Advanced Nuclear Industry: Next Generation

Reactor Design Types
- Molten Salt Reactor
- Fluoride Salt-cooled High Temperature Reactor
- Liquid Metal-cooled Fast Reactor
- High Temperature Gas Reactor
- Pebble Bed Reactor
- Nuclear Battery Reactor
- Designs Advanced Nuclear Fuels
- Small Modular Reactor
- Fusion Reactor
- Super-Critical CO₂ Reactor
- Accelerator Driven System
Health physics codes evaluate the advanced reactor lifecycle: Phases

- Design
- Licensing
- Operation
- License Termination and Decommissioning
- Safety & Environmental Reviews
Health physics codes evaluate the advanced reactor lifecycle: Phases

- **PRA:** SAPHIRE
- **Fuel Behavior:** FRAPCON-3, FRAPTRAN, COBRA, MELCOR, GALE, SCALE/ORIGEN
- **Reactor Kinetics:** PARCS
- **Thermal Hydraulics:** TRACE, RELAP5
- **Accidents:** MACCS, SNAP/RADTRAD, ARCON, PAVAN, SCDAP/RELAP5, IFCI, HABIT
- **Radiological Protection:** VARSkin, PiMAL
- **Environmental Dispersion:** NRCDOSE, XOQDOQ, LADTAP, GASPAR, GENII
- **Transportation:** RADTRAN, TRAGIS
- **Materials Performance:** LEAPOR

Design → Licensing → Operation → License Termination and Decommissioning

- **EM:** RASCAL
- **DandD**
- **VSP (MARSSIM)**
- **RESRAD**
- **VICTORIA**

Safety & Environmental Reviews
Health physics codes evaluate the advanced reactor lifecycle: Phases

- NRC staff rely on software during each phase to determine:

  **Source Term**
  What radionuclides are available for potential release to the environment?

  **Release Conditions**
  How they are released, e.g., chemistry, particle size, buoyancy, building size, stack height?

  **Environmental Dispersion**
  Where does it go...how much, how far, how fast?

  **Environmental Consequences**
  What is the dose?

Open questions:
- Is existing software appropriate for use with Advanced Reactors?
- Several dozen potential reactor vendors and designs...where to start with any needed changes?
- What steps can be taken now to minimize delays later?
NRC’s advanced reactor infrastructure project (2010-2014)

- PNNL is a member of a consortium of five DOE national laboratories (PNNL, Oak Ridge, Brookhaven, Sandia, and Argonne) supporting NRC’s Advanced Reactor Licensing Program. NRC’s Advance Reactor Program’s five-year infrastructure project was completed in 2014.

- Purpose: develop new guidance documents to expedite reviews of DCD, COL, and ESP applications for advanced reactors:
  - Develop recommendations for updating the Standard Review Plan
  - Develop recommendations for updating office instructions
  - Develop recommendations for updating NRC regulations

- This consortium assisted NRC in developing the SMR licensing infrastructure including the Design-Specific Review Standards for mPower and NuScale

- PNNL developed COL/ESP-ISG-027 "Interim Staff Guidance on Specific Environmental Guidance for Light Water Small Modular Reactor“
NRC’s advanced reactor infrastructure development process

Task 2 – Assess current NRC requirements and key guidance documents

Task 3 – Lab SME teams identify design characteristics n/a or different from LWRs

Existing LWR Licensing Doc’s & Reg’s

Gap Analysis

Task 4 – draft changes to NRC documents (Limited to SRP Updates)

Task 5 – characterize changes (scope)

- International Experience
- Vendor Information
- Previous NRC licensing
  - MHTGR/PBMR + NGNP
  - PRISM
- ANS & ISO standards development

Develop Recommendations
Task 3 approach envisioned separate teams of reactor-specific SMEs.

