Loss of Ultimate Heat Sink

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Available ultimate heat sinks at 1F1~3

- **1F1 (Fukushima Dai-ichi Unit 1)**
  - Sea water through HX and RHRSW
  - Atmosphere
    - Isolation Condenser; water evaporation in the tank and steam into the air
  - Atmosphere (in Severe Accident Management, both P/S and M/S)
    - ADS or SRV opening to depressurize RPV
    - Coolant make up
    - PCV venting (release high temp and high pressure steam into the air)

- **1F2, 3 (Fukushima Dai-ichi Unit 2 and 3)**
  - Sea water through HX and RHRSW
  - Atmosphere (in Severe Accident Management, both P/S and M/S)
    ---- the same as 1F1
Isolation Condenser for Unit 1

Train A    Heat sink = atmosphere
Train B

Source: Boiling Water Reactor (BWR) Systems (Modified)
USNRC Technical Training Center

No accident condition
Normal Decay Heat Removal mode

Source: Boiling Water Reactor (BWR) Systems (Modified)
USNRC Technical Training Center
Ultimate Heat Sink: No Diversity for Unit 2 & 3

Diversity of Ultimate Heat Sinks

Source: Boiling Water Reactor (BWR) Systems (Modified)
USNRC Technical Training Center
1F1~3: EDG startup after LOOP

- LOOP (Loss of Off-site Power)
- PCV isolation
- EDG start-up
- DHR mode
  - 1F1 Isolation Condenser (IC); two trains A & B, DC power available; > 55°C/hr then B-train closed; pressure control by the A train; and HPCI standby
  - 1F2 and 1F3 Reactor Core Isolation Cooling (RCIC) manually on; and HPCI standby; RHRSW to heat sink (sea), sea water pump with AC power available

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SBO, no S/C-RHR pumps w/o AC power:

Loss of Ultimate Heat Sink (Ocean)

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<th>Isolation Condenser (IC) for 1F1</th>
<th>Make-up and heat removal</th>
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<td>Reactor Core Isolation Cooling (RCIC) for 1F2 and 1F3</td>
<td>Make-up but no heat removal capability (after S/C boiling)</td>
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<td>High Pressure Coolant Injection (HPCI) for 1F3</td>
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LUHS as a direct result of SBO because of no diversity
Auxiliary cooling system down as well as mechanical components failure

Loss of DC power prevented valve control (core make-up and PCV venting, etc) ⇒
Super SBO ---- IC, RCIC, HPCI
LUHS and core damage

- LUHS results in S/C boiling (containment cooling failure);
- RPV over-pressure, SRV opening;
- Make-up by IC or RCIC/HPCI;
- Termination of IC or RCIC/HPCI leading to the loss of coolant;
- Core exposure – core melt – meltdown

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After SBO, no S/C-RHR pumps w/o AC power:

Event Sequence after Loss of Ultimate Heat Sink (Ocean)

- Immediately after eventual loss of DC power (Super SBO), IC or RCIC and HPCI stop
  - RPV pressure high – SRV open
  - depressurization and evaporation
  - water level to the TAF
  - rapid core uncover
  - fuel overheating
  - clad oxidation and H2 generation
  - cladding and fuel liquidus states and melting
  - core meltdown

  ---- all within an hour to a few hours

- No SAM
  - Alternative make-up should have been made before the core exposure [use fire engine pumps (in tandem), etc. --- and immediately when the RPV pressure lowered to 6~7 bars]
  - Core melt due to delays in alternative make-up to prevent core meltdown; and
  - PCV failure/radiological release due to the delay in PCV venting; thus failed in mitigating the consequence of core meltdown
1F1 core meltdown March 11, 6-8pm
1F2 after March 14, 1F3 ~ March 14


damaged fuel rods

: Require DHR w/o AC/DC power

- With DC power lost, termination of IC or RCIC/HPCI resulted in a rapid core exposure and fuel melt
- With DC power continuously available (recharged or replaced or ..), the core would survive with make-up water
  - RHRS or other alternative heat removal system employing forced convection cooling did not work as a result of tsunami flood, and
  - Therefore, DHR systems that work w/o AC/DC power would render higher reliability of the decay heat removals (DHR) under the SBO condition

- Current GEN-III+ NRx meets this requirement; so do sodium cooled fast reactors and SMRs

- One of the strong candidates to overcome the long-term SBO is Natural Circulation Decay Heat Removal (NCDHR) system
- NCDHR system should survive the earthquake and tsunami as the added defense in depth
Passive cooling Example

- Isolation Condenser (BWR)
- Passive Containment Cooling by Natural Circulation (BWR & PWR)
- IRIS (Integrated Primary System Reactor): ADS+PSS+LTCS; EHRS
- ESBWR: IC and PCCS with Gravity Driven Cooling System

Good practice in 2F NPS

- Fukushima-Daiichi NPP Accident, GLOBAL2011, Makuahri, Japan
  Koji Okamoto
Loss of Ultimate Heat Sink

Fukushima-Daini #1

*Just after tsunami*  
(Mar. 11, 15:34)

*LUHS Declared*  
(Mar. 11, 18:33)

Source: Global 2011  Koji Okamoto
Loss of Ultimate Heat Sink

Fukushima-Daini #1

**Accident Management**

- Make-up water system
- Fuel Heat exchanger
- Sea water
- Control Rod
- Pump
- Motor
- Power Panel
- Source: Global 2011, Koji Okamoto

(Mar. 12, 00:00)

**Depressurization**

- Ready for Vent
- Source: Global 2011, Koji Okamoto

(Mar. 12, 06:20)

**Auxiliary Water Injection**

(Mar. 12, 03:50)

Loss of Ultimate Heat Sink

Fukushima-Daini #1

**Cold Shut-down**

- Power Car
- Power Panel
- Replace

(Mar. 14, 17:00)

(Mar. 14, 01:24)

Source: Global 2011, Koji Okamoto
Summary for Loss of Ultimate Heat Sink

- LUHS has relatively large time margin if AC power is available
- Super SBO should be prevented under any conditions
- For quicker recovery/restoration, relevant backup components should be prepared onsite/offsite
- Seawater pump should be protected in waterproof building
- Air-cooling System might be considered for improving the diversity of the heat sink, especially, S/C and Spent Fuel Pool
- Natural circulation decay heat removals will be a key to avoid LUHS when SBO and postulated super SBO

- (SAM) W/o built-in or alternative heat sinks,
  - Alternative coolant injection must be provided; and both
  - Depressurization of RPV by opening RPV (in the absence of ADS) and
  - PCV venting
    must be made possible manually;

Source (modified): Global 2011 Koji Okamoto
Some other comments from the disaster

- AC power restored 10 days later but SC/RHR not. No alternative “Ultimate Heat Sink” was provided but leakage from PCV to RB/TB basement compartments.

- SAM guidelines, emergency response procedures, safety design guidelines must be reinforced and containment vent, core cooling system (natural circulation capabilities), for long term SBO [due to tsunami in this case] to be implemented.

- Risk of NPP, the mistakes committed, success, .. were learned and better understood from the disaster → Lessons

    Nuclear power plants are made much safer by putting the lessons from Fukushima-Daiichi into practice

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