

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

The diagram shows a timeline of nuclear reactor generations from 1950 to 2030. It is divided into four generations:

- Generation I (1950-1960):** Early Prototype Reactors. Examples: Shippingport, Dresden, Fermi-I, Magnox, AVR, MSBR.
- Generation II (1970-1990):** Commercial Power Reactors. Examples: LWR: PWR/BWR, CANDU, VVER.
- Generation III (2000-2010):** Advanced LWRs. Examples: ABWR, EPR, AP1000, ESBWR.
- Generation IV (2020-2030):** Enhance safety, Reduce costs, Minimal waste, Prolif. resistant.

Michael Corradini

## 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  $P_0$ ) 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

The diagram illustrates various safety actions implemented after the Fukushima incident, including:

- Station Blackout Mitigation Strategies, Order
- Station Blackout Mitigation Strategies, Rulemaking
- Filter Strategy, Rulemaking
- Hardened Vents Order
- Flooding Walkdowns
- Seismic Walkdowns
- Seismic Reevaluations
- Flooding Reevaluations
- Emergency Procedures
- Emergency Preparedness Communications
- Emergency Preparedness Staffing
- Special Fuel Pool Instrumentation
- FLEX Equipment
- FLEX Offsite Equipment

## NAS Fukushima Study

NAS Study commissioned by Congress 2012: Task Statement

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

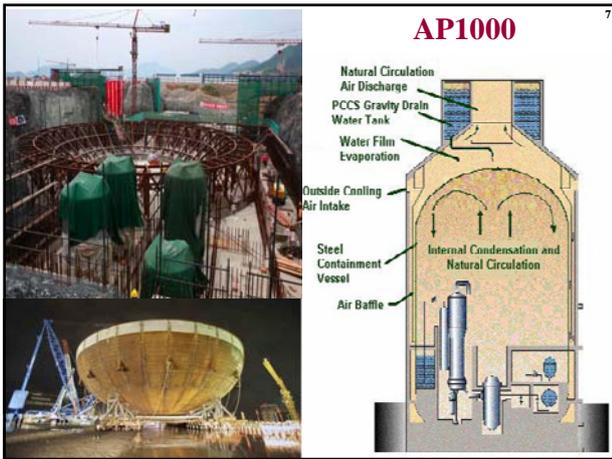
*Note: Most findings and recommendations in NAS report mirror those made by other organizations, including the USNRC Near-Term Task Force. But, NAS report provides different perspectives on some issues.*

## 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*



**Advanced Reactor Systems**

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**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)**

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EPACT 2005 Authorized

Characteristics

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

Key Benefit

- o High thermal efficiency
- o Hi-Temp Process Heat

Reactor equipment maintenance and repair building  
Crane central room  
Electrical-technical building  
Positioner  
Refueling machine  
Reactor auxiliary building  
Power-conversion system  
Reactor cavity cooling system  
Reactor  
Reactor containment building

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

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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**

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(1) REACTOR PRESSURE VESSEL  
Pressurizer

(2) CONTAINMENT  
Control Rod Drives  
Reactor Vent Valves  
Control Rods  
SG Annulus/Cold Leg  
Feed Header  
Downcomer  
Shroud

(3)

(4) Core

(5) Hot Leg Riser

(6) Steam Generator Tubes  
Steam Header  
Steam Header

Sump Recirc Valves

NOT TO SCALE

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

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Top Cavity  
Control Rods  
Thermal Shield  
Top Seismic restraint (Shielding Floor)  
RPV  
RCCS  
Concrete  
Support: Carbon Steel  
Support: Stainless Steel  
Thermal Shield

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## UW Scaled Water-Cooled RCCS

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3 story facility, 24' total height

**Data Acquisition**

- x60 Thermocouples
- x1 Magnetic mass flow
- x3 UDV velocity TDX
- x8 Heat flux sensors
- x4 X-ray void fraction

**Facility**

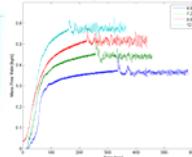
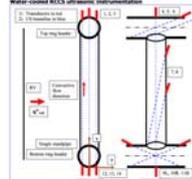
- Variable scale
- 1.4 distorted
- 1.6 true
- 2 bar max
- 350 gal. capacity

**Test Section**

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

**Power**

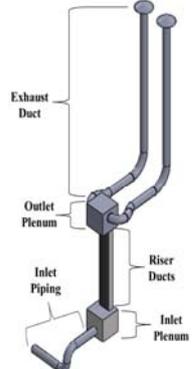
- 34 heaters
- 6 control zones
- 42.5 kW max

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## UW Scaled Air Cooled RCCS

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Inlet Plenum    Heated Cavity    Outlet Plenum

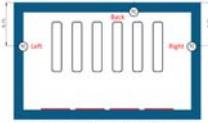
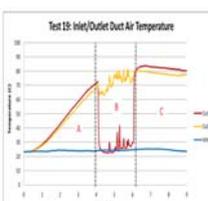


Figure 27 - Heated cavity wall thermocouples (thermocouples in inches)



Test 19: Inlet/Outlet Duct Air Temperature

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## Current Observations on Resilience

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- 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.

