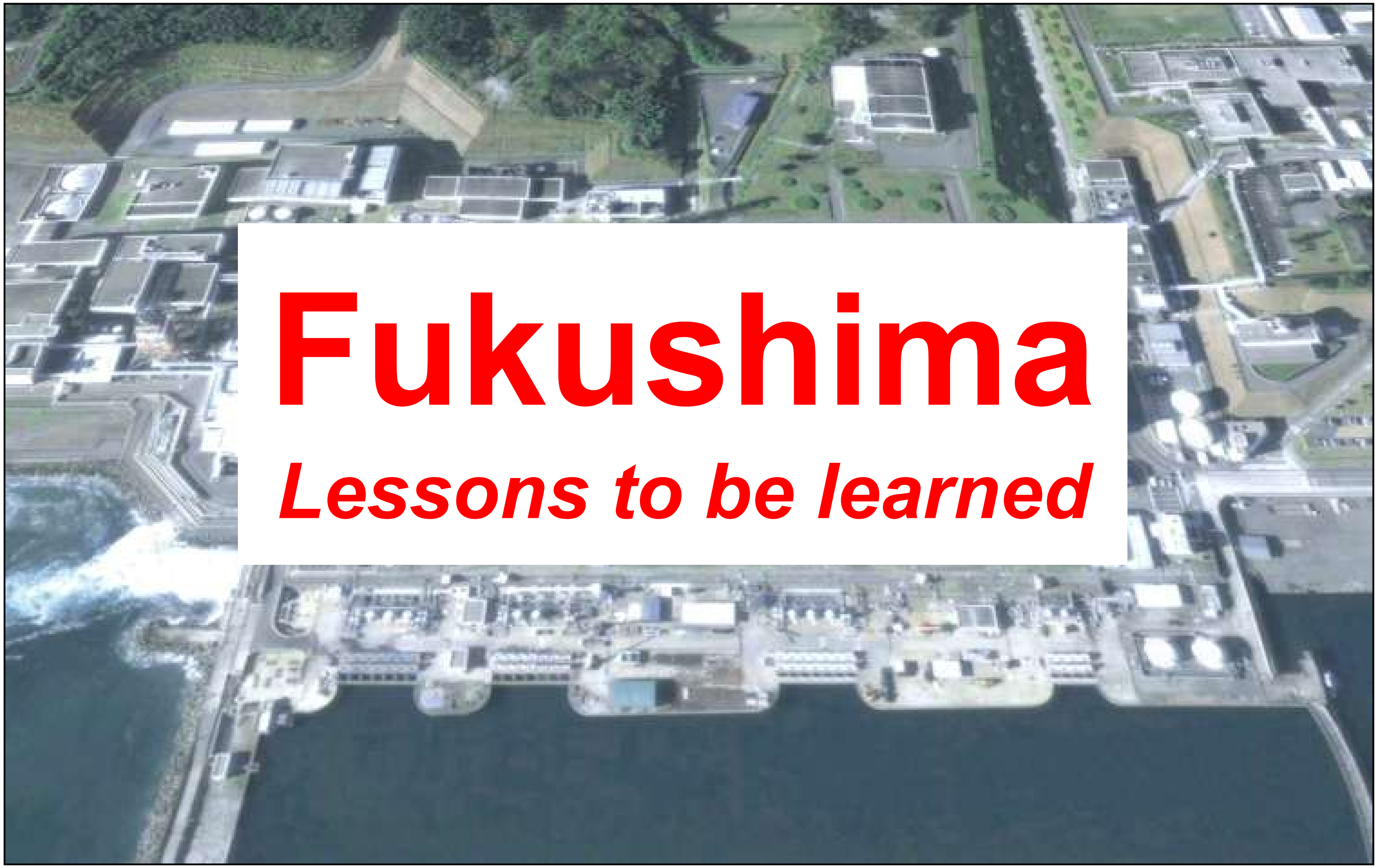
Fukushima

Lessons to be learned



Fukushima – Lessons to be learned

11.03.2011

Tōhoku Earthquake
14.46 JST
Magnitude 9 (MW)

