Advanced Reactor Designs and Health Physics Codes

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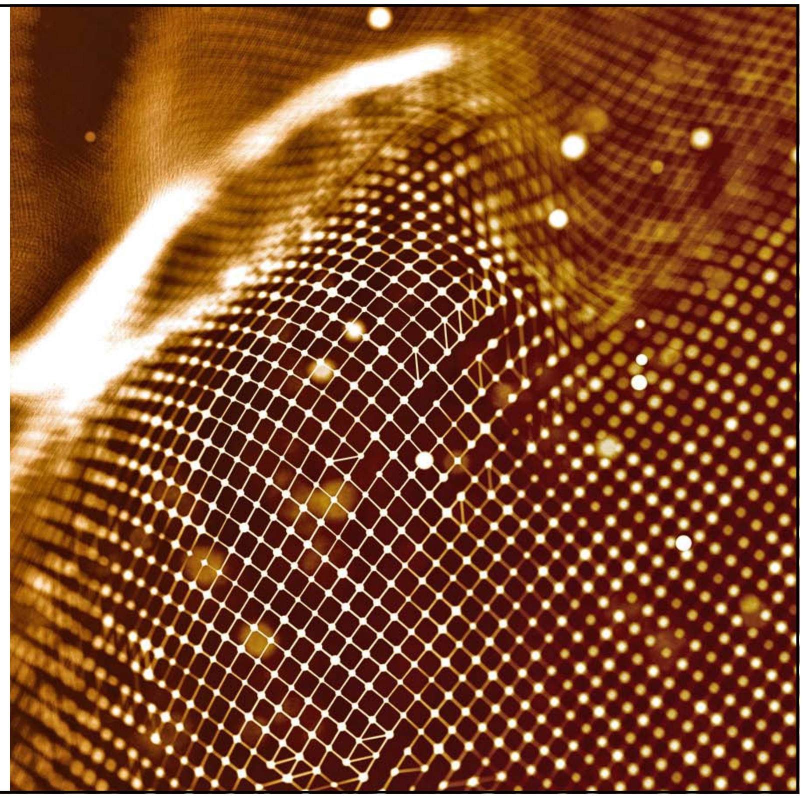
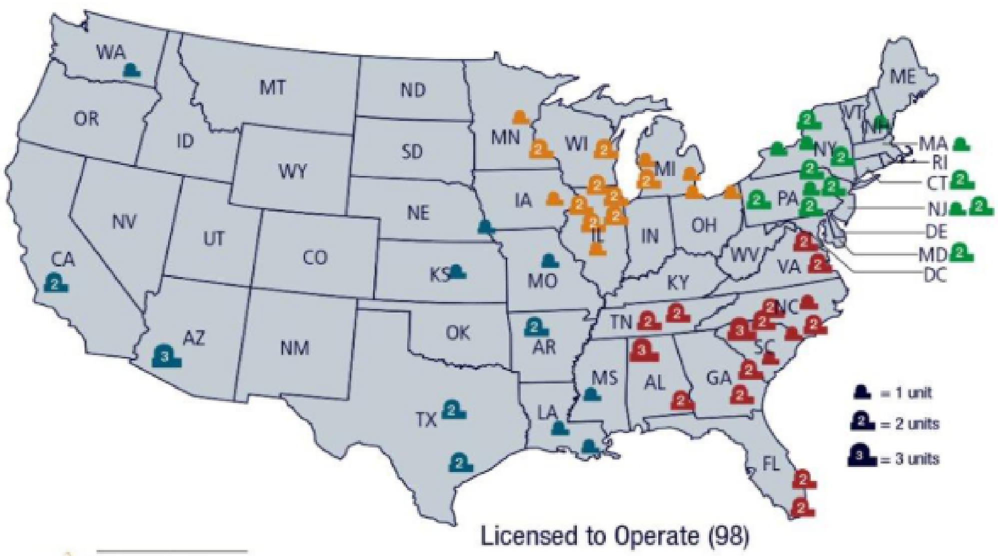


U.S. Operating Commercial Nuclear Power Reactors



U.S.NRC
As of Sept. 2018

Advanced Nuclear Industry: Next Generation

third way fresh thinking

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NRC expects to receive applications for Design Certification for multiple non-LWR designs

