

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

**Generation I**  
Early Prototype  
Reactors



Shippingport  
Dresden Fermi-I  
Magnox AVR MSBR

**Generation II**  
Commercial Power  
Reactors



LWR: PWR/BWR  
CANDU, VVER

**Generation III**  
Advanced  
LWRs



ABWR  
EPR AP1000  
ESBWR

**Generation IV**

Enhance safety  
Reduce costs  
Minimal waste  
Prolif. resistant

Gen I	Gen II	Gen III	Gen IV
1950	1970	2000	2030

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**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

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## 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.

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## Safety Actions after Fukushima



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## 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.*

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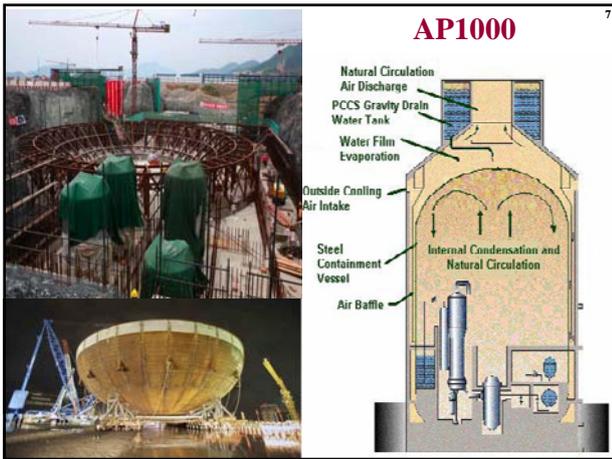
## NAS Fukushima Recommendations

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*

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**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

AP600 (Babcock & Wilcox) 125 MWth  
NuScale (NuScale) 45 MWth  
Westinghouse 200 MWth  
Holtec HI-SMR 140 MWth  
GE PRISM  
GA MHTR  
Hyperion

**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

9

**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

W

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

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(1) REACTOR PRESSURE VESSEL  
Pressurizer

(2) CONTAINMENT

(3)

(4) Core

(5) Hot Leg Riser

(6) Steam Generator Tubes

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

Steam Header  
Steam Generator Tubes  
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**

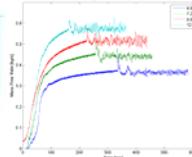
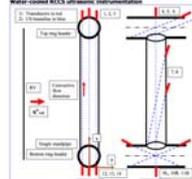
- Variable scale
- 1.4 distorted
- 1.6 true
- 2 bar max
- 350 gal. capacity

**Test Section**

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

**Power**

- 34 heaters
- 6 control zones
- 42.5 kW max

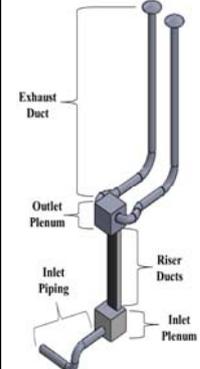



Water-cooled RCCS schematic (top-down view)

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## UW Scaled Air Cooled RCCS

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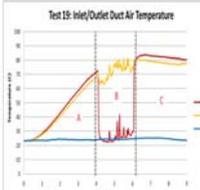




Inlet Plenum

Heated Cavity

Outlet Plenum



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.

