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Small Modular Reactor

IAEA:

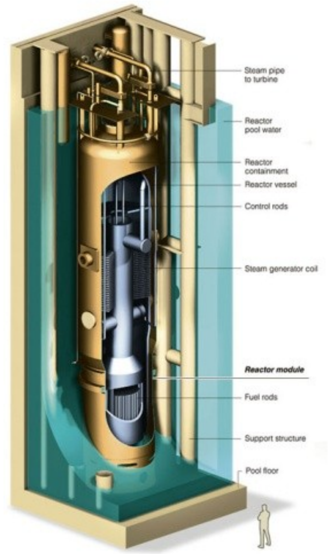
- Small Modular Reactors are defined as advanced reactors that produce electricity of up to 300 MW(e) per module
- Have advanced engineered features
    - Deployable either as a single or multi-module plant
    - Designed to be built in factories and shipped to utilities for installation as demand arises

US NRC

- Refers to light water reactor (LWR) designs generating 300 MWe or less as small modular reactors (SMRs).

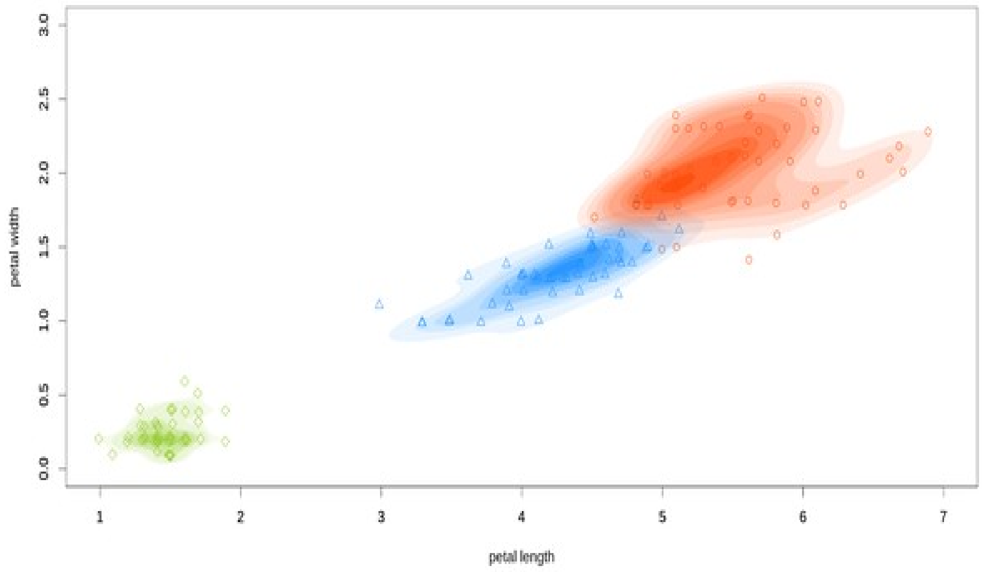
US DOE:

- Small Modular Reactors, envisioned to vary in power size from tens of megawatts up to hundreds of megawatts
- Can be used for power generation, process heat, desalination, or other industrial uses.



SMR Properties

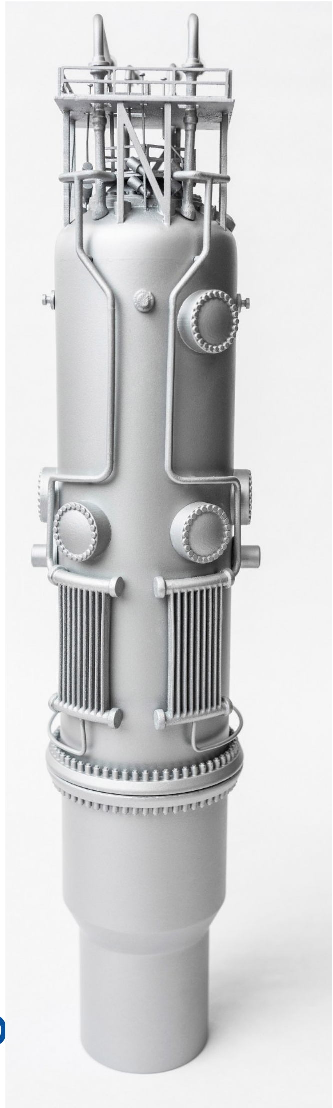
- Small – less than 300MWe (Greater than ~10 MWe?)
- Safe – Passive operation, low water use, small source terms, low electric demands, slow transients
- Modular Designs – Factory built and transported to the site. (Right sized)



- Flexible power generation for a wide variety of applications.
- Economic – lower initial costs, serial production, smaller inputs
- Small footprint – smaller Emergency Protective Zones
- Well suited to replace fossil plants
- Support Integrated Energy Systems and non-Electric Production

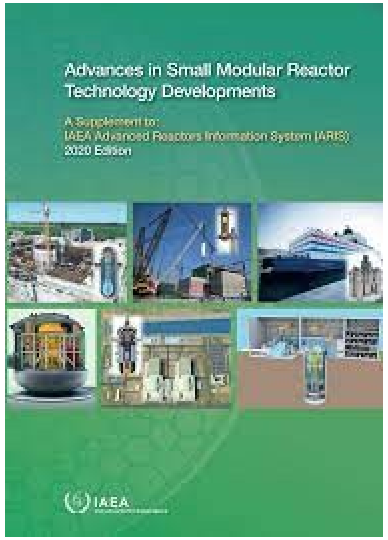
SMR Enabling Features

- Simplified Design
  - Integral
  - Fewer active components
- Modular
  - Economics of multiples
- Designed for Safety
  - Below grade construction
  - Reduced safety systems for cyber improvements
  - Reduced size and source term
- Passive
  - Improves safety response
  - Smaller vessel and containment allow passive coo