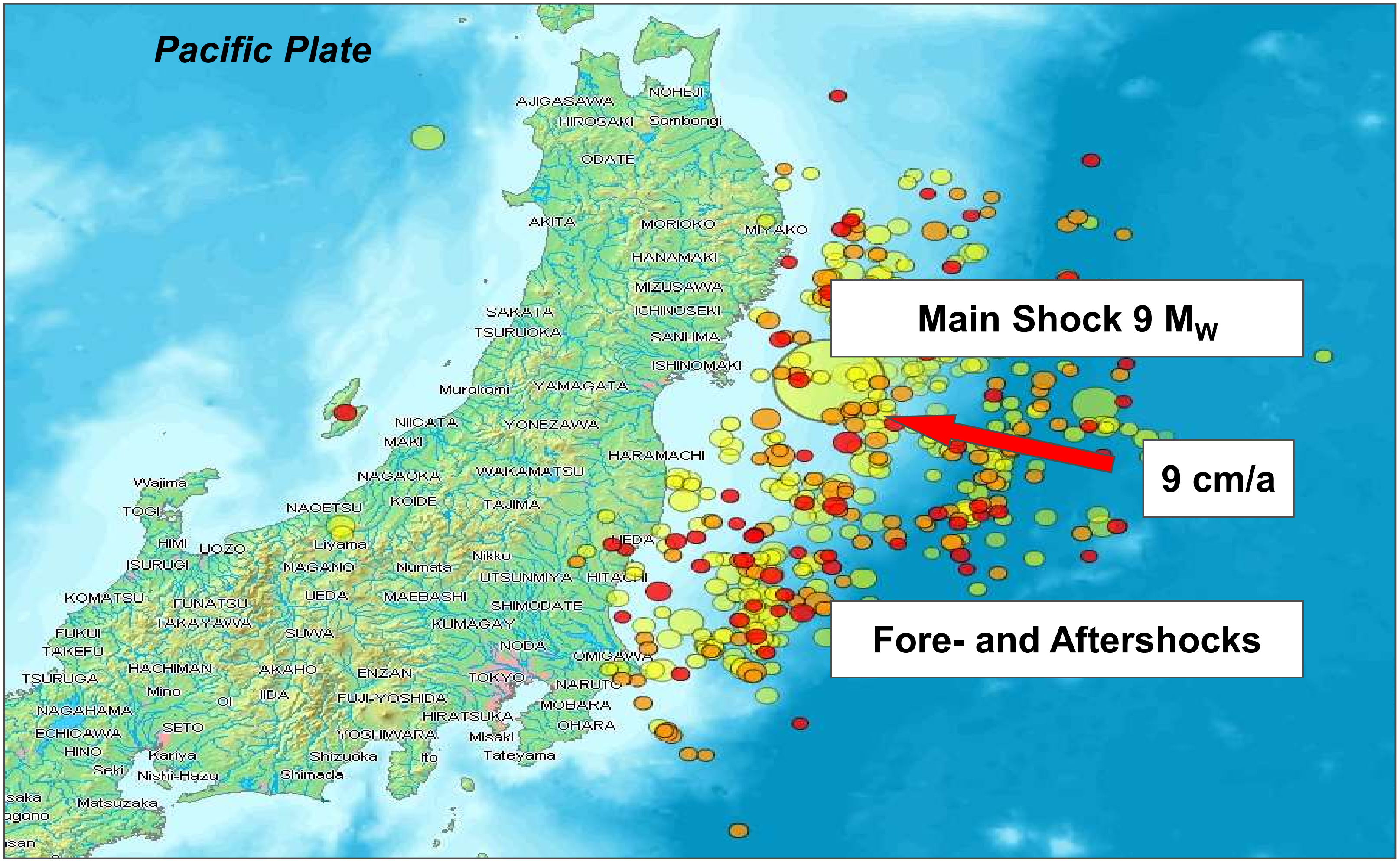
→

Tsunami
14 m Height

→

Station 1,2,3,4
Black-out

Fukushima – Lessons to be learned

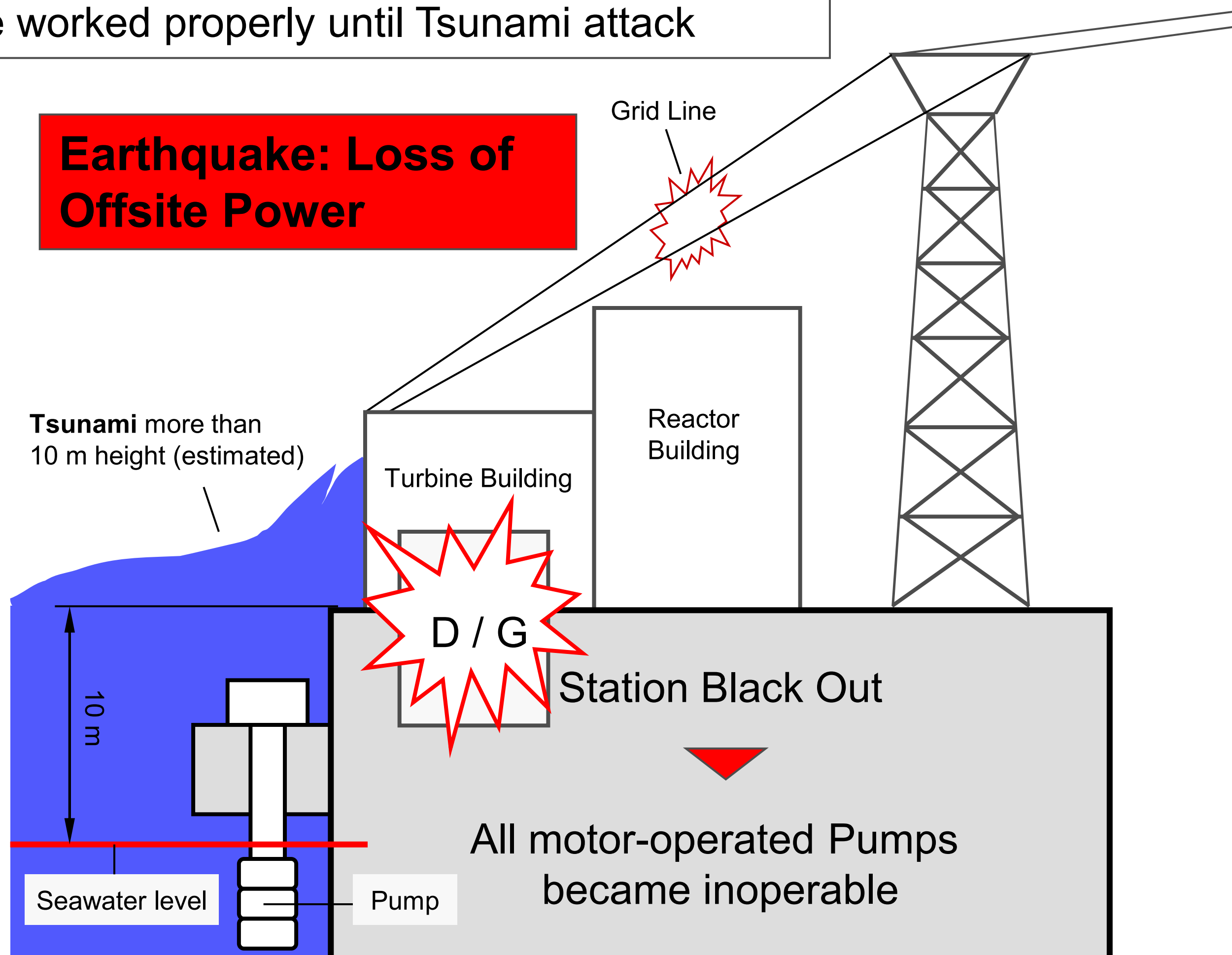


Fukushima – Lessons to be learned

Fukushima – Lessons to be learned

- All operating units were automatically shut down
- Emergency D/Gs have worked properly until Tsunami attack

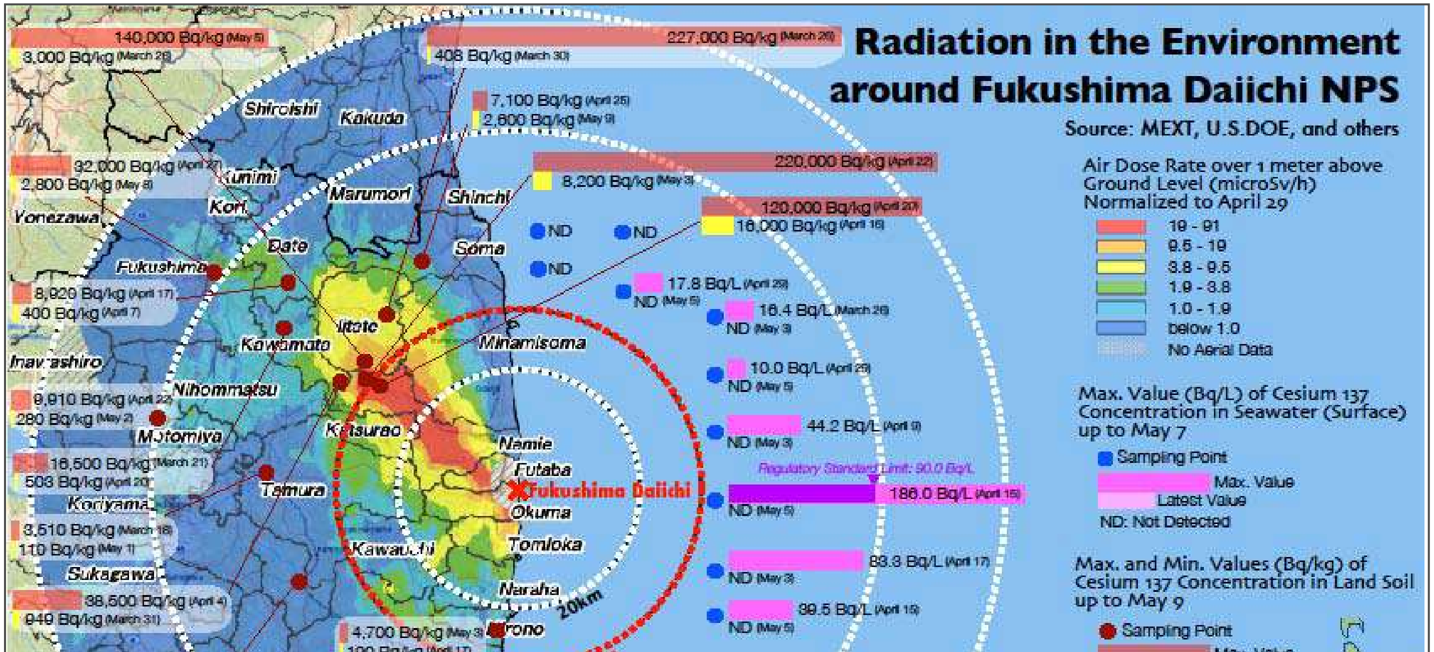
Tsunami:	14 m
Design:	5,7 m
Protection:	6,5 m