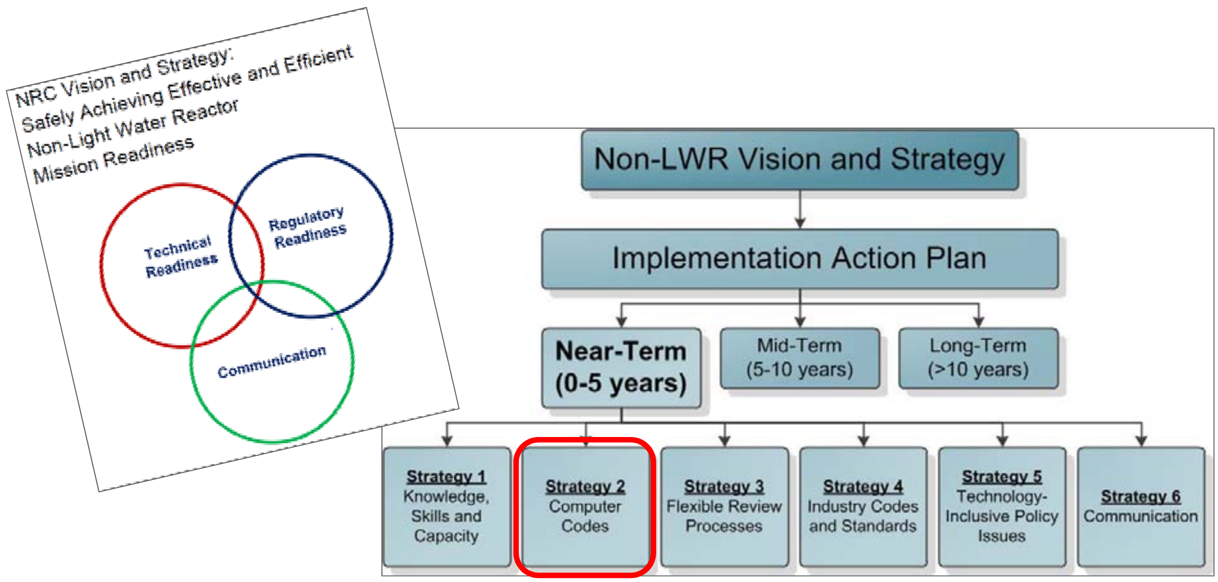
NRC considers high temperature gas-cooled reactors, sodium-cooled fast reactors, and molten salt reactors as the designs of interest in the near-term[1].

Below is a summary of non-LWR reactor designers that have formally notified the NRC of their intent to engage in regulatory interactions[2].

Design	Developer	Technology
Oklo	Oklo Inc.	Compact Fast Reactor
Integral Molten Salt Reactor (IMSR)	Terrestrial Energy USA Ltd	Molten Salt Reactor
Xe-100	X-Energy LLC	Modular High Temperature Gas-Cooled Reactor
Molten Chloride Fast Reactor (MCFR)	TerraPower, LLC	Molten Salt Reactor
Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR)	Kairos Power LLC	Molten Salt Reactor

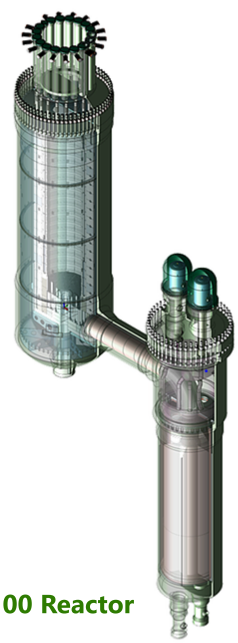
1. NRC Non-Light Water Reactor Near-Term Implementation Action Plans, ML17165A069
2. Source: www.nrc.gov/reactors/new-reactors/advanced.html#preAppAct

NRC has created a Vision and Strategy for licensing non-LWR technologies



High-Temperature Gas-Cooled Reactor Designs

- High-temperature reactors that conceptually can reach high outlet temperatures (up to 1000 °C)
- Typical coolant: Helium
- Two main types:
  - pebble bed reactors
  - prismatic block reactors
- Fuel is coated fuel particles, usually TRISO



Xe-100 Reactor

Vendor/Developer	Size
Los Alamos National Laboratory (MegaPower)	2 Mwe
U-Battery	4 Mwe
Ultra Safe Nuclear Corporation	5 Mwe
HolosGen	13 Mwe
Starcore Nuclear	20 Mwe
X-Energy	75 Mwe
General Atomics	265 Mwe
Framatome	625 MWt

U.S. Experience:

Reactor	Operations
Peach Bottom – Unit 1	1966 – 1974
Fort St. Vrain	1979 – 1989

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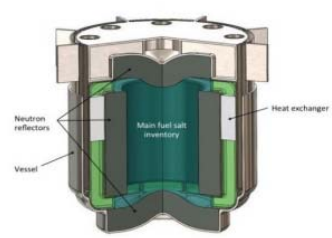
Molten Salt Reactors

- Two major types – salt cooled and salt fueled
  - High temperatures for non-electric applications
  - Low operating pressures
- Fluoride salt-cooled high temp reactor (FHR)
  - Molten fluoride salt as coolant; typically FLiBe
  - Solid fuel; typically TRISO in pins, pebbles
- Liquid Fueled Molten Salt Reactor
  - Molten salt used as both coolant and fuel
  - Salts typically fluoride or chloride
  - Thermal or fast spectrum
  - No fuel fabrication
  - Online refueling
  - Online waste Management

Vendor/Developer
ThorCon
Northern Nuclear (Leadir-PS100/Lead-Cooled)
Kairos Power
Terrestrial Energy (IMSR)
TerraPower (MCFR)
Elysium Industries
Yellowstone Energy



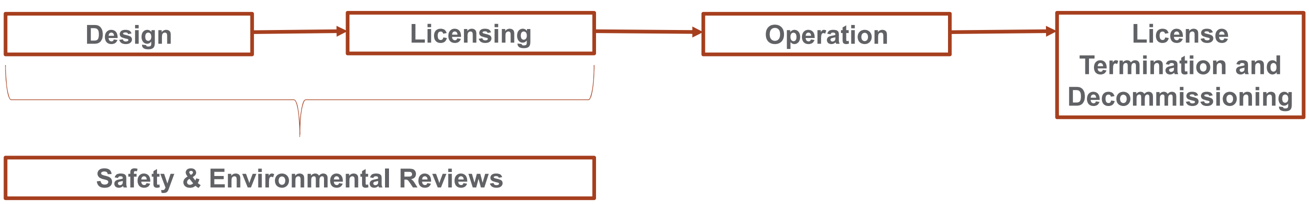
TerraPower MCFR

Fast Reactors

- Sodium-Cooled Fast Reactors
  - Fast neutron spectrum
  - Low pressure for simplified compact operation
  - Liquid metal coolant – high conductivity
  - Enhanced passive safety
  - High fuel utilization
  - Flexible fuel cycle applications that can be self-sustaining
- Lead-Cooled Fast Reactors
  - Liquid metal coolant that is not reactive with air or water
  - Lead or lead-bismuth eutectic options
  - Fast neutron spectrum
  - Low operating pressure
  - High fuel utilization
  - Flexible fuel cycle applications that can be self-sustaining

Vendor/Developer	Size
OKLO	2 MWe
LeadCold Reactors	10 MWe
Westinghouse (eVinci)	25 MWe
Advanced Reactor Concepts	100 Mwe
Columbia Basin Consulting Group	106 MWe
ANL (SUPERSTAR)	120 Mwe
Hydromine AS-200	200 MWe
GE – Hitachi (PRISM)	311 Mwe
Westinghouse (LFR)	450 MWe
TerraPower (TWR)	1150 MWe

Health physics codes evaluate the advanced reactor lifecycle: Phases



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Health physics codes evaluate the advanced reactor lifecycle: Phases

Design → Licensing → Operation → License Termination and Decommissioning

Safety & Environmental Reviews (Design, Licensing)

- **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

Operation

- **EM:** RASCAL

License Termination and Decommissioning

- DandD
- VSP (MARSSIM)
- RESRAD
- VICTORIA

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Advanced reactor lifecycle: Calculations

- 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?

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Technology-neutral code improvements can increase efficiency in licensing reviews

Installed Capacity	Scalable from 2 -- 1200 MWe
Cooling	Molten Salt, Liquid Metal, and High Temperature Gas
Time to Construct	1 - 5 years combination of on-site construction and factory module fabrication
Operation Flexibility	Includes designs that are "Walk-away" safe without operator intervention
Proliferation Concerns	Multiple fuel options including enriched uranium, depleted uranium and used nuclear fuel

- 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

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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.