SMR Under Development

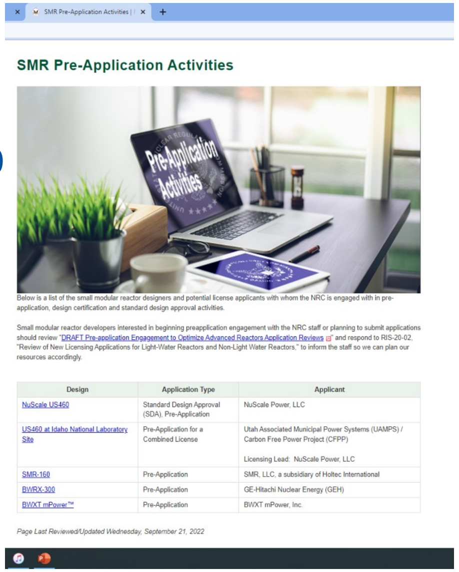
Advanced Reactor Information System (ARIS)



Database of international designs -- Not all reactors under development

- 6 micro reactors
- 10 molten salt reactors
- 11 fast reactors
- 14 high temperature gas reacto
- 6 barge mounted reactors
- 25 light water reactors
- 15 Countries represented
- 5 Light Water Reactors
  pre-licensing at NRC
- 1 Advanced reactor under review
- 10 Preapplication interactions

U.S. NRC Licensing Documentation

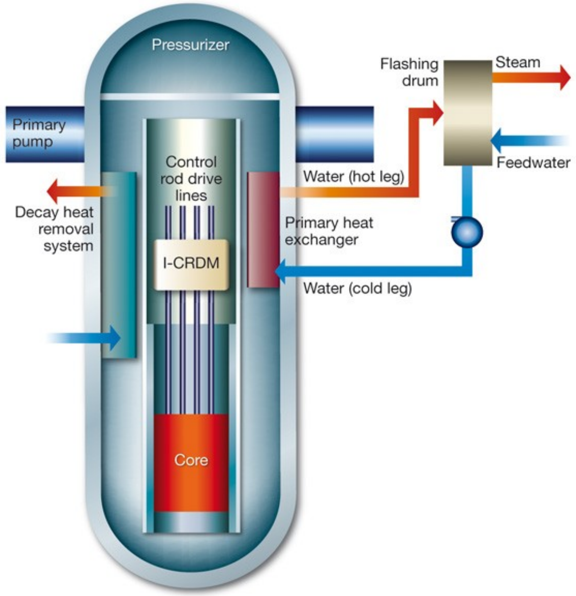


Mature concepts

Economics

- Designed for complex grid
  - Match renewable performance
    - Rapid power changes
    - Provides predictable grid support
  - Support Integrated Energy Systems
    - High temperatures if needed
    - Sized for industrial applications
    - Modular units can be optimized
- Modular benefits
  - Deployed individually for a right size NPP
  - Deployable to match financing support
  - Deployed where energy is most useful
    - Can support smaller grids
    - Can support growing grids
  - More predictable deployment costs and schedule
- Improved safety reduces insurance requirements?

Safety Features of SMR



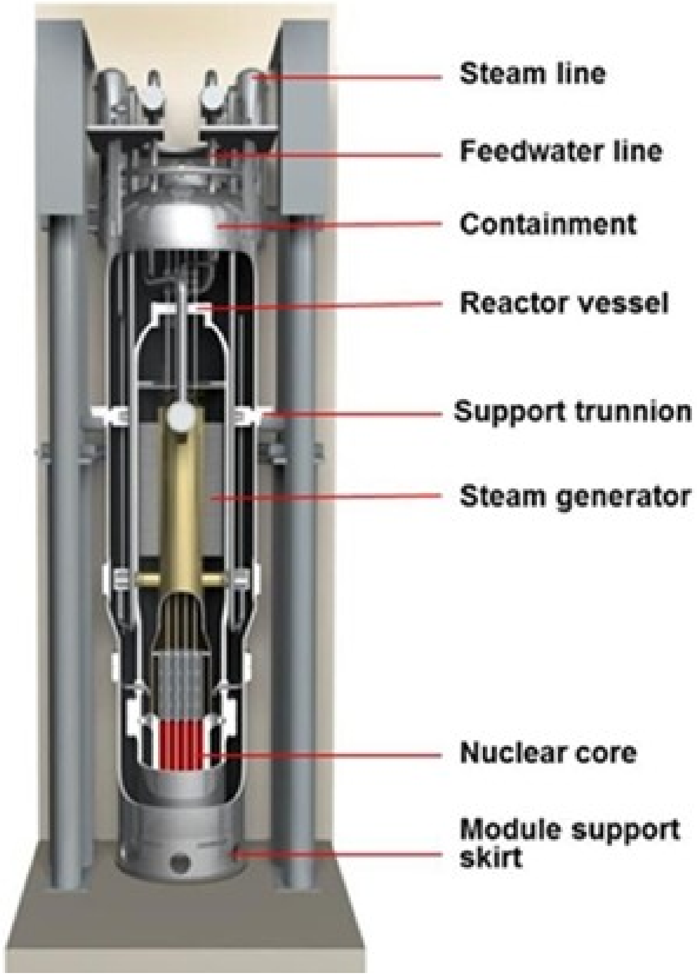
- Integrated Designs
  - Eliminates failure points
    - Fewer/no pipes
    - Fewer valves, controls
    - Eliminates/reduces pipe break accidents
  - Simplifies factory build
    - More precise construction
    - Improved quality
  - Steel containment instead of concrete improves thermal performance post accident
  - Submerged containment improvements
    - Longer release paths
    - High thermal mass
    - Improved security
- Passive Operation
  - Reduced active components simplify reactor
  - Fewer actions needed to operate reactor, safe passive shutdown
  - Less maintenance on few components
  - Reduced safety system complexity creates a smaller cyber target