Each of three teams made up of 3-5 reactor experts from labs:

- **iPWRs**
  - Eva Hickey (LWR experience)

- **GCRs**
  - Mark Mitchell (Fort St Vrain Experience)

- **LMRs**
  - Ron Omberg (FFTF experience)
Regulatory Gap Analysis

- Regulatory gap analyses for iPWR, HTGR, and LMRs considered changes necessary for a comprehensive range of relevant regulations and guidance.
- Review started with NRC’s Standard Review Plan (NUREG-0800) and included multiple layers of references.

**Documents Reviewed**

<table>
<thead>
<tr>
<th>NRC Regulations and Guidance</th>
<th>Relevant External References</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUREG-0800 Standard Review Plan</td>
<td>Technical Manuals</td>
</tr>
<tr>
<td>Other NUREGs and NUREG/Crs</td>
<td>ANSI Standards</td>
</tr>
<tr>
<td>Relevant Codes of Federal Regulations</td>
<td>ASME Standards</td>
</tr>
<tr>
<td>Regulatory Guides</td>
<td>ASTM Standards</td>
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<tr>
<td>Branch Technical Positions</td>
<td>EPRI Technical Reports</td>
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<tr>
<td>Generic Letters</td>
<td>IEC Standards</td>
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<tr>
<td>Interim Staff Guidance</td>
<td>IEEE Standards</td>
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<tr>
<td>SECY Papers</td>
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</table>


NRC is currently reviewing the NuScale Design Certification utilizing the DSRS approach.
### SRP Reviews - by Chapter, all data

<table>
<thead>
<tr>
<th>Document</th>
<th>Document Type</th>
<th>Document Title</th>
<th>Change Needed</th>
<th>IPWR/HTGR/LMR/Tech Neutral</th>
<th>Action By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorted by Chapter then Document</td>
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</table>

#### SRP Chapter: 1 Introduction and Discussion

**01.1 2007**

NRC SRP 01.1 Areas of Review, Rev 1 - November 2007

- **Change Sectn**: 1 AREAS OF REVIEW, 1.
- **Change**: Change wording to “the type of containment structure, if applicable, and its designer or the containment functional performance criteria and their technical bases for acceptance”
- **Key Issues**: NRC decision needed on SRM on staff’s SECY providing containment functional performance requirements. Section assumes containment function to be determined by a containment structure and needs to be revised to reflect the NRC’s plans for the acceptance of alternative containment functional performance criteria under SECY-10-0034.
- **Basis**: Change wording to “the type of containment structure, if applicable, and its designer or the containment functional performance criteria and their technical bases for acceptance”

**01.1 2008**

NRC SRP 01.1 Areas of Review, Rev 1 - November 2008

- **Change Sectn**: 1 AREAS OF REVIEW, 1.
- **Change**: Include reactor technology and plant application (e.g., power generation, process heating) in the list of principal design aspects. In addition, the SRP needs to address 10CFR50.69 on risk-informed categorization and treatment of SSCs and RTNSS guidance from the Consolidation of SECY-94-084 and SECY-95-132.
- **Key Issues**: Sections assumes LWR reactor type and does not expand on important to safety SSCs to acknowledge 10CFR50.69 and the RTNSS staff positions.
- **Basis**: Change wording to “the type of reactor technology, the reactor technology,…”

**01.1 2009**

NRC SRP 01.1 Areas of Review, Rev 1 - November 2009

- **Change Sectn**: 1 AREAS OF REVIEW, 2.
- **Change**: Delete “water” from “cooling water”
- **Key Issues**: Section assumes LWR reactor type
- **Basis**: Change wording to “the cooling and other auxiliary systems…”