Industry And Investors → GAIN → DOE National Labs →

Modeling and Simulation

Verification and Validation

Reactor Physics

Licensing Framework

Advanced Designs

GAIN
Gateway for Accelerated Innovation in Nuclear

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

30 Members participate in a TWG	**2016 NE Vouchers awarded to 8 companies**	**2017 NE Vouchers awarded to 14 companies**	**2018 NE Vouchers awarded to 11 companies**	**2019 NE Vouchers awarded to 3 companies**	**66 Other companies involved with GAIN**

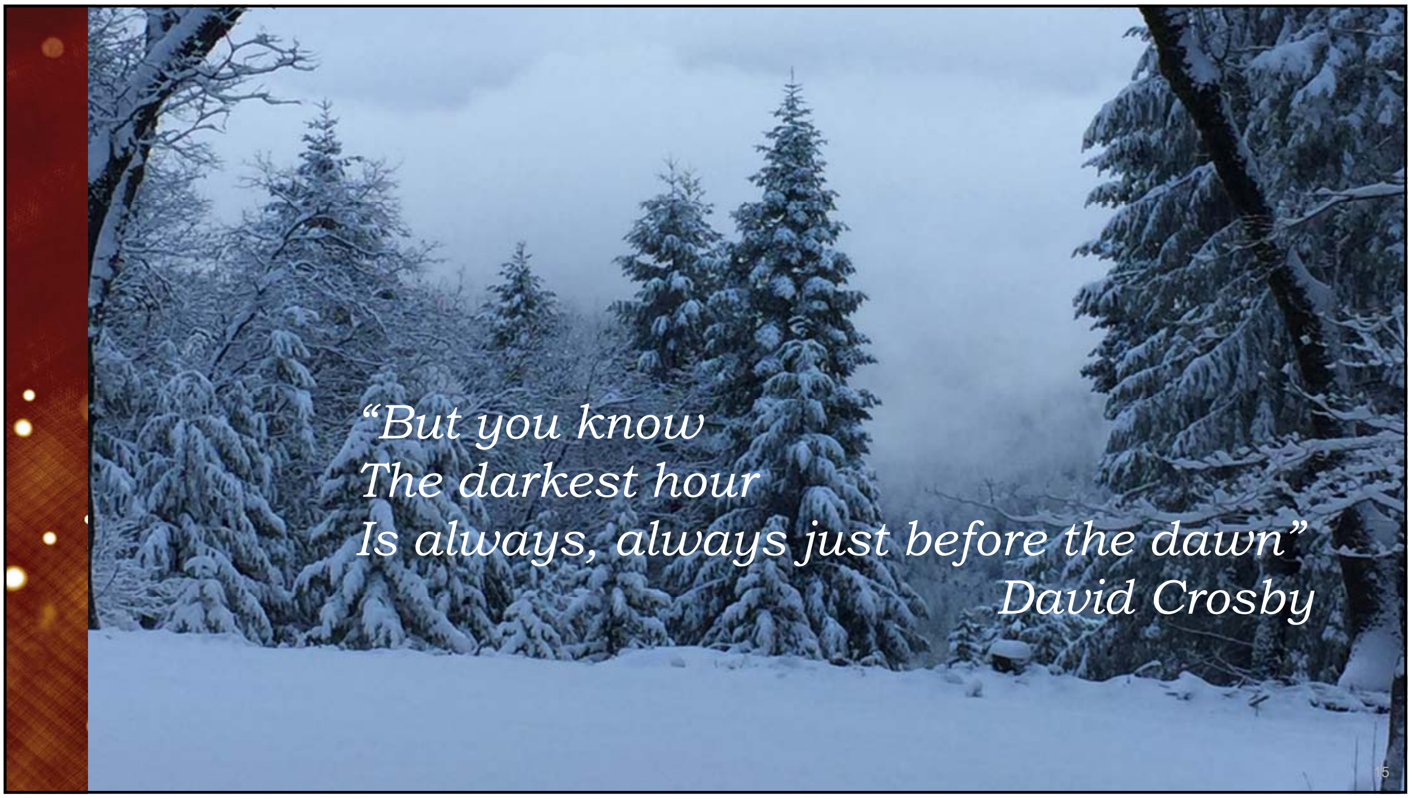
EPRI ELECTRIC POWER RESEARCH INSTITUTE

NEI NUCLEAR ENERGY INSTITUTE

Summary

- NRC considers high temperature gas-cooled reactors, sodium-cooled fast reactors, and molten salt reactors as the designs of interest in the near-term[1]
- 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


"But you know
The darkest hour
Is always, always just before the dawn"
David Crosby
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Thank you