Fukushima – Lessons to be learned

"Three of the reactors at Fukushima I overheated, causing meltdown that eventually led to explosions, which released large amounts of radioactive material into the air"

Fukushima – Lessons to be learned



The events have been rated at Level 7 on the International Nuclear Event Scale INES

(major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures)

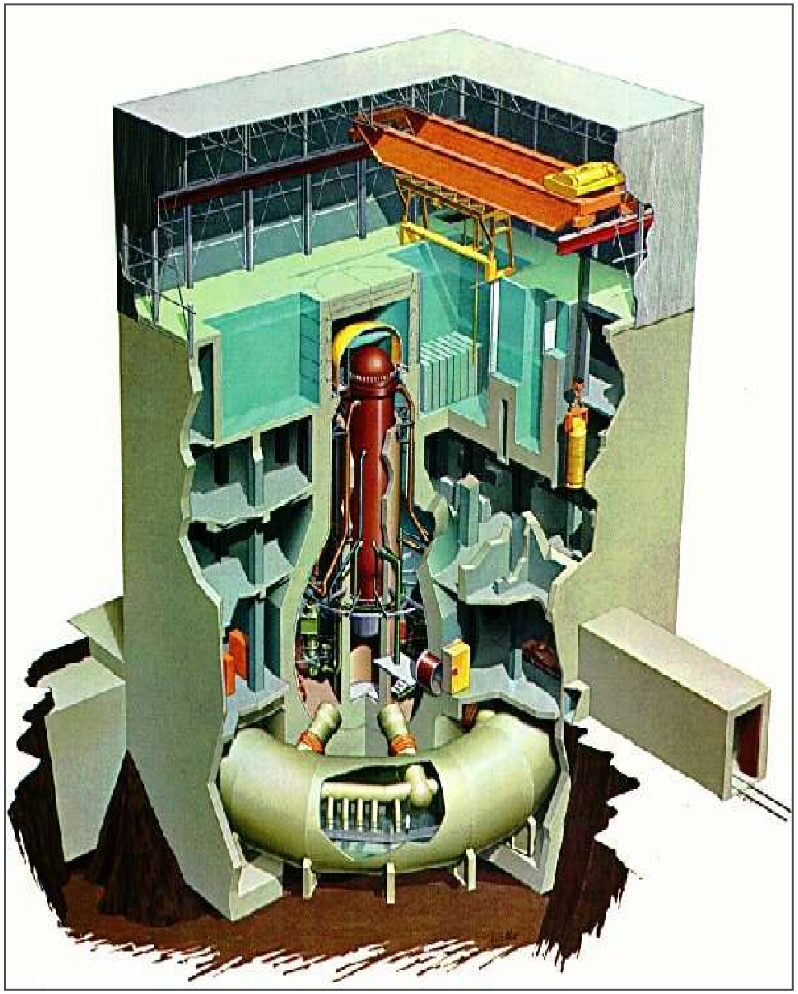
Fukushima – Lessons to be learned

We feel deep sympathy with the Japanese People

We
the international nuclear community,
the engineers, authorities, owners, and media
are concerned and take the responsibility

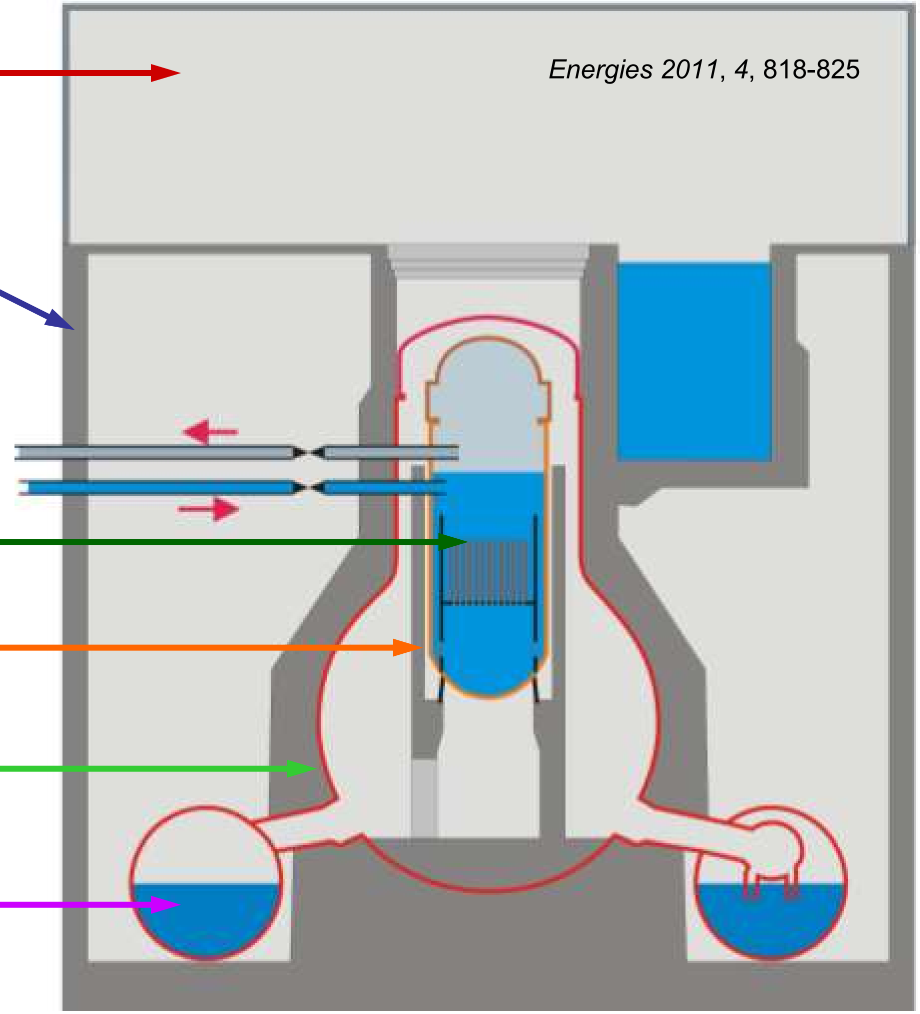
We
have to learn the lessons from Fukushima

