based on
  a) Radiation protection based on ALARA principle
  b) Safety in design
    - Prevention of accidents: highly reliable reactor systems with low probability of failure and enhanced measures against severe accidents
    - Ensure that the consequences are below limits with enhanced safety margins under DBA
    - Likelihood of accidents with serious radiological consequences is extremely low with an increased emphasis to prevent DEC
    - Ensure that even in the accident with core melt, only limited counter measures are needed in the public domain and sufficient time is available to implement these measures
    - Ensure that DEC with significant radioactivity release are practically eliminated
c) Defence in depth (DiD)
   • Five independent levels of defense in depth for preventing harmful effects of radiation on people and the environment
   • Due consideration for common cause failures and incorporation of inherent and passive features

d) Maintaining the integrity of design of the plant throughout the lifetime of the plant
   • Establishment of a design authority within the responsible organization

e) Nuclear Security to minimize the risk of unauthorised removal of nuclear material and radioactive material
Management of safety in design

• The safety criteria establishes conditions for
  – Management of Safety in Plant Design
  – Management System for Plant Design
  – Safety of the Plant Design throughout the Lifetime of the Plant
  – Operational Experience feedback and Safety Research
  – Safety Assessment and Independent Verification
  – Quality Assurance
General plant design

• Design basis for the plant
  – Establishment of design safety limits
  – Design based on classification of SSC based on safety and seismic considerations
  – Incorporation of principles of redundancy, diversity, single failure criterion, fail safe design and LBB
  – Consideration for PIE, internal and external hazards including aircraft impact
  – Consideration for DBA and DEC
  – Definition of reactor safe states to ensure the fulfilment of fundamental safety functions under various conditions
Plant design should ensure that following AOO or accidents, the fundamental safety functions are ensured and the reactor is taken to a long term safe shutdown state through safe intermediate transition states

- Time limits are specified for each transition state
- Design of systems required for each transition state should be designed based on the time limit specified
  - Controlled state shall not be continued for more than 24 h
  - Design should have capability to maintain safe state for 72 h
  - Severe accident safe state should be reached within 1 week
• Design for safe operation over the life time of the plant
  – Provision for Testing, Calibration, Maintenance, Inspection and Monitoring
  – Ageing management
  – Equipment qualification
• Design for optimum operator performance
• System performing safety and process functions, sharing of systems between multiple units
• Safety analysis
  – Probabilistic and deterministic approaches
  – Quantitative safety targets for Core Damage Frequency
    • CDF should be < 1E-6/ry due to internal events
    • CDF should be less than 1E-5/ry for all internal events and external hazards including seismic hazards
    • Accident sequences with early or large release have to be practically eliminated. Early or large release shall be less than 1E-7/year.
Consideration for Design extension conditions

• For the design extension conditions, the following additional considerations are to be incorporated in the design
  – Large mechanical energy release beyond the structural capability of reactor shall be avoided
  – Means for decay heat removal shall be in addition to a residual heat removal system for AOO and DBA, or the capability of existing systems shall be enhanced with the following considerations
    • (a) Cooling of reactor core is possible even under extreme external events and their consequences, such as long-term loss of all AC power supplies,
    • (b) Passive mechanisms are used to the extent practicable, and
    • (c) Residual heat removal system has diversity to the extent practicable.
  – The design of the containment system shall take into account all identified DBA and DEC
  – Consideration shall be given for emergency power supply system for DEC including severe accident conditions
  – Continuity of DC power shall be ensured such that any short term actions necessary to mitigate the consequences of DEC can be completed despite the loss of the AC power sources and the event that triggered it.
  – A dedicated power source shall be provided capable of supplying power to the equipment necessary to mitigate the consequences of DEC involving a loss of the off-site power combined with the failure of emergency power source
  – Equipments shall be provided at the nuclear power plant to ensure that there is adequate radiation monitoring in operational states and DBA conditions and, as far as is practicable, in design extension conditions
## Dose limits