Safety Features of SMR

- Smaller reactors have smaller source terms
  - Physically smaller size and power reduce fission materials
  - Separating power across cores reduces release fraction
- Lower power density
  - Lower post event cooling requirement
  - Lower chance of challenging fission barriers
- Increased coolant fraction
  - SMR tend to have higher coolant fraction
  - Increased thermal mass
  - Easier to provide long term cooling
- Smaller containment size
  - Easier to cool smaller systems
  - Passive systems able to cool containment

iPWR Solutions

- Addresses major challenges of large reactors
  - Simplified design with smaller size and inputs
  - Increased safety with passive features
  - Lower total costs, lower operating costs
  - Smaller optimized projects
    - Nuclear Plant can be right sized to grid
    - Less changes to grid required for integration
    - Can be installed in stages (add modules over time)
  - Factory built
    - Reduces construction uncertainties
    - Changes quality control
    - Less uncertainty in schedule
  - Cost per MWh decreases as power increases
  - Further improvements as technology develops

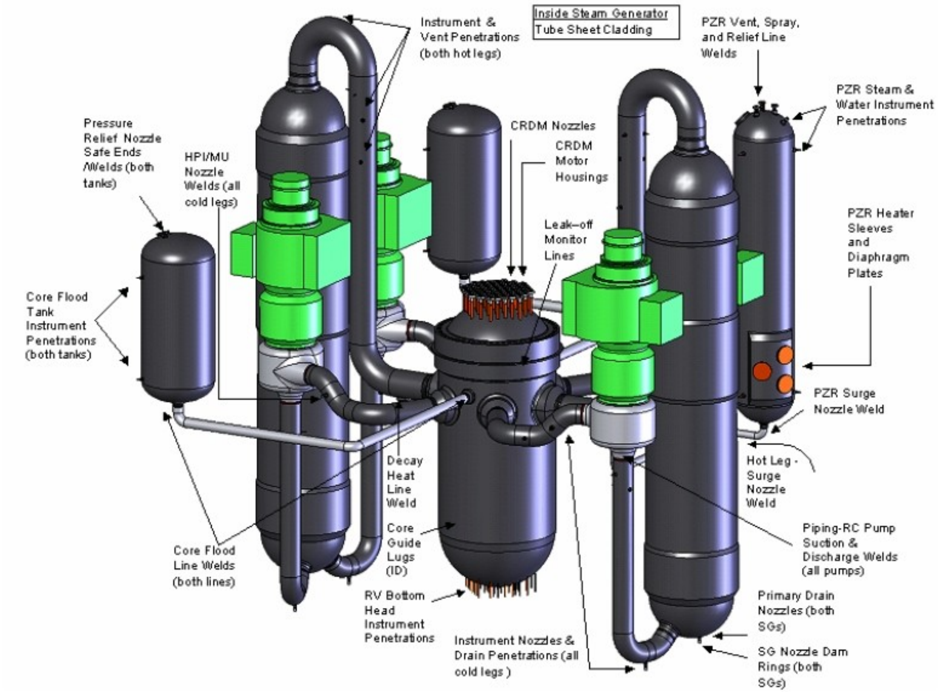


Integrated Reactor

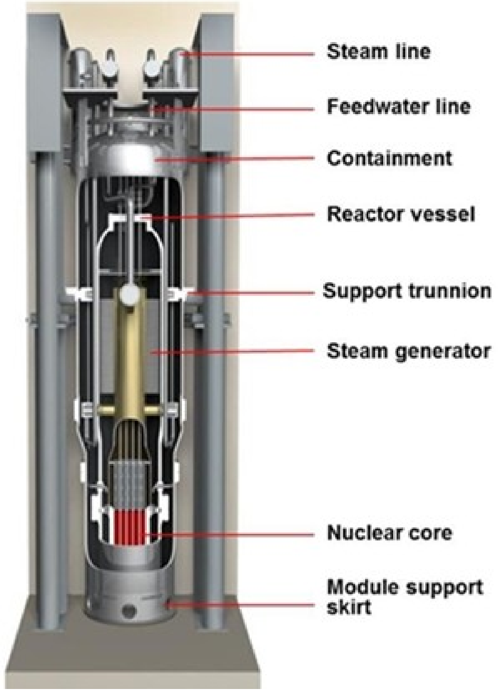
SMR reactor and full primary system in one vessel

Simplified systems

Fewer failure modes



PWR Reactor



iPWR Reactors

LWR Safety Systems compared to SMR

Typical/Partial LWR safety systems

Reactor Pressure Vessel	Containment Vessel
Primary Coolant System	Decay Heat Removal System
Emergency Core Cooling	Emergency Control Systems
Active Containment Control	Ultimate Heat Sink
High Pressure Injection	Low Pressure Injection
Stored Water	Containment Cooling
Emergency Electrical Supply System	Emergency Shutdown