**01.1 2010**

NRC SRP 01.1 Areas of Review, Rev 1 - November 2010

- **Change Sectn**: 1 AREAS OF REVIEW, 9.
- **Change**: Add paragraph similar to “Advanced and Evolutionary Light-Water Reactor Design Issues” for SMRs and cite the appropriate or relevant series of SECY documents such as Consolidation of SECY-94-084 and SECY-95-132, SECY-98-144, SECY-03-0047, SECY-94-0103, SECY-94-0157, SECY-05-0006, SECY-05-0130, SECY-06-0007, SECY-07-0101, and SECY-10-0034.
- **Key Issues**: Section makes no reference to SMRs and the emerging staff positions on non-LWR and SMR licensing based on risk-informed performance-based approach
- **Basis**: Add similar statement for SMR design issues based on SECY-10-0034 and previous pertinent SECY documents
# Gap Analysis Results

## SRP Reviews - by Chapter, all data

<table>
<thead>
<tr>
<th>Document Type</th>
<th>Document Title</th>
<th>Reference In, Change Sectn, Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>empirical observations of similar well-performing commercial facilities</td>
<td>10CFR Change 10 CFR 50 App I</td>
</tr>
<tr>
<td></td>
<td><strong>Sorted by Chapter then Document</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change Needed</td>
<td>iPWR/HTGR/LMR/Tech Neutral</td>
</tr>
<tr>
<td></td>
<td>Key Issues, Comments, Basis, Added Info</td>
<td>NRC/Labs/Others</td>
</tr>
<tr>
<td>11.2 NRC SRP</td>
<td>11.2 Liquid Waste Management System</td>
<td>4</td>
</tr>
</tbody>
</table>

**CHANGE SECTN: III.7; IV.3**

**CHANGE:** Currently mentions N-16 skyshine from BWR turbine buildings. Need to include similar discussion regarding radioactive contaminants for gas turbine buildings.

**KEY ISSUES:** Primary circuit surface contamination in HTGRs containing fission products needs to be included.

**COMMENTS:** Complete review. SRP 11.2 cites extensive numbers of other SRP sections and references that would need to be modified to reflect the characteristics and attributes of advanced reactor designs.

**BASIS:** Cs and Ag are expected to preferentially plate out on the turbine during normal operation, resulting in a significant radiation dose which could complicate turbine maintenance.

**ADDED INFO:** IAEA-TECDOC-978 provides relevant information concerning fuel performance and fission product behaviour in gas cooled reactors.
## Gap Analysis Results – GALE Code Example

<table>
<thead>
<tr>
<th>Code – SRP Section Reviewed</th>
<th>Recommendation</th>
<th>Comments</th>
<th>Changes Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>GALE - 11.1 Source Terms, Rev. 3 - March 2007</td>
<td>Develop methodology for assessing source terms other than empirical observations of similar well-performing commercial facilities 10CFR Change: 10 CFR 50 App I</td>
<td>A decision on methodology for evaluating the source term to be used in radioactive waste system analysis for reactors other than traditional BWRs and PWRs is needed before this SRP can be revised.</td>
<td>iPWR – 3 (many changes)  HTGR – 3 (many changes)  LMR – 3 (many changes)</td>
</tr>
<tr>
<td>GALE - SRP Acceptance Criteria 6.A, 6.D; II Technical</td>
<td>Need to generalize to not be specific to LWRs and include examples of SSCs that are applicable to HTGRs and LMRs.</td>
<td>Lists design basis fission product levels specific to PWR and BWR, which may not be applicable to advanced reactors.</td>
<td>iPWR – 2 (limited changes)  HTGR – 2 (limited changes)  LMR – 2 (limited changes)</td>
</tr>
<tr>
<td>NRC BTP 11-5, “Postulated Radioactive Releases Due to a Waste Gas System Leak or Failure.”</td>
<td>Need to generalize and not be specific to light-water cooled reactors and add specifics regarding where waste gas may come from for HTGR and LMR</td>
<td>BTP is currently very specific for LWRs and would need to be modified to cover other non LWR types. Currently indicates that source terms and releases may be developed using the BWR and PWR GALE codes.</td>
<td>iPWR – 1 (tech neutral now)  HTGR – 3 (many changes)  LMR – 3 (many changes)</td>
</tr>
<tr>
<td>NUREG-0017, “Calculation of Releases of Radioactive Materials in Gaseous and Liquid Effluents from Pressurized Water Reactors (PWRs) (PWR GALE Code).”</td>
<td>This document is the manual for a computer code used to calculate radionuclide inventories in effluents from a traditional PWR.</td>
<td>Revision to reflect HTGR attributes such as TRISO fuel particles, lack of a fuel pellet-clad gap, higher burnups, no spent fuel pool, configuration of the GCR fuel into spheres or compacts in prismatic blocks, confinement versus containment, and dry storage.</td>
<td>iPWR – 3 (many changes)  HTGR – 3 (many changes)  LMR – 3 (many changes)</td>
</tr>
</tbody>
</table>
NRC is currently pursuing a new advanced reactor infrastructure development program.
NRC’s current approach is similar to the approach taken to develop the DSRSs