<table>
<thead>
<tr>
<th>Plant condition</th>
<th>Dose for individual at off-site</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal operation</strong></td>
<td>• 1 mSv/year for entire site</td>
</tr>
</tbody>
</table>
| **DBA**          | • There shall be no need for offsite countermeasures involving public, beyond exclusion zone  
                   • Effective dose shall be less than 20 mSv/year following the event |
| **DEC-A**        | • There shall be no necessity of protective measures in terms of sheltering or evacuation for people living beyond Exclusion Zone.  
                   • Required control on agriculture or food banning should be limited to a small area and to one crop.  
                   • The design target for effective dose, with such interventions considered, remains same as for DBA. (20 mSv/year) |
| **DEC-B**        | • The release of radioactive materials should cause no permanent relocation of population.  
                   • The need for offsite interventions should be limited in area and time. |
Post Fukushima considerations

- Additional considerations for reinforcing and enhancing safety further is emphasized on the basis that
  - The capability to predict and control an event becomes increasingly more difficult as the frequency of occurrence of the event decreases
  - This can be addressed only by providing sufficient safety margins
  - Design should foresee additional provisions to support the accident management infrastructure that might be needed to handle extreme events, along with unexpected failure of existing safety features/systems.

- Safety approach in case of unexpected events
  - Provide a diverse and flexible accident response capability that would provide a backup to permanently installed plant equipment, and would supplement the equipment already available for responding to severe accidents
  - Aim for improving the capability of a plant to survive an extended loss of all AC power, loss of normal heat sinks and loss of normal access to plant site, etc.

- Requirements for Additional Facilities
  - The design should recognise the need to provide accident management capabilities when the onsite and the offsite infrastructure are severely damaged
  - The means for core and spent fuel cooling should be such as to cope with prolonged loss of all AC power sources
  - Enhanced command and control, improved emergency data acquisition and transmission, containment energy and non-condensable gas management capabilities or comparable measures to ensure containment integrity
Post Fukushima considerations (Contd…)

- **Specific design provisions and means** shall be provided for
  - Enhanced Off-site Power Supply Systems: multiple power transmission lines from diverse routes and sources, improved seismic resistance of the switchyard and substations, and additional high voltage and temporary cables along with backup electrical equipment compatible with existing switchyard and substations
  
  - On-site Power Supply Systems: means shall be provided to cope with a prolonged SBO by portable (battery recharging, instrumentation and controls supplies, etc.) spot power and mobile generators (for larger electricity demands) for enhancing electrical supplies
  
  - Cooling Systems for core and spent fuel shall be such that robustness of ultimate heat sinks is maintained and it shall be able to remove decay heat for very long term in the event of extended SBO

- The design should consider alternative pathways to the existing ultimate heat sink

- Protection of containment under severe accident conditions shall be ensured under any extreme situation due to external events

- I&C systems design enhancement shall ensure monitoring plant conditions under extreme environmental conditions associated with severe accidents.
Key Issues: Identification of DEC events

- Design extension conditions are classified into DEC-A (accident sequences without core melt) and DEC-B (accident sequences with core melt).
- Few Potential events identified are:

<table>
<thead>
<tr>
<th>DEC-A</th>
<th>DEC-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended station blackout</td>
<td>Total instantaneous flow blockage of a single subassembly</td>
</tr>
<tr>
<td>Very large sodium water reaction in a steam generator module</td>
<td>Unprotected transient over power event (UTOP)</td>
</tr>
<tr>
<td></td>
<td>Unprotected transient loss of flow event (ULOFE)</td>
</tr>
<tr>
<td></td>
<td>Unprotected loss of heat sink (ULOHS)</td>
</tr>
</tbody>
</table>

Robustness and accommodating of external events in the list
## Potential PEC events

<table>
<thead>
<tr>
<th>Sl no.</th>
<th>Event description</th>
<th>Design guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Power excursion due to failure of core support structure or ejection of all control rods</td>
<td>To be ruled out by stringent design, ISI and redundancy in supports</td>
</tr>
<tr>
<td>2.</td>
<td>Simultaneous failure of both main and safety vessels</td>
<td>To be ruled out by stringent design, material choice and monitoring of interspace between vessels</td>
</tr>
<tr>
<td>3.</td>
<td>Total loss of all DHR systems on demand</td>
<td>To be ruled out by stringent design, multiple paths for DHR and diversity</td>
</tr>
<tr>
<td>4.</td>
<td>Sodium – concrete reaction due to leakage from safety vessel after a leak from main vessel</td>
<td>To be ruled out by providing steel liner for reactor vault and choice of sodium resistant concrete</td>
</tr>
<tr>
<td>5.</td>
<td>Failure of both RCB ventilation dampers to isolate RCB on demand</td>
<td>To be ruled out by stringent design, diversity, fail safe design and surveillance features</td>
</tr>
<tr>
<td>6.</td>
<td>Spent fuel melting</td>
<td>To be ruled out by providing adequate water capacity for the bay, double barrier concept and water addition features</td>
</tr>
</tbody>
</table>