Typical/Partial SMR safety systems

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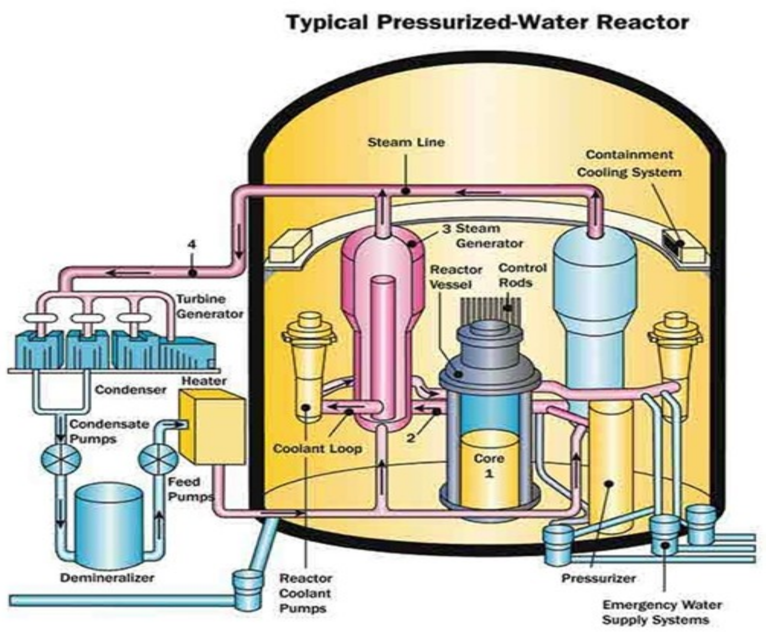
Emergency Core Cooling	Emergency Control Systems
Ultimate Heat Sink	

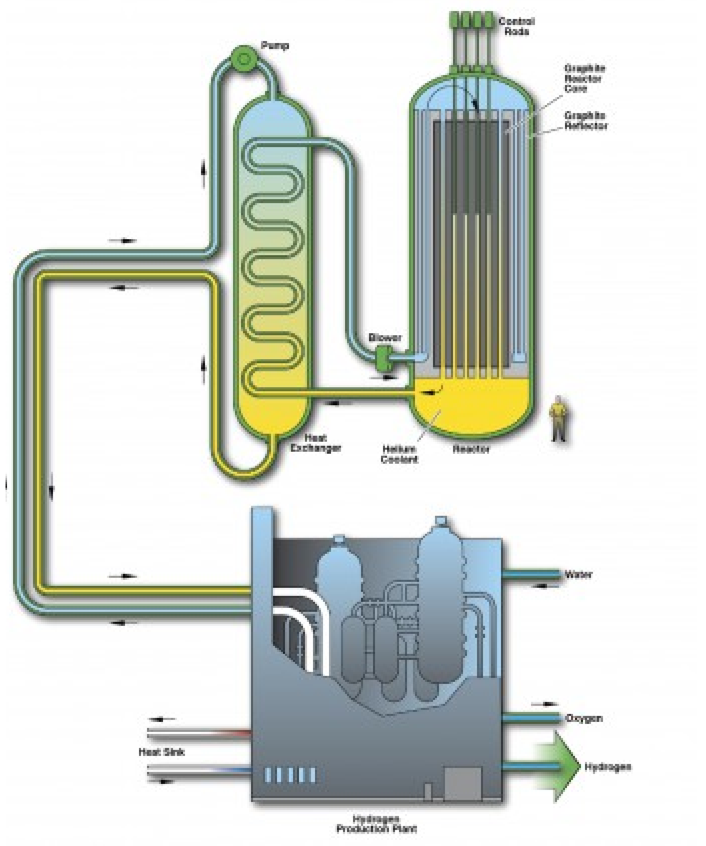


Non-core SMR Safety Features

- SMR can support black start grid conditions
- SMR can operate in island mode supporting critical local systems
- Underground construction
  - reduces impact risks from debris and aircraft
- Small physical footprints

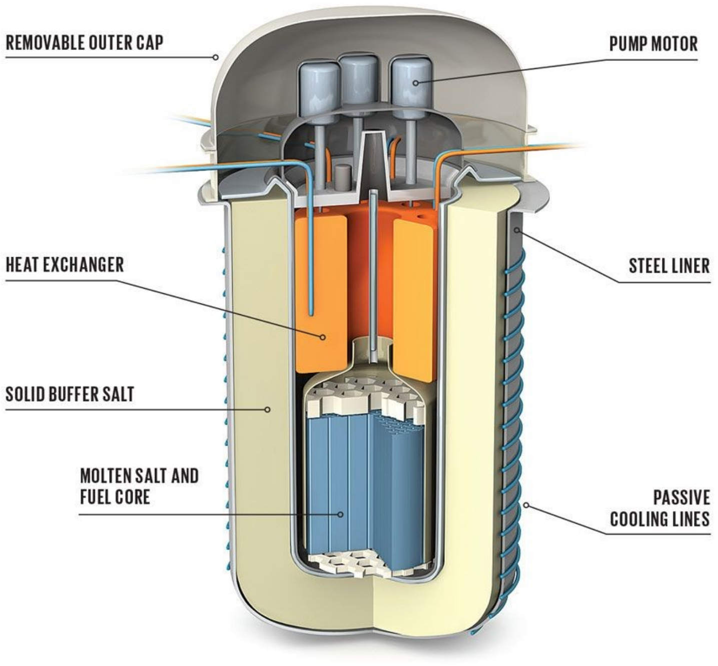
HTGR Safety Features

- High Temperature Gas Cooled Reactor Safety Features
  - High temperature limits
    - High temperature suitable for industrial uses
    - Higher thermal efficiency
    - Designed around TRISO fuel designs
  - High thermal capacity
  - Low Power Density
  - Slow Transient Reactions
  - Non-reactive Coolant (Helium)
  - Graphite Moderated