Fukushima – Lessons to be learned



Fukushima – Lessons to be learned

- Reactor Service Floor (Steel Construction)
- Concrete Reactor Building (secondary Containment)
- Reactor Core
- Reactor Pressure Vessel
- Containment (Dry well)
- Containment (Wet Well) / Condensation Chamber



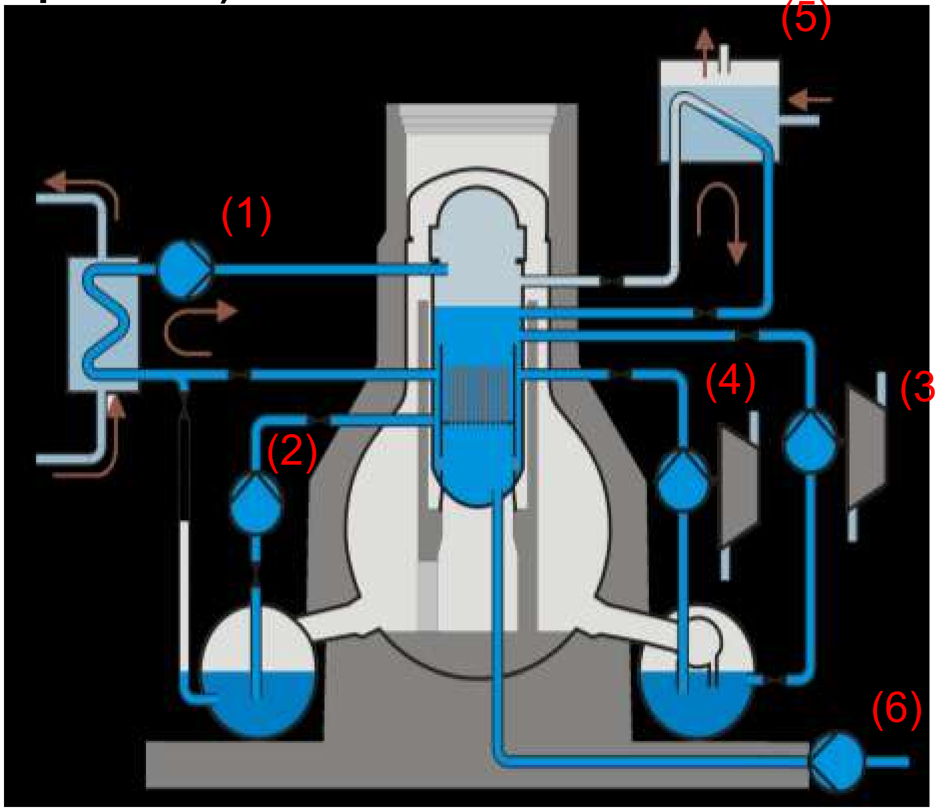
Course of Events

Heat generation: (due to decay of fission products)

After SCRAM ~6% After 1 Day ~1%

Emergency Core Cooling Systems

1) Residual Heat Removal System
2) Low-Pressure Core Spray (for LOCA)
3) High-Pressure Core Injection (for LOCA)
4) Reactor Core Isolation Cooling (Unit 2,3 [BWR4])
5) Isolation Condenser (Unit 1 [BWR3])
6) Borating System



Course of Events

Fukushima I Unit 1

(1) **Isolation Condenser**

- Steam enters heat exchanger
- Condensate drains back to reactor pressure vessel
- Secondary steam released from plant

Need pumps for water supply

Fukushima I Unit 2 and 3

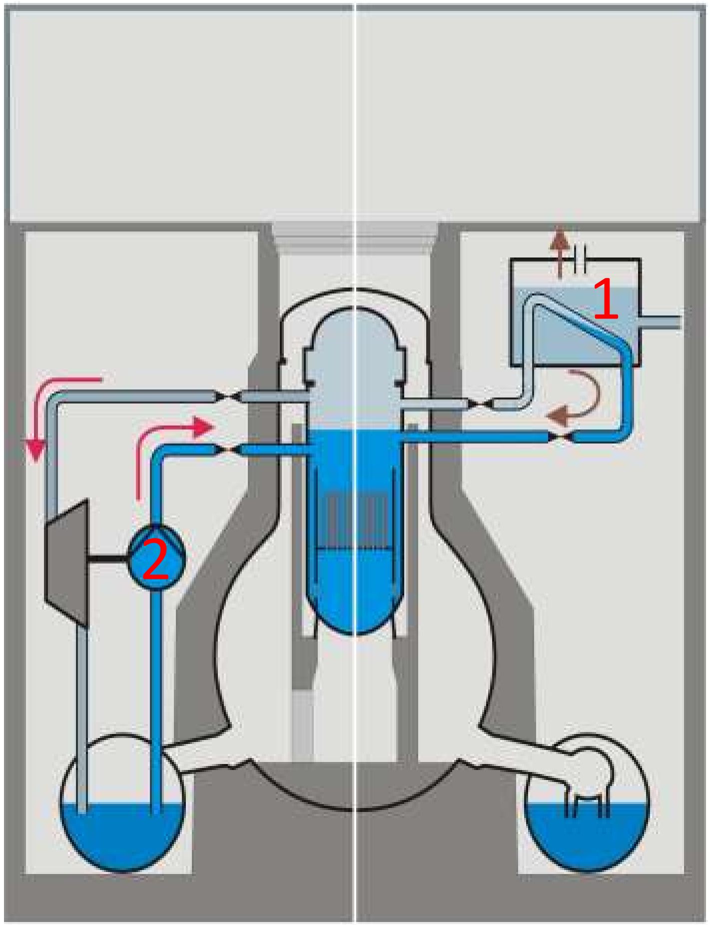
(2) **Reactor Core Isolation Pump**

- Steam from reactor drives turbine
- Turbine drives a pump, pumping water from the wet-well in the reactor
- Steam gets condensed in wet-well

Necessary:

- Battery power
- Wet-well temperature < 100°C

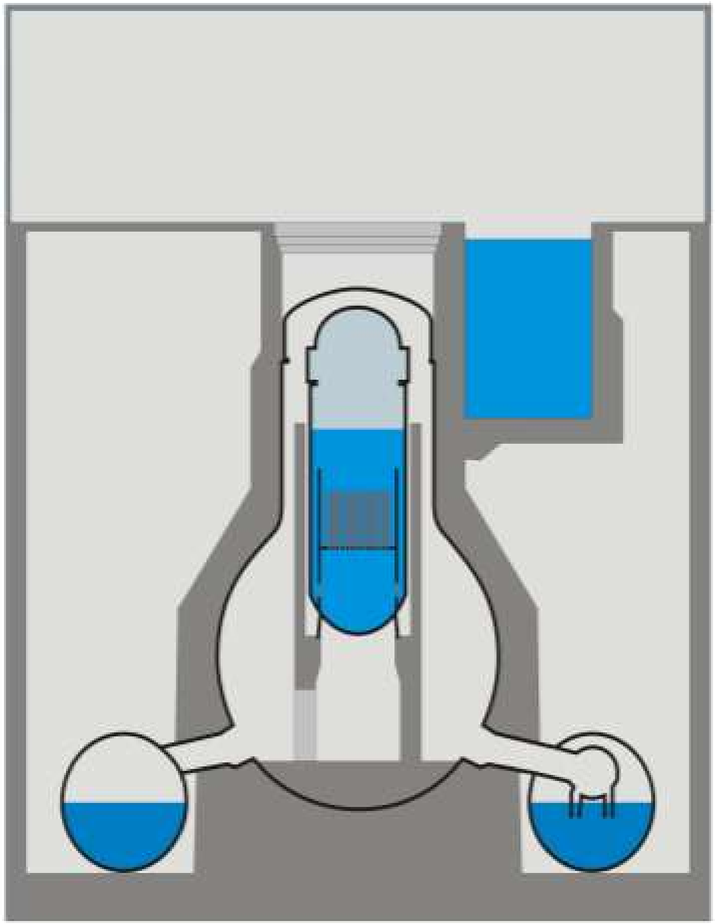
No heat sink from the buildings



Course of Events

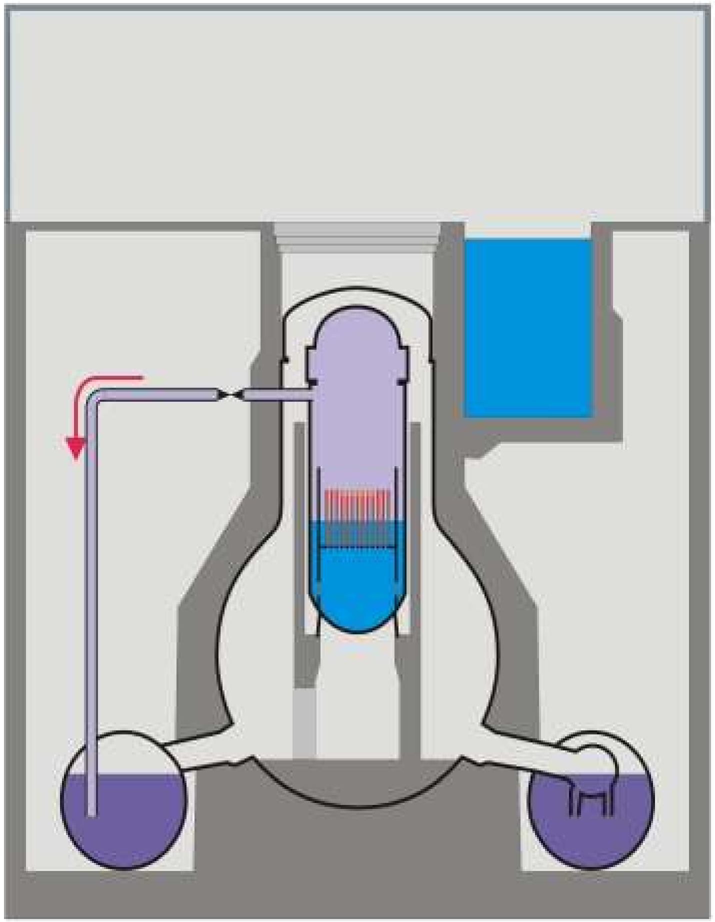
Loss of Coolant Accident LOCA

- **11.3. 16:36 in Unit 1**
  - Isolation condenser stops
- **13.3. 5:30 in Unit 3**
  - Reactor Isolation pump stops
- **14.3. 13:25 in Unit 2**
  - Reactor Isolation pump stops
- **Reactors of Units 1-3 are cut off from any kind of heat removal**



Course of Events

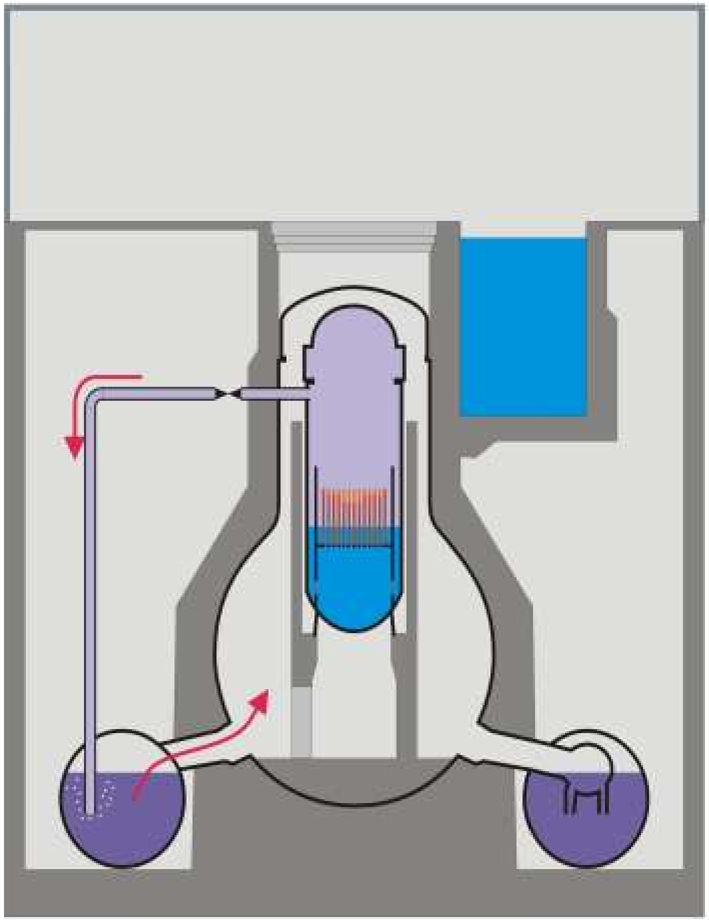
- **~50% of the core exposed**
  - Cladding temperatures rise, but still no significant core damage
- **~2/3 of the core exposed**
  - Cladding temperature exceeds ~900°C
  - Balooning / Breaking of the cladding
  - Release of fission products from the fuel rod gaps



Course of Events

~3/4 of the core exposed

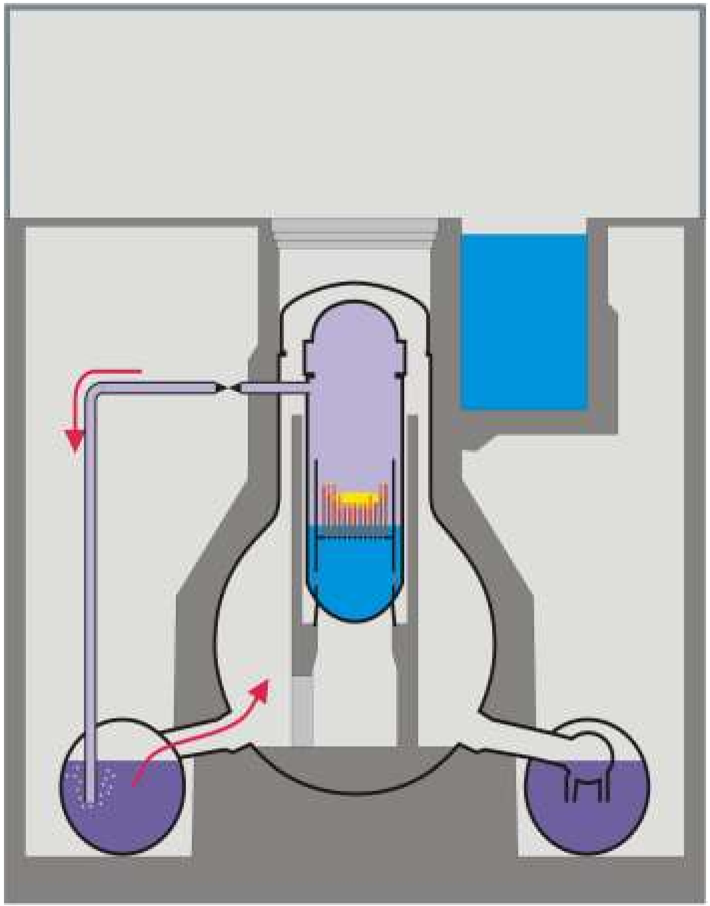
- Cladding exceeds ~1200°C
- Zirconium water reaction starts under steam atmosphere
  $Zr + 2H_20 \rightarrow ZrO_2 + 2H_2$
- Exothermal reaction heats the core additionally
- Generation of hydrogen
  - Unit 1: 300-600kg
  - Unit 2/3: 300-1000kg
- Hydrogen gets pushed via the wet-well, the wet-well vacuum breakers into the dry-well



Fukushima – Lessons to be learned

Course of Events

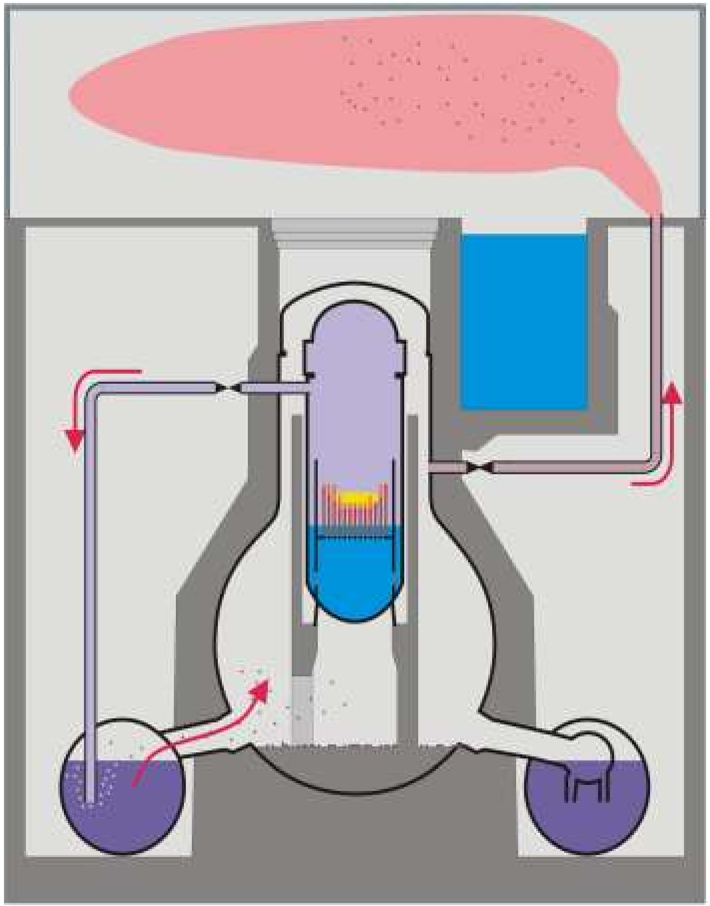
- at ~1800°C [Unit 1,2,3]
  - Melting of the cladding
  - Melting of the steel structure
- at ~2500°C [Unit 1,2]
  - Breaking of the fuel rods
  - debris bed inside the core
- at ~2700°C [Unit 1]
  - Melting of Uranium-Zirconium eutectics
- Supply of seawater to the reactor pressure vessel stops the core melt in all 3 Units
  - Unit 1: 12.3. 20:20 (27h w/o water)
  - Unit 2: 14.3. 20:33 (7h w/o water)
  - Unit 3: 13.3. 9:38 (7h w/o water)



Venting

Course of Events

- **Containment (MARK I)**
  - Last barrier between fission products and environment
  - Wall thickness ~30 mm
  - **Design pressure 4-5 bar**
- **Pressure reached up to 8 bars**
  - Normal inert gas filling (Nitrogen)
  - Hydrogen from core oxidation
  - Boiling in the condensation chamber
  - Possible leakages at containment head seal
- **Depressurization of the containment**
  - Unit 1: 12.3. 4:00
  - Unit 2: 13.3 00:00
  - Unit 3: 13.3. 8:41

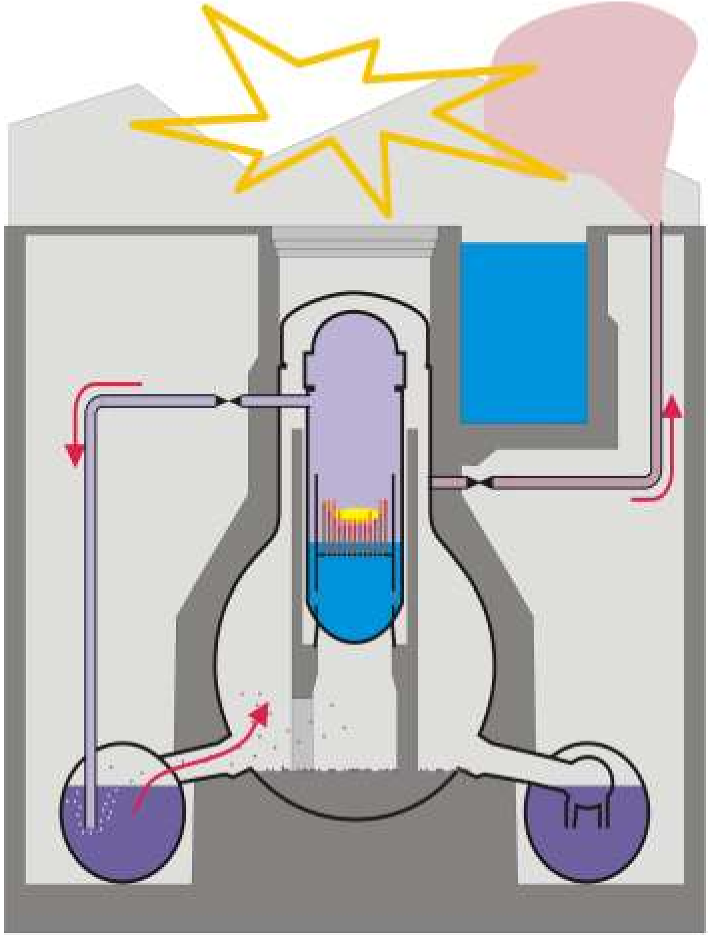


Course of Events

- **Unit 1 and 3**

  Hydrogen explosion inside the reactor service floor

  - Destruction of the steel-frame construction
  - Reinforced concrete reactor building seems undamaged

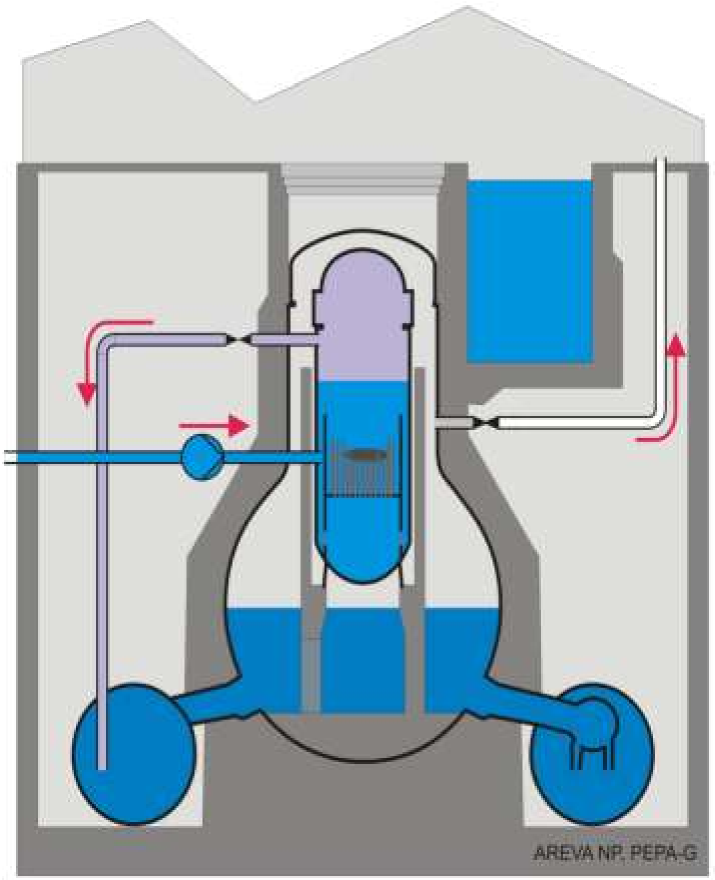


Mark of Respect

We pay full respect for the accident management
to
the technicians, engineers, and management,
for their
reasonable, professional, and eventually successful commitment
under the
concurrence of extremely severe circumstances

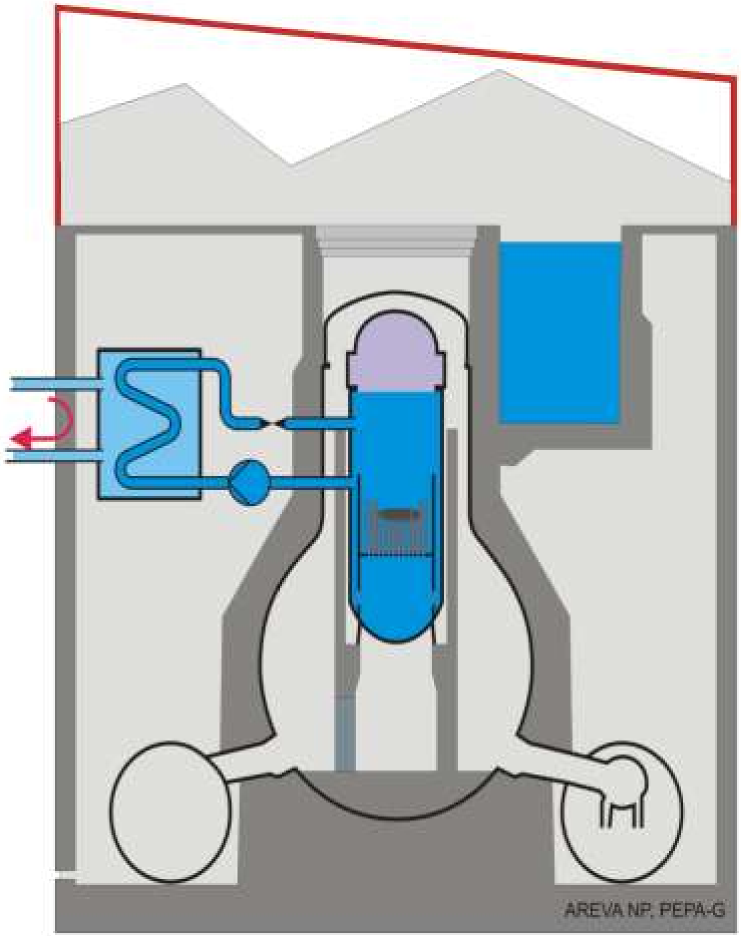
Accident Mangement

- **Sea water stopped accident progression**
  - No further core degradation
  - RPV temperatures decline
  - No further releases from fuel
- **Further cooling of the reactors via**
  - Unit 1: Isolation Condenser
  - Unit 2 & 3: Containment Venting



Accident Mangement

- **Short-term recovery steps**
  - Trap fission products on ground with dust binders (Epoxy)
  - Install closed cooling cycles
  - Decrease the water inventory in the Reactor buildings
  - Build storm-prove shelters around the reactors (especially a roof)
- **Long-term recovery steps**
  - Build a water cleansing facility to decontaminate the stored water
  - Remove Salt from Reactors
  - Empty the spend fuel pools
  - Wait 10 Years that radioactivity declines [see TMI2]
  - Remove Core inventory



Fukushima – Lessons to be learned

Accident Mangement

Happy Moments:

Recovery of Main Control Room Light

Unit 3: March 22   Unit 2: March 26
Unit 1: March 24   Unit 4: March 29

Fukushima – Lessons to be learned

Accidental Damage

Earthquake & TSUNAMI	FUKUSHIMA
a natural disaster of historic magnitude	a man-made disaster of cat. 7 on INES
Death Count: 25,000 People	Radiation Fatality: No Exposure > 250 mSv: 6 Release ~ 10% Chernobyl
Economic Loss: $ 250 billion	Decommissioning: $ 2.53 billion (TEPCO Allocation)

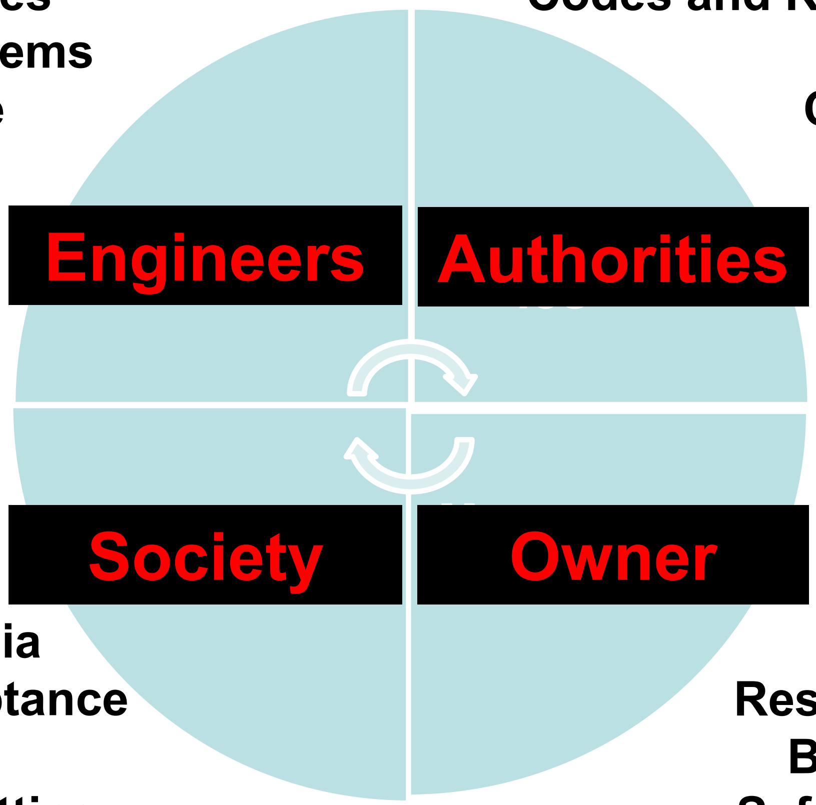
Fukushima – Lessons to be learned

Lessons learned

Design Rules
Aging Systems
Knowledge

Codes and Regulations
Licensing
Controlling

Key Focus:
Nuclear Safety



Public Media
Risk Acceptance
Framing&
Agenda Setting

Responsibility
Business &
Safety Culture

Engineering Lessons

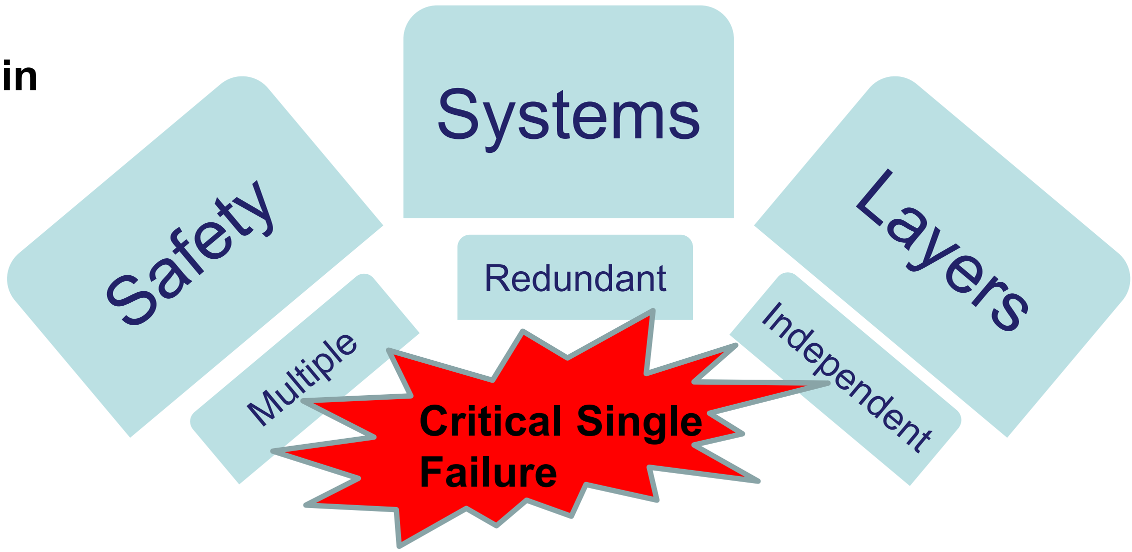
Broad Claim on System Safety Engineering Resilient Structures that Mitigate & Recover from Catastrophic Failures

Engineering Lessons

NUCLEAR SAFETY SYSTEMS (as defined by the NRC)

- **Shut down and maintain in shut down condition**
- **Prevent the release of radioactive material**

Defense in Depth



Engineering Lessons

PROBABILISTIC RISK EVALUATION for COMPLEX SYSTEMS
(SYSTEM SAFETY ANALYSIS)

MAGNITUDE (SEVERITY) of CONSEQUENCES	X	LIKELIHOOD (PROBABILITY) of OCCURENCE

Fukushima – Lessons to be learned

Engineering Lessons

ROBUST BASIC SAFETY DESIGN

INHERENT SAFETY DESIGN of CONTROL SYSTEMS + **PASSIVE SAFETY DESIGN of SAFETY SYSTEMS**

"An 'inherently safer' approach tries to:

- Avoid or eliminate hazards
- Reduce their magnitude and severity and likelihood of occurrence by careful attention to the fundamental design and layout"

Engineering Lessons

WEAKNESS:

Probabilistic Risk Assessment does not account for UNEXPECTED FAILURE MODES

Difficult Modeling
of
"COMMON-CAUSE" FAILURES

SYSTEM SAFETY RESEARCH (MIT):
"Any complex system,
no matter how well it is designed and engineered,
cannot be deemed failure-proof"

Fukushima – Lessons to be learned

Engineering Lessons

CATASTROPHIC NUCLEAR ACCIDENTS ARE INEVITABLE

Safety Indicator:
Frequency f of Core Melt Accidents

NRC (**Mandated)**: f < 1 in 10,000 years
Modern design: f < 1 in 100,000 years

"First and most elementally, nuclear accidents happen…we can never have confidence that we will succeed absolutely."
(*John Ritch, Director General, WNA)*

NON-COMPLIANCE WITH SYSTEM SAFETY DESIGN PRINCIPLES

After lessons we know better:

06-11: IAEA Ministerial Conference

- External Hazards
- Accident Management
- Emergency Preparedness

Report of Japanese Government

IAEA Ministerial Conference on Nuclear Safety, Vienna, 21 June 2011

Fukushima – Lessons to be learned

Engineering Lessons

NO OVERCONFIDENCE - SEVERE ACCIDENTS MAY HAPPEN

GLOBAL COOPERATION IN SAFETY ENGINEERING

APPROPRIATE EVALUATION AND PROTECTION
AGAINST EXTERNAL HAZARDS

CONTROLLED SYSTEM SAFETY DESIGN RULES (INSAG)
-DEFENCE IN DEPTH & INHERENT/PASSIVE SAFETY-
ACCORDING TO THE LATEST STATE-OF-THE-ART

SAFETY CULTURE

DEFENSE IN DEPTH with PROBABILISTIC RISK ANALYSIS	INHERENT SAFETY DESIGN with HIGHEST BASIC REQUIREMENTS

Report of Japanese Government to the IAEA Ministerial Conference

External Hazard / Common Mode Failure

- Flooding
- Black-Out
- Loss of Heat Sink
- H_2 in the Service Floor
- Loss of Spent Fuel Pool Cooling

NPS and Component Design

- TSUNAMI Height: 14 – 15 m
- Seawater Pump
- Switