Implications of the Fukushima Accident for RRs

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Introduction

- *32 years ago the most serious nuclear accident in US history - Three Mile Island*
- *25 years ago the worst nuclear accident in history - Chernobyl*
- *8 months ago Fukushima accident occurred*
  - An IE of extraordinary magnitude
  - No evidence of major human errors
  - Cause a long term LOEP producing the failure of defence-in depth barriers
  - Leading to final release of radioactive material to atmosphere
  - Direct damage due to the earthquake and tsunami far exceeded damages due to the accident at the NPP
  - Future safety reviews will require facing severe scenarios
  - Importance of identifying the ESF that can mitigate undesirable consequences

Introduction

Purpose of the presentation

- ✓ *Present an overview of current practices commonly used in the Safety Analysis of RRs*
- ✓ *Asses the evolution and management of Fukushima BDBA (LOCA + long- term blackout) in RRs*

Some questions arose

- ✓ *Is it possible to avoid core melt down?*
- ✓ *Which is the figure of merit to look at? Core power? Power density? Heat flux?*

Safety Approach

Basic purpose of reactor safety is to comply with

Safety Objectives

General Nuclear Safety Objective:

To protect individuals, society and the environment from harm

Basic Safety Functions

- *Shutdown the reactor and maintain it in a safe shutdown state for all operational states or DBAs;*

- *Provide for adequate removal of heat after shutdown, in particular from the core;*

- *Confine radioactive material in order to prevent or mitigate its unplanned release to the environment.*

To maintain the integrity of multiple barriers we apply D-in-D philosophy:

1. **Prevention of deviations** from normal operation and of system failures by a sound and conservative design

2. **Control of such deviations and failures** by detection and intervention so as to prevent AOO from escalating into accident conditions

3. **Control of the consequences of any resulting accident conditions in the unlikely event that the escalation anticipated in the design basis is not arrested by a preceding level** → ***ESFs***

4. **Control of severe conditions** including prevention accident progression and mitigation of the consequences of a severe accident – BDBA

5. **Mitigation of the radiological consequences** of significant releases of radioactive materials

Safety Evaluation

PIE: Anything may fail, including components of Safety Systems. There is a large universe of foreseeable events

Loss of electrical power supplies ⟵

Insertion of excess reactivity

Loss of flow

Loss of coolant ⟵

Erroneous handling or failure of equipment or components

Special internal events

External events ⟵

Human errors

Reactor types

*Classification is based on **power density** instead of core power*

Two main groups

Open pool

Slight pressurization, few bars

Downward flow / Upward flow

Tank-in pool

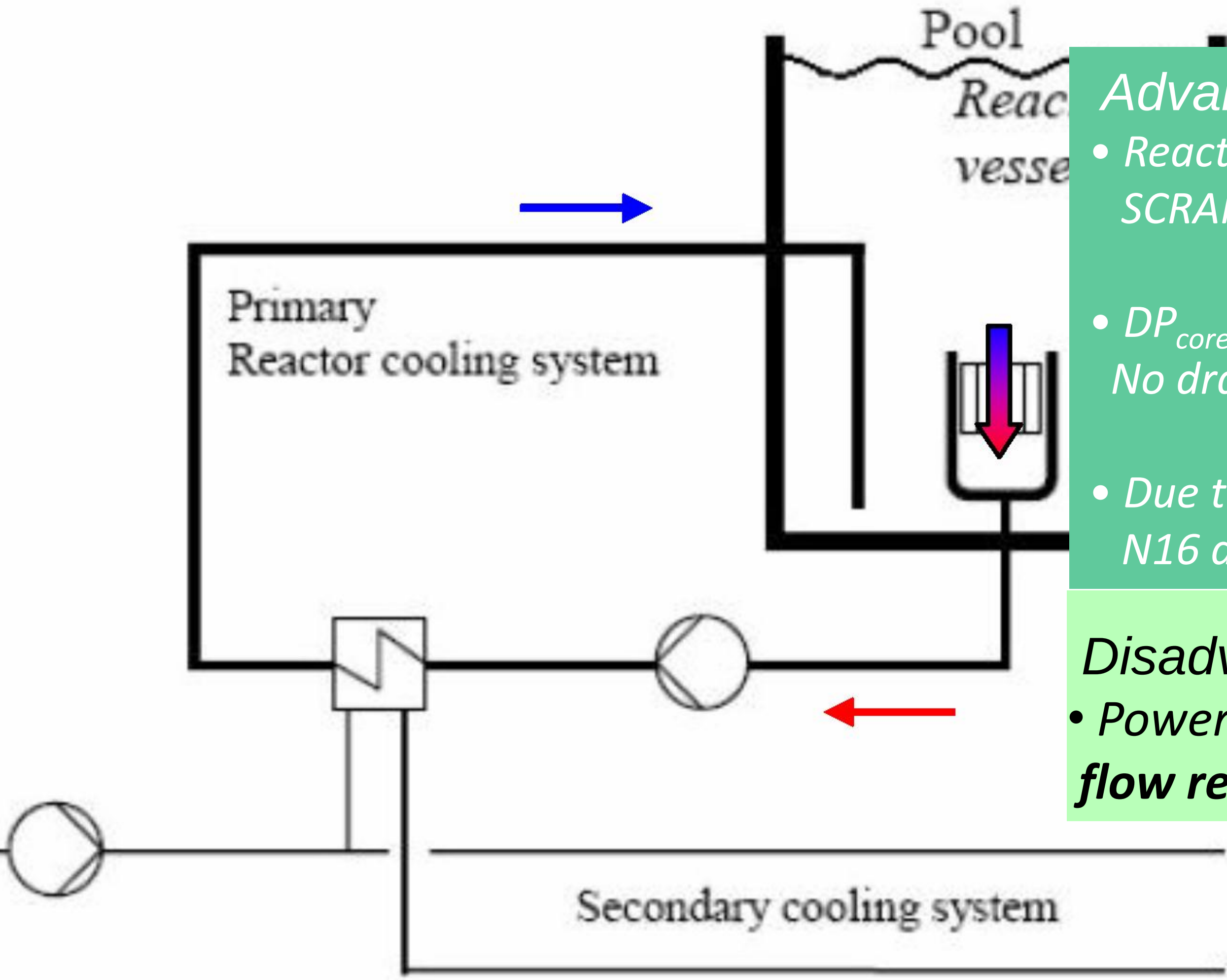
High power / high power density

Some tens of bars

Flow direction is irrelevant

Reactor types – Low power

- Power densities < 100 kW/lt
- Downward flow more appropriate



Advantages

- Reactivity CRs enter from above
  SCRAM aided by flow direction
- DP_{core}
  No drag
- Due to
  N16 does not reach pool surface

- Confinement system for potential release of radioactive material

Disadvantage

- Power is limited due to **flow reversal**, in a pump stop

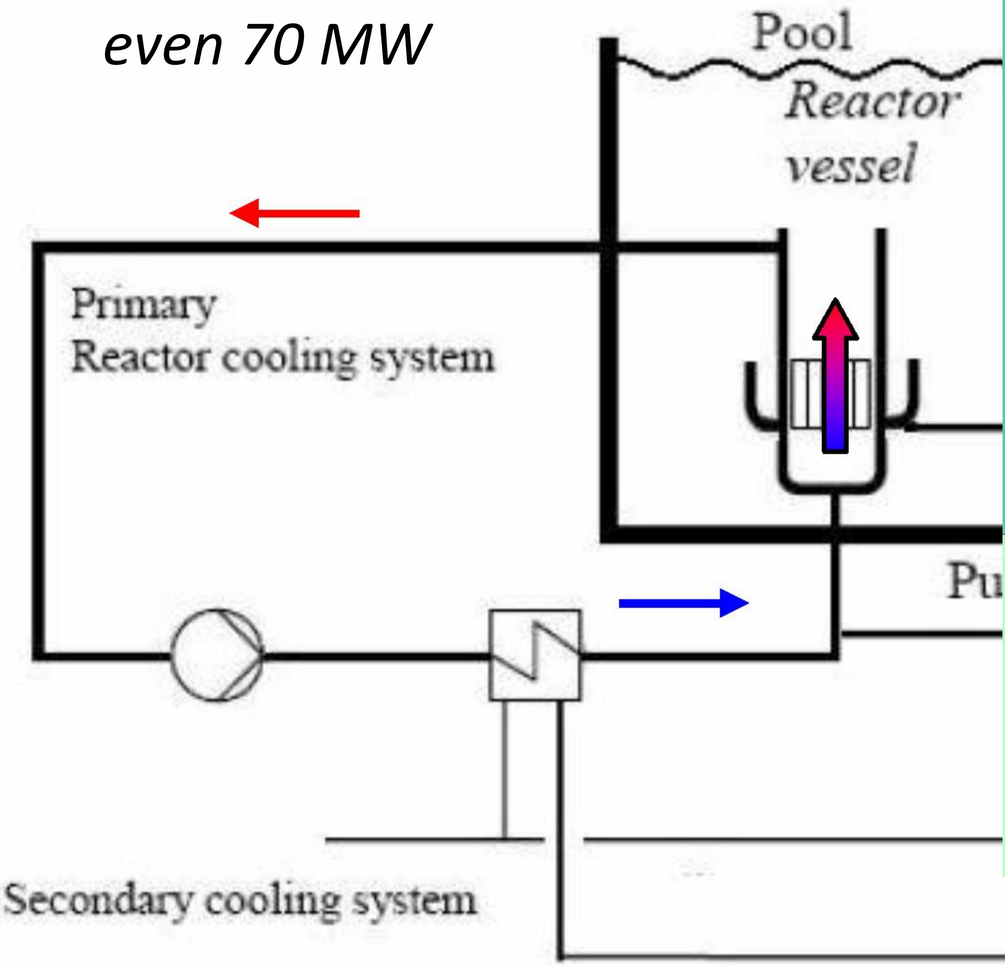
– **RA-3, 10 MW**

– **RP-10, 10MW**

Reactor types – Medium power

- *Power densities > 100 kW/l*
- *Core power > 10 MW, ≈ 30/40 MW, even 70 MW*

- *Upward flow*



Advantages

- *The hydrau*
dynamically p
- *No flow rev*
- *Natural con*
established
- *A riser enha*
in shutdown cooling mode

- *Confinement system commonly adopted*
- *Negative pressure in case of accident*

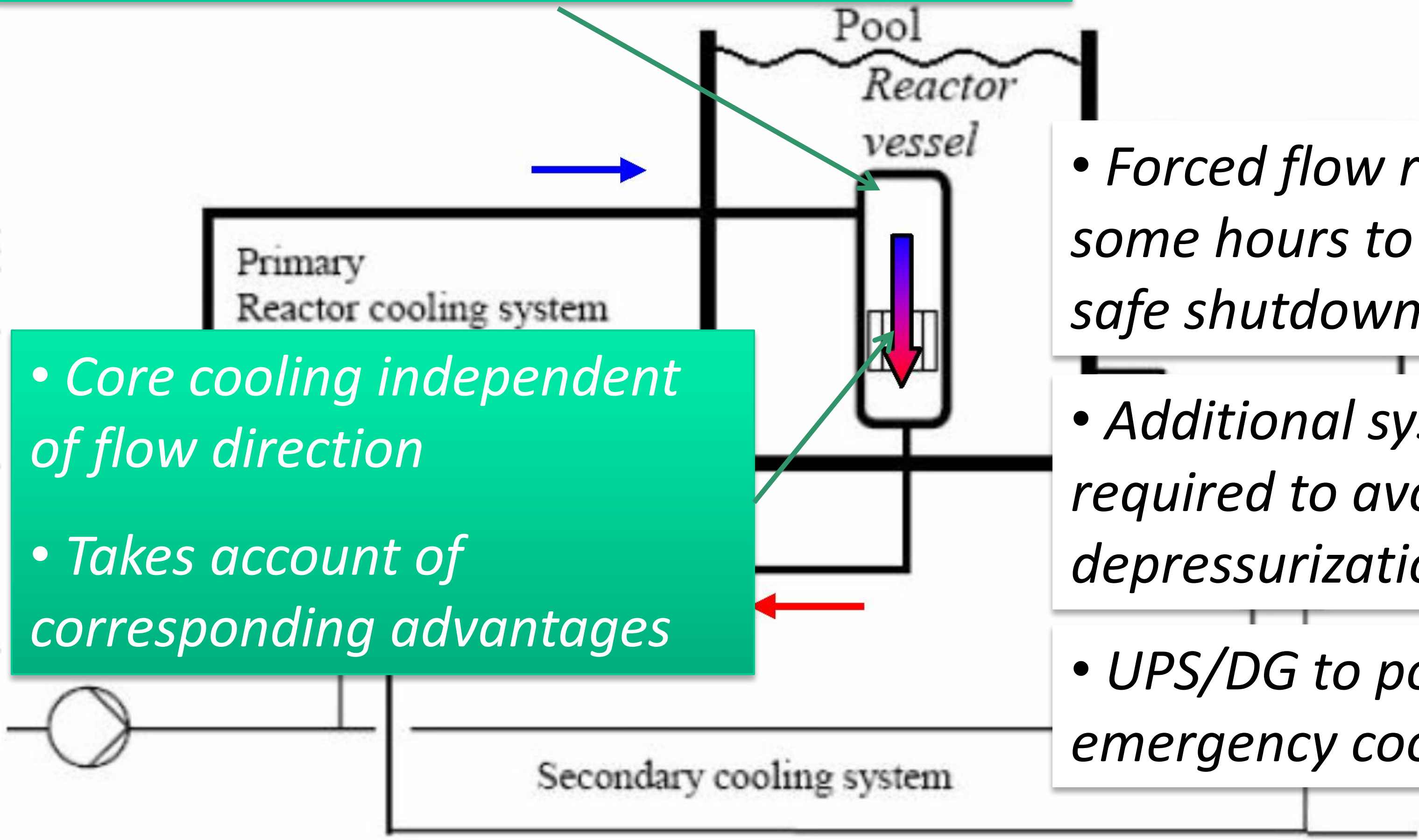
Disadvantages

- *Drag force of upward flow implies clamped FA*
- *Reactivity control elements move opposite to the flow in case of SCRAM*

– ***ETRR2, 22 MW***
– ***OSIRIS, 70MW***

Reactor types – High power

- *Tank-in pool design is commonly adopted*



- *Core cooling independent of flow direction*
- *Takes account of corresponding advantages*

- *Forced flow required for some hours to remain safe shutdown*
- *Additional systems required to avoid sudden depressurization*
- *UPS/DG to power the emergency cooling pump*

Confinement / containment systems depending on radioactive inventory

HFR (50 MW), CARR (60 MW), BR-2 (100MW)

Engineered Safety Features - ESFs

ESFs are <u>always</u> determined by the analysis of accident for each particular design (SAR) → some of the "usual" ESFs could not be needed

Safety systems:

Reactor Protection System
Shutdown System
Emergency Core Cooling System
Emergency Make-up Water System
Emergency Electrical Power Supply
Reactor Containment System / PAM

Components of systems

Flywheel of the Primary Pumps
Flap Valves of Primary in the pool (NC)
Siphon breaker
Reactor Pool Pressure Boundary

Characteristics of systems / components

Power reactivity coefficient of the core
Pressure Reversal on HX
Pool dimensions

ESFs - Residual/Emergency Core Cooling System - RECCS

Function: *To remove the decay heat when the PCS is not running and core cooling by natural circulation is not feasible –* ***Black-out events***

For open pool types:

Passive features are enough, e.g.,

- *coolant flow direction*
- *inertia fly-wheels*
- *flap valves and*
- *core chimney*

For tank-in pool cases:

RECCS requires On-site Emergency Power Supply

ESFs - Emergency Make-up Water System - EMWS

***Function**: To compensate the loss of water from the pool in case of LOCA*

Depending on total power and maximum q" the EMWS may be:

- *Neglected*
- *A passive system*

} *For open pool type*

Powered by the On-site Emergency Power Supply → *For tank-in pool type*

ESFs - Reactor pool pressure boundary & Pool dimensions

***Function**: To keep sufficient amounts of reactor coolant available*

Time after shutdown	Energy (MJ/MW)	Mass of Evaporated Water (kg/MW)
1 s	0.3	0.1
10 s	1.1	0.5
1 h	76	33.5
10 h	354	157
1 d	703	312
1 m	6771	3000

- ✓ *A pool of 3.5 m of Φ and 5 m height gives ≈ 50 m^3*
- ✓ *Enough for 20 MW and 1 month before the core uncovers*

***Additional function** for a tank-in pool* → *EMWS injects water from the pool to the PCS*

ESFs - Provisions for Flow & Pressure decrease

***Function**: For open pool types, allows a flow compatible with the decay power until natural convection establishes*

Depending on flow direction it represents:

- *A delay for flow reversal* ↓ *flow*
- *Postpones the natural circulation regime* ↑ *flow*

For pressurised tank-in pool types:

- *Pressure decrease is required & most demanding than flow coast down*
- *Cooling provisions until the RECCS starts*

ESFs - Flap Valves for natural circulation - FV

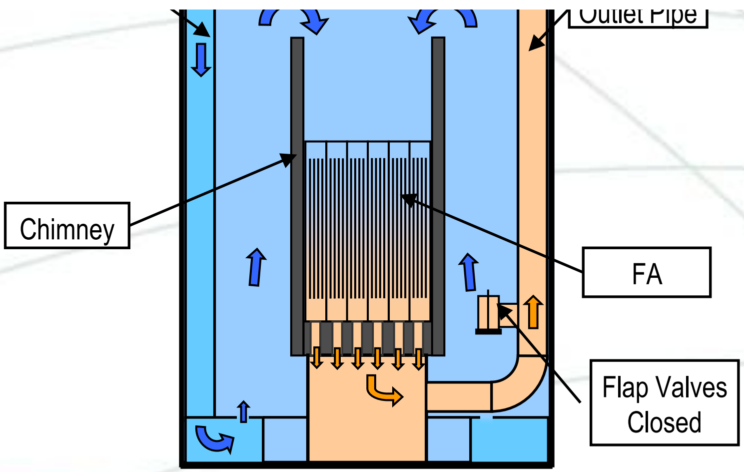
***Function**: connects the PCS lines to RPO to remove decay heat by NC*

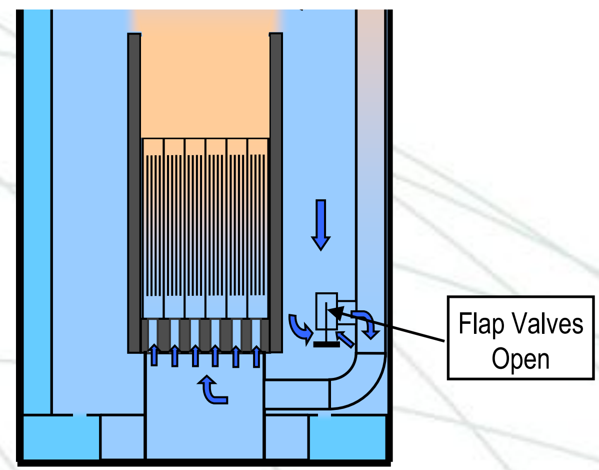
Normal **Natural**

✓ *FVs deal with Black-out scenarios*

✓ *Sometimes play the role of Siphon-breakers dealing with LOCA*

✓ *Redundant FVs at ≠ heights cope with LOCA + Black-out events*





Comparison between RRs and a typical BWR

	Low power	*Medium power*	*High power*	*NPP*
Facility	**RA-3**	**OPAL**	**FRM-2**	***BWR***
Power (MW)	10	20	20	***3600***
q'''_{ave} (kW/l)	60	300	1100	***60***
q''_{max} (MW/m^2)	1.0	2.1	4.4	***1.1***
P_{in} (bar)	≈ 2.0	≈ 4.0	20.0	***70.0***

Related to water inventory for long term cooling

Related to cooling regime in the short term

Key issues in Fukushima

Emergency Power Supply

At Fukushima:

The **loss of offsite power** due to the **earthquake** and onsite AC power due to the **tsunami,** resulted in a complete blackout, afterwards to fuel overheating and damage

In RRs:
In general, low and medium power reactors have a large water inventory/power ratio so, it's enough as final heat sink

Core cooling is ensured by a coast-down flow compatible with the decay power until natural convection establishes

However, high power reactors require the RECCS after shutdown before natural circulation is feasible

Key issues in Fukushima

Fresh Water Supply

At Fukushima:
The unavailability of large quantity of fresh water for the cooling system after the earthquake caused an unprecedented emergency response, injecting sea water into the core

For RRs:
A large water inventory and the low rate of evaporation provide enough time to take "more conventional" actions – Fire hoses

Some design alternatives include stored onsite water for the EMWS passively injected (by gravity)

Key issues in Fukushima

Hydrogen Generation

At Fukushima:
The loss of power supply caused a deficient fuel cooling

An overheating of the fuel occurred, enabling rapid oxidation of the zirconium cladding

Large amounts of H_2 (extremely flammable) generated

There was explosion and destruction of the reactor buildings

For RRs:
The fuel has aluminium clad and H_2 production due to steam oxidation of aluminium is minimal

H_2 explosion is not a believable scenario

However, developments of new fuel with UMO are considering the use of Zr cladding for plate type fuels

Key issues in Fukushima

Spent Fuel Pools

At *Fukushima:*
One of the major issues involved the spent fuel pools, causing radioactivity releases

Lack of the cooling (due to loss of power supply) combined with the elevated location (damaged from hydrogen explosions) and earthquake-induced water leakage have worsen the accident

In RRs:
The stored energy and radioactive inventory is orders of magnitude lower than a NPP

The dispersed fuel has a significantly different behaviour in term of fission product retention

The spent fuel pools in some RRs are SS-lined and built into the concrete structure seismically qualified

Key issues in Fukushima

Containment Failure

At *Fukushima:*
Due to the station blackout, the containment was vented to prevent containment over-pressurization

Some vented gases leaked into the reactor building, which had no ventilation (again due to the station blackout)

In RRs:
The building boundaries, access doors with sealing airlocks, pipe penetrations and electric cable penetrations can be assumed "airtight" and inwards leakage rate is accepted at the nominal negative pressure

The air is ventilated and conditioned by a single system with backup power systems

In a long-term black-out + radioactive release in the facility, the safety function of the confinement could be threatened

Findings

Findings involve:

- *Nuclear designers*
- *Operating organizations*
- *Regulatory authorities*

Encouraging actions such as:

- ✓ *a continuous update of natural hazards database;*
- ✓ *the defence-in-depth philosophy;*
- ✓ *diversity and redundancy concepts applied to extreme external events and*
- ✓ *periodic reviews and/or upgrade of safety analysis concerning these extreme events*

Conclusions

- ✓ *Fukushima accident has opened a new discussion on the safety features of RRs and how this kind of accident can be managed*

- ✓ *An analysis focused on the basic SF of "decay heat removal" was performed for a wide range of power/power density reactor types*

- ✓ *A BDBA (Fukushima-like, black-out + LOCA) was assessed for different designs of open pool reactors and it can be concluded that it can be managed by passive systems and components due to design ESFs*

- ✓ *Some findings arise involving nuclear designers, operating organizations and regulatory authorities encouraging them to include new tasks and revisiting old ones*

Thank you for your attention