Source: NRC, Lynn Mrowca
Advanced Reactor Workshop
April 25, 2017
Technology-neutral code improvements can increase efficiency in licensing reviews

- NRC considers high-temperature gas-cooled reactors, sodium-cooled fast reactors, and molten salt reactors as the designs of interest in the near-term.
- Anticipated designs have many different plant configurations, cooling types, fuel configurations, and operational conditions.
- Expected new and/or major rewrites of MELCOR and GALE to determine source terms, and updates to other codes for release conditions, environmental dispersion, and environmental consequences will consider these plant parameters.
- Collaborations with industry and other users of HP codes will help identify opportunities to create new or modified codes for multiple designs that are technology-neutral.

<table>
<thead>
<tr>
<th>Installed Capacity</th>
<th>Scalable from 2 -- 1200 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td>Molten Salt, Liquid Metal, and High Temperature Gas</td>
</tr>
<tr>
<td>Time to Construct</td>
<td>1 - 5 years combination of on-site construction and factory module fabrication</td>
</tr>
<tr>
<td>Operation Flexibility</td>
<td>Includes designs that are &quot;Walk-away&quot; safe without operator intervention</td>
</tr>
<tr>
<td>Proliferation Concerns</td>
<td>Multiple fuel options including enriched uranium, depleted uranium and used nuclear fuel</td>
</tr>
</tbody>
</table>
There are multiple resources available to address code updates.

**DOE’s Gateway for Accelerated Innovation in Nuclear (GAIN)**

- Provides advanced nuclear technology innovators with access to the extensive nuclear research capabilities and expertise available across the DOE National Labs.

- Three industry-led working groups have been established with NEI and EPRI:
  - Molten Salt Reactor
  - Fast Reactor
  - High Temperature Reactor

**GAIN**

- Modeling and Simulation
  - Verification and Validation
  - Reactor Physics
  - Licensing Framework
  - Advanced Designs

**Industry And Investors**

- GAIN

<table>
<thead>
<tr>
<th>2016 NE Vouchers awarded to companies</th>
<th>2017 NE Vouchers awarded to companies</th>
<th>2018 NE Vouchers awarded to companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 companies</td>
<td>14 companies</td>
<td>11 companies</td>
</tr>
</tbody>
</table>

**30 Members participate in a TWG**

**66 Other companies involved with GAIN**
Summary

• NRC considers high temperature gas-cooled reactors, sodium-cooled fast reactors, and molten salt reactors as the designs of interest in the near-term¹

• Current codes used in safety, siting and environmental reviews are based on past LWR designs

• The primary challenge is to develop information and codes for source terms in the new reactor designs

• Lesser Challenges: Release Conditions, Environmental Dispersion, Environmental Consequences

• Code improvements that are technology-neutral can increase efficiency in licensing reviews

• NRC’s RAMP User Group provides a forum for engagement with industry groups and other users on code improvements; other resources such as the GAIN program are available

1. NRC Non-Light Water Reactor Near-Term Implementation Action Plans, ML17165A069
Questions?