**Guidelines for demonstration of practical elimination of events:** deterministic and probabilistic approaches
Key Issues: Complete independency of DiD levels

– For control of reactivity, FBRs are traditionally designed with two shutdown systems, both working based on rod drop principle
– For ensuring effective heat removal, a very reliable natural convection based decay heat removal system utilizing air as the ultimate heat sink is adopted
– The concept of DEC may require a dedicated/independent DiD level to be incorporated in the design for DEC
– This may necessitate the provision of third or additional shutdown system, such as, HSAR, TSMS etc.

• How well the common cause failure be addressed?
– Alternate decay heat removal concepts such as vessel cooling system, steam generator casing cooling system, etc. have only limited heat removal capacity

• How well the complete independency of DiD levels be claimed from the point of view of residual heat removal?
Key Issues: Consideration of aircraft impact

• The criteria says,
  ‘A design-specific assessment of the effects on the plant of the impact of an aircraft shall be conducted to show that:
  – the reactor core remains cooled, or the containment remains intact; and
  – spent fuel cooling or spent fuel pool integrity is maintained’
• If shutdown and decay heat removal systems are protected from aircraft impact, requirement for containment function does not arise
• Without the decay heat removal system, containment system alone cannot assure the required level of safety
• Thus, there is higher emphasis on decay heat removal system design against aircraft impact

Can the approach for protection of RCB and safety systems by suitable layout satisfy the requirement of ‘aircraft impact resistant’ design?
Key Issues: Active Vs Passive safety features

- Fast reactor operating experience has demonstrated the reliable operation of active safety systems with redundancy, diversity and fail safe features for reactor shutdown and decay heat removal.
- Such systems can be continued to be utilized for the protection and mitigation systems envisaged for AOO and DBA.
- For design extension conditions, further enhancement of safety systems are essential.
- One potential way for achieving safety enhancement with respect to DEC is to incorporate passive design features to the existing active systems.
- Passive systems appear to be more reliable compared to active. However, there are significant functional uncertainties associated with them.
- Rigorous R&D measures are essential to understand the uncertainties associated with passive systems to establish the comfortable range of their applicability.

Can the passive systems, in view of their high reliability be credited for both DBA as well as for DEC.
Key Issues: Design approach for RCB if energetic scenario is eliminated

- Innovations in the design of reactor core and shutdown system may make an energetic scenario to be practically eliminated.

- Can the need for containment be eliminated?

- If containment is to be retained, design basis for RCB needs redefinition.

- Design pressure and leak rate for RCB needs to be defined in the absence of pressurization and large scale radioactive release into RCB resulting from energetic accident scenario.
Major Safety and R&D Issues

• How much margin should be adopted for external events like seismic and flooding?

• Identification of design extension conditions and establishing plant capability to withstand damage and spell out margins

• Safety studies & Modeling:
  - Core transients, melt down and melt through, molten fuel coolant interaction, re-criticality and PAHR

• Passive safety systems for reactor control and decay heat removal – Additional alternative cooling systems

• Design measures to assure there is no radiological impact on public for any event both internal & external

• Na void coefficient – in large size metallic fuelled core??
Summary

• Evolution of strong safety criteria – fundamental to assure safety

• The safety criteria document under preparation by AERB in discussion with IGCAR would form the basis for the design of Sodium cooled Fast Reactors to be deployed in future in India

• SDC is largely in line with the international approach

• A common approach in a collaborative mode and sharing of knowledge, under the aegis of IAEA, with regard to safety, among member states / agencies involved in development of SFRs, is desirable.
Thank You for the Attention