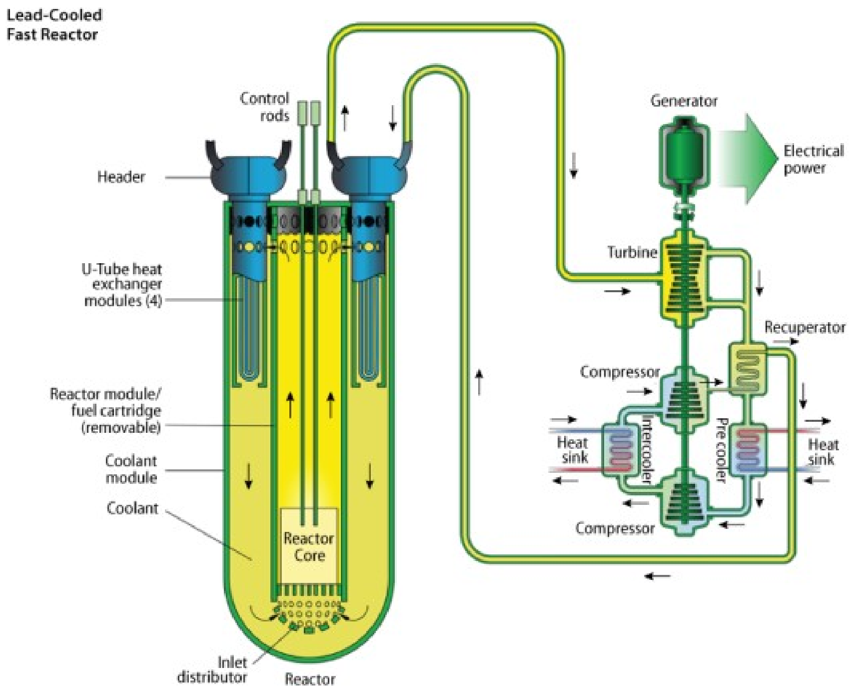
Molten Salt SMR Safety Design Features

- High Temperature System
  - Suitable for Industrial applications 600C++
  - High thermal conductivity coolant and cooling systems
    - Physically smaller systems
  - Low pressure system
  - Non-reactive coolant
  - Multiple coolant concepts
    - Dissolved fuel – minimum excess reactivity
    - TRISO inclusion – minimum excess reactivity
    - Fixed TRISO fuel forms
  - Potential to remove fission products on-line



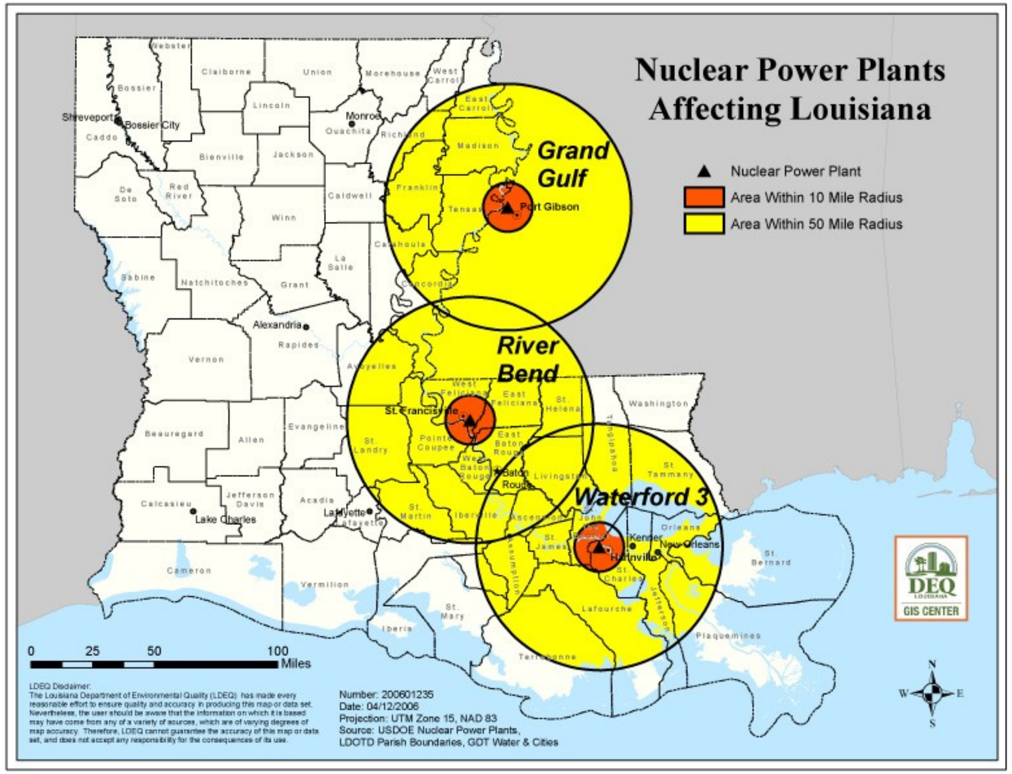
Liquid Metal Cooled SMR Safety Design Features

- High Temperature System
  - Suitable Industrial applications 600C++
  - High thermal conductivity coolant and cooling systems
    - Physically smaller systems
  - Low pressure system
  - Non-reactive coolant for Pb and PB/Bi
  - Inherent safety from fast spectrum
    - EBR-II demonstration of stopping cooling at full power
  - Fast spectrum reduces affects of fission products



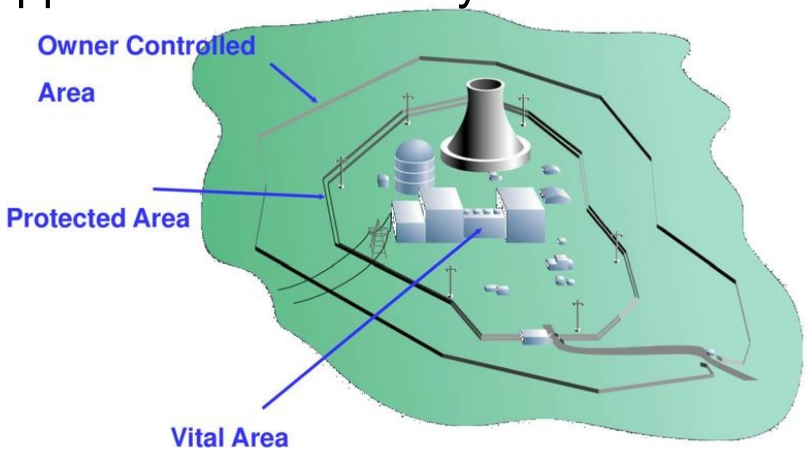
Emergency Protective Zones

- Increased safety reduces chance and severity of radioactive releases.
- Small amount of fission products limits total release activity.
- Low release fractions allow reduced dose near the plant.
- Safety levels allow EPZ to be greatly reduced.
  - Potentially at building or site fence boundary



Security Benefits from Increased SMR Safety

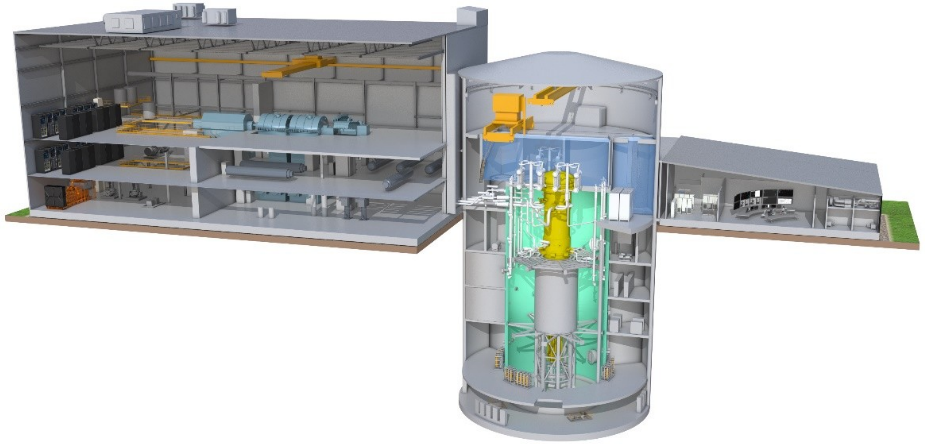
- The security design basis threat is based on realistic assessments of the tactics, techniques, and procedures used b y opposition and security forces.
- SMRs may have lower security risks because of:
  - smaller reactor core sizes,
  - lower power densities,
  - lower probability of severe accidents,
  - slower accident progression,
  - RPV containing most safety systems,
  - more passive safety systems,
  - fewer safe shutdown systems,
  - below ground construction
  - smaller accident offsite consequences per module
  - Minimal operator actions needed



- Improved security design principles for SMR:
  - Locate and configure vital components to be difficult and time consuming to reach
  - Space out critical equipment
  - Incorporate multiple delaying barriers
  - Have limited (minimized) access points

Multiple Units

- SMR Nuclear Power Plants are built with multiple reactors
  - For example, NuScale Nuclear Power Plant 12 units 77 MWe, GEH BWRX-300, 2 units 300MWe, Kairos KP-FHR 145 MWe, Holtec SMR-160 160 MWe, X-energy, XE-100, 4 units, 80 MWe
- Benefit of multiple smaller reactors
  - Lower costs
  - Progressive deployment and separate operation
- Allows operational flexibility and alternate uses
- Unique operation
  - Some units can be dedicated to non-electrical use
  - Allows maintenance scheduling
  - Partial plant outage
  - Different units at different powers
  - Economic response to grid demands
  - Deploy as power need grows



Factory Built

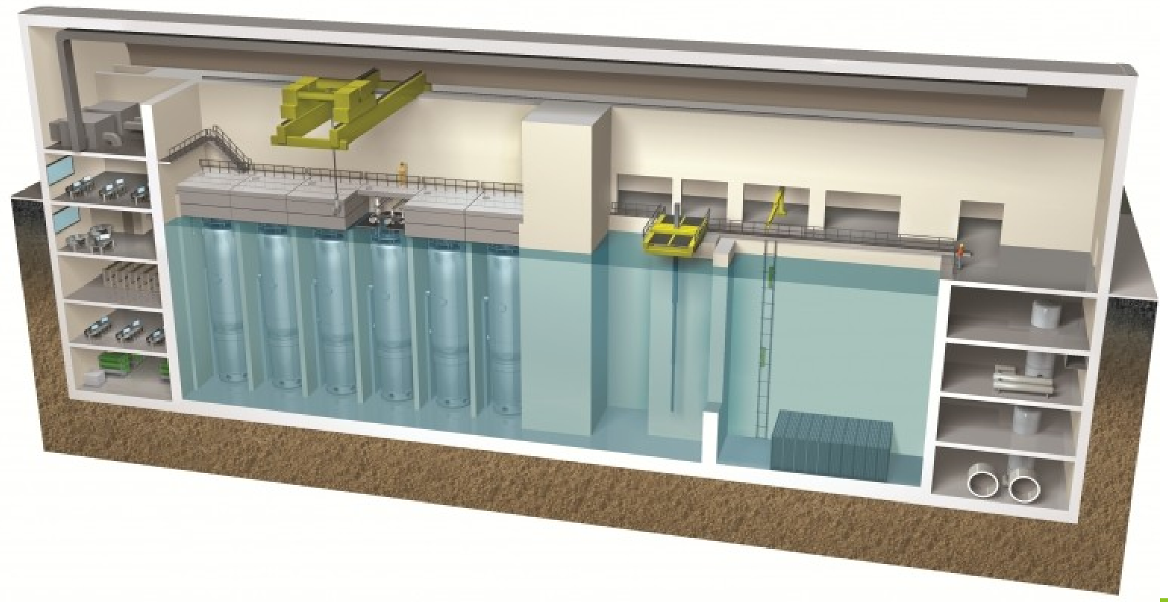
Flexible Operations

- Reactor control systems and steam systems built to allow rapid changes in power.
- Multiple units can allow dedicated operations tied to industrial applications
- Increasing temperatures in advanced reactors allow for use in more industrial applications, LWR can supplement heat with electrical use.
- Increased value products and inventory can be created.
  - Hydrogen, ammonia, liquid fuels, drying, chemical processing, concrete, desalination and district heating are non-electric applications being studied.

NuScale VOYGR Nuclear Power Plant

Single unit

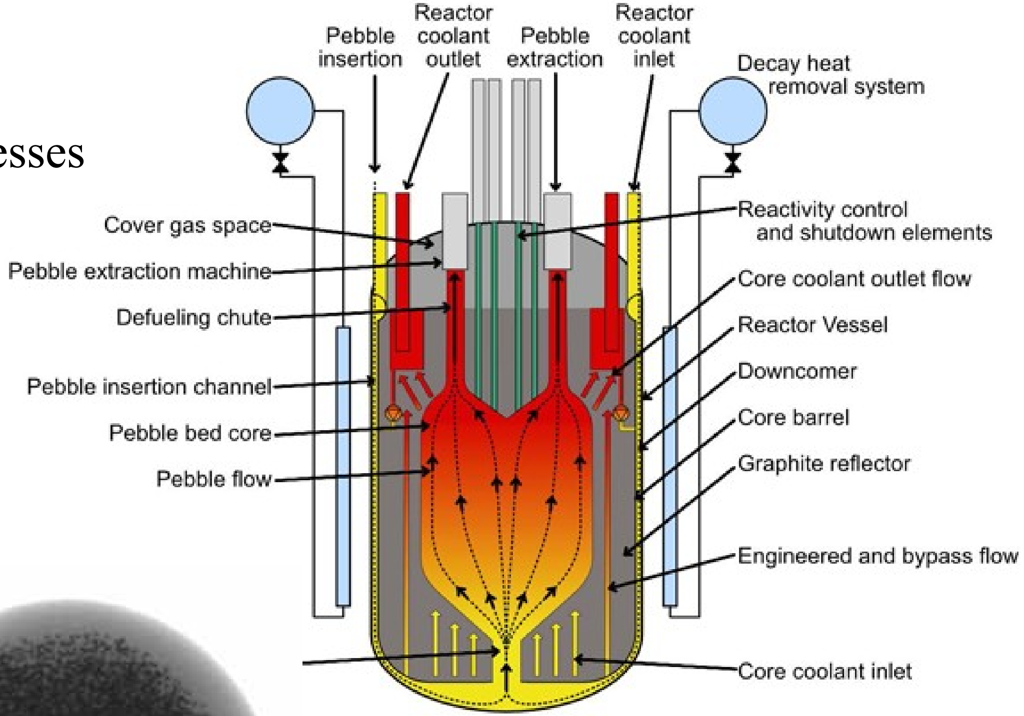
- 77 MWe, 28% efficient
- Up to 12 units per plant planned 924 MWe total
- Vessel 2.7m diameter, 20m high, 264t
- Rail, truck or barge shipping
- Natural circulation for operation
- Emergency core cooling is passive, utilizing natural circulation

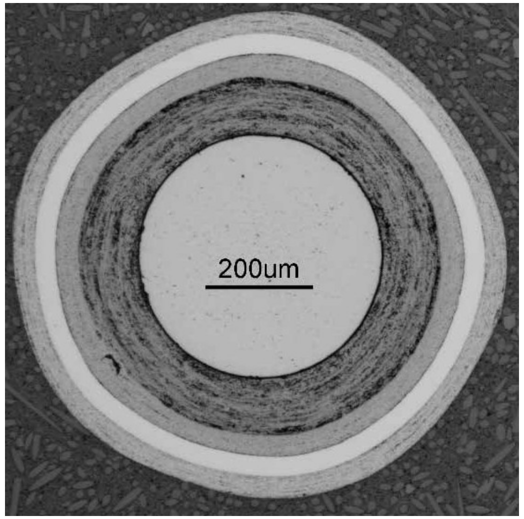


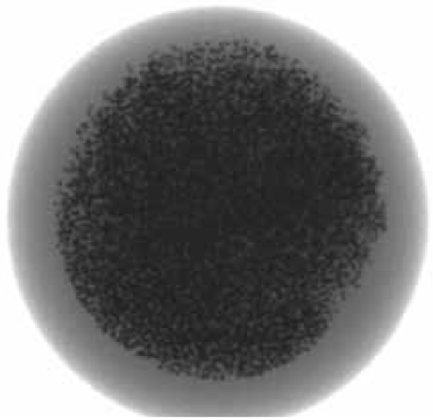
NuScale plant showing multiple reactors with largely below grade construction

Kairos KP-FHR

Molten Floride Salt Cooled Reactor
Triso Fuel Sphere Design
High temperature for industrial processes
140 MW_e, 320 MW_{th}
Core exit temperatures (C) 585
Online refueling

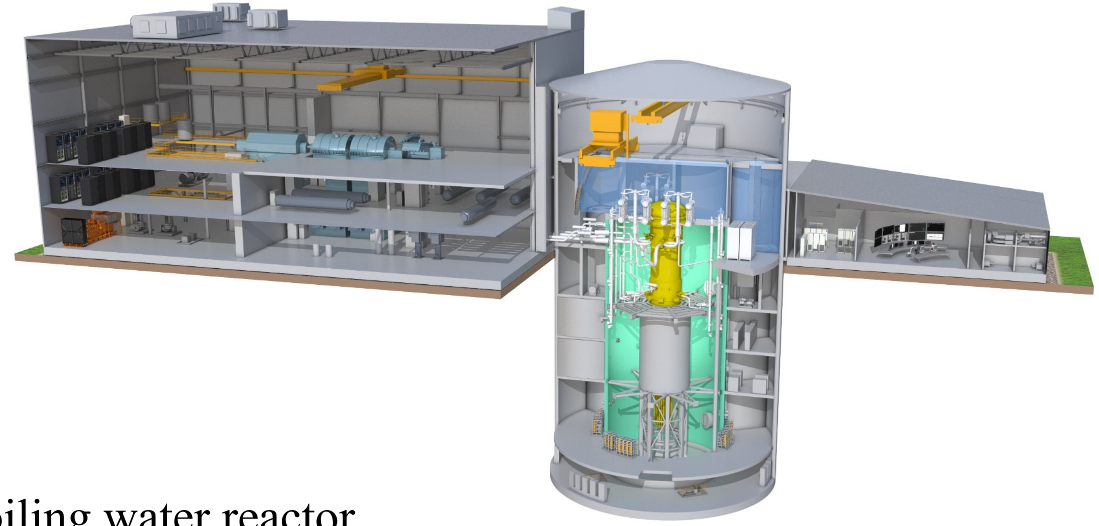






Pictures from Kairospower.com and INL

GE/Hitachi BWRX-300

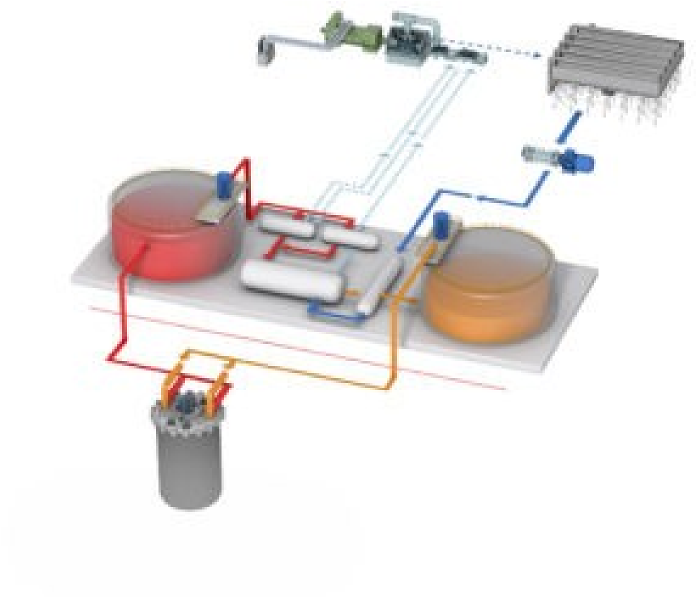


- Water cooled boiling water reactor
- Conventional UO_2 fuel+
- Designed to be easily deployed based on modern experience
- Electric generation and district heating applications
- 300 MW_e, 870 MW_{th}
- Core inlet/exit temperatures (C) 270/285
- Heat Use at (C) 100/200

Pictures from nuclear.gepower.com

TerraPower, NATRIUM

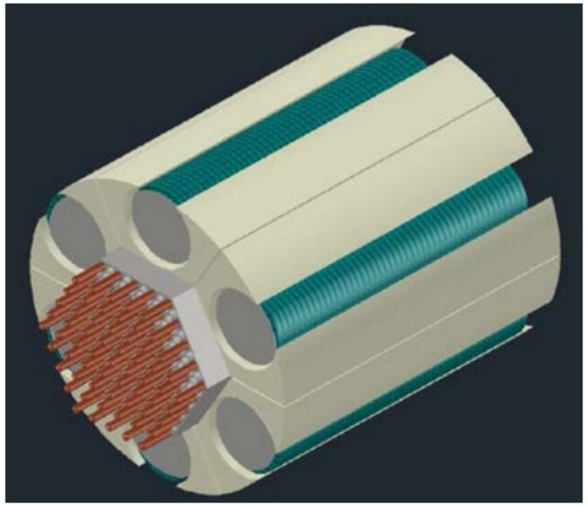
Na Cooled Fast Reactor
Metallic Fuel
Flexible electric generation, industrial use
345 MW_e,500MW_e peak -5.5 hours
Core exit temperatures (C) 500-550
Reduced Concrete Use

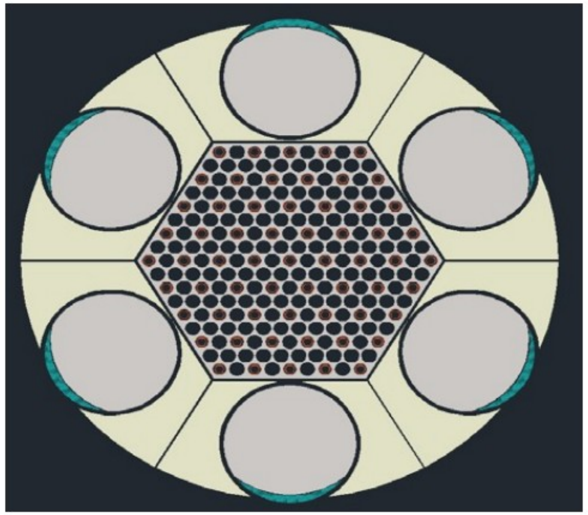


Pictures from terrapower.com

OKLO Microreactor

- Heat Pipe Fast Reactor
- Metallic Fuel
- Based on space reactor concepts
- Flexible electric generation, industrial use
- $4MW_{th}$
- Core exit temperatures (C) 600
- Supercritical CO_2 p





Conclusions

- SMR have complex sets of properties to improve:
  - Cost
  - Schedule
  - Uncertainty
  - Safety
- SMRs offer safety is increased based on many physical and design feature
- Improved safety benefits security, siting, economics and EPZ, cybersecurity.
- Work is underway on SMR licensing, deployment, economics and market
- SMR market is rapidly developing

Contact Information

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Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

Challenges to Traditional Nuclear Power

- Long times to license new technology
- Large projects that are more difficult to manage, supply and build out
- Large plants require a large grid

and are optimized for base load electrical supply

- Long construction times
- Difficult to finance
- Energy markets are rapidly changing

and flexible systems are attractive