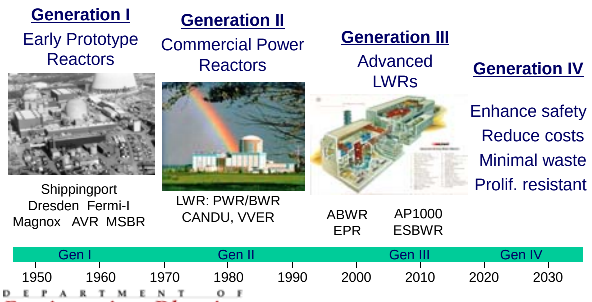
# Resilience in Safety Engineering: Long-Term Cooling in Nuclear Power Plants

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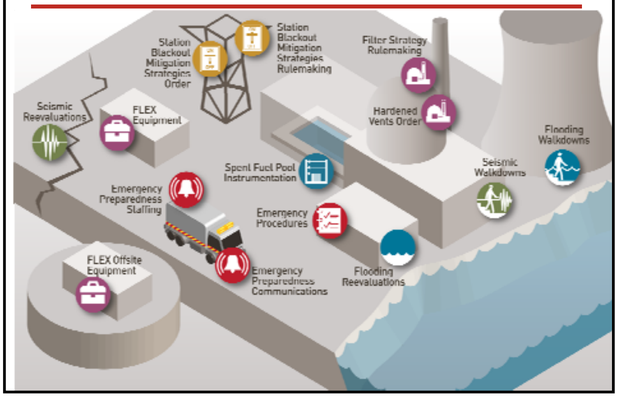
## Technical Perspective

- The inherent nature of a nuclear power plant design recognizes that after the fission process stops, thermal heat is still produced by the decay of fission products that remain and must be removed to a heat sink
- This 'decay heat' while small (<1% of $P_O$) is still substantial enough that safety systems must be designed and operational procedures must be developed to assure long-term heat removal
- Resilience in safety engineering is a key objective

## Technical Perspective

- USNRC (2008) began to evaluate the design basis for the long-term core cooling approach for each new reactor design considering extended time periods (days)
- Fukushima only sharpened the focus on the need to assure long-term cooling for beyond design basis events
- Finally, in all advanced nuclear plant designs, so-called Generation IV plants, this concept of long-term cooling is imbedded in the inherent plant design.

## Safety Actions after Fukushima




## NAS Fukushima Study

NAS Study commissioned by Congress 2012: Task Statement

1. Causes of the Fukushima nuclear accident.
2. Re-evaluation of conclusions from previous NAS studies on safety and security of spent nuclear fuel and high-level radioactive waste storage.
3. Lessons that can be learned from the accident to improve commercial nuclear plant safety and security systems and operations.
4. Lessons that can be learned from the accident to improve commercial nuclear plant safety and security regulations

*Note: Most findings and recommendations in NAS report mirror those made by other organizations, including the USNRC Near-Term Task Force. But, NAS report provides different perspectives on some issues.*



## NAS Fukushima Recommendations

USNRC & US nuclear industry should improve nuclear plant systems:

- DC power for instrumentation and safety system control.
- Tools for estimating real-time plant status during loss of power.
- Long-term Decay-heat removal and reactor depressurization and containment venting systems and protocols.
- Hydrogen monitoring and mitigation.
- Instrumentation for monitoring critical thermodynamic parameters in reactors, containments, and spent fuel pools as well as offsite radiation monitoring.
- Communications and real-time information systems to support communication and coordination between control rooms and technical support centers.

***Additional recommendation were in the areas Operator Training, Offsite Emergency Response and Risk Assessment; e.g., beyond design base analysis***

# AP1000

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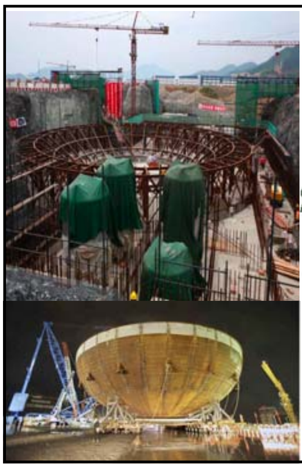
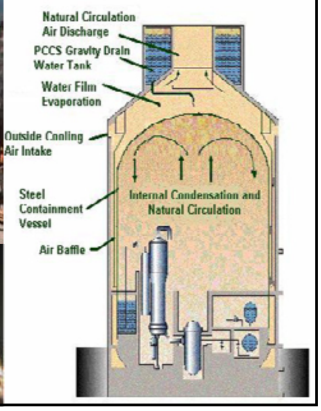




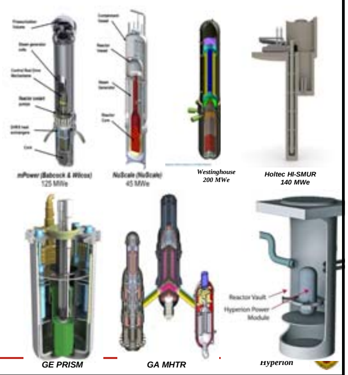

# Advanced Reactor Systems

**Near-Term LWR Designs**

- Well understood Technology
- Fuel <5% U-235 oxide fuel
- Regulatory & operating experience
- Deployment in <10 years

**Longer-Term Gen IV Designs**

- New innovative technologies
- Mostly non-LWR based designs
- Deployment 20+ years
- Broader applications
- Process heat applications
- Transportable/mobile
- Long-lived cores

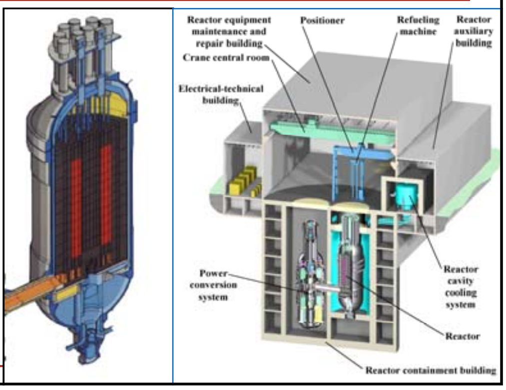



# Very-High-Temperature Reactor (VHTR)

EPACT 2005 Authorized

Characteristics
- Helium cooled
- 900° C temp.
- 600 MWth

Key Benefit
- High thermal efficiency
- Hi-Temp Process Heat

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*Fluoride Salt-Cooled High-Temperature Reactor (FHR)*


General Electric S-PRISM

Passively-Safe Reactor

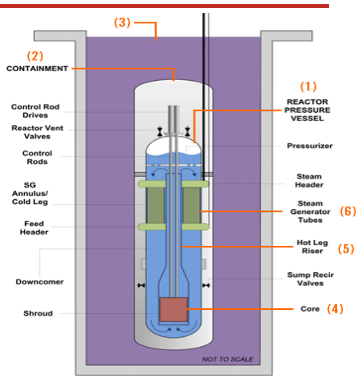

GE Power Systems MS7001FB

Nuclear Brayton Combined Cycle

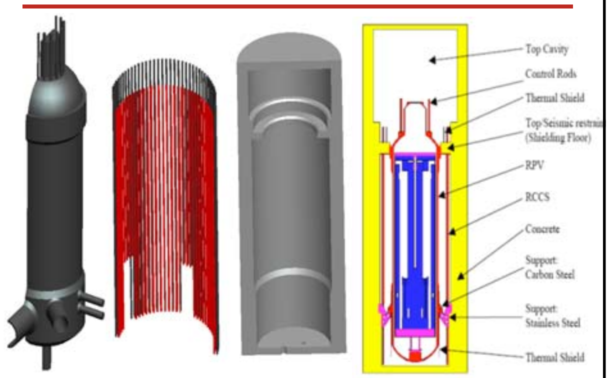
Hi-Temperature Coated-Particle Fuel

High-Temp, Low-Pressure Liquid-Salt Coolant

# SMR Long-term cooling issues: Natural Circulation and Condensation




# High-Temp Reactor Long-term Cooling: Natural Circulation & Flow Instabilities



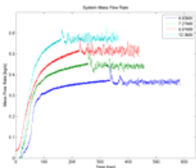
## UW Scaled Water-Cooled RCCS

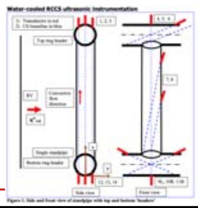
Data Acquisition
- x60 Thermocouples
- x1 Magnetic mass flow
- x3 UDV velocity TDX
- x4 Heat flux sensors
- x4 X-ray void fraction

Facility
- Variable scale
  1:4 distorted
  1:6 true
- 2 bar max
- 350 gal. capacity

Test Section
- 3 risers
- 3 radiant fins
- 18.5' total
- 12.0' heated

Power
- 34 heaters
- 6 control zones
- 42.5 kW max





*3 story facility, 24' total height*

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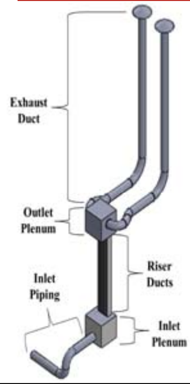
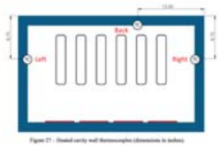
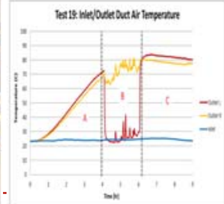
## UW Scaled Air Cooled RCCS










## Current Observations on Resilience

- Fukushima events reminded us that the key objective of nuclear safety engineering is to demonstrate long-term cooling of decay heat to an ultimate heat sink.
- Current plants need to show this ability by upgraded decay heat removal systems (e.g., FLEX approach)
- Advanced LWR plants are designed to use passive safety systems with minimal operator action
- Generation IV plants need to be designed and tested to demonstrate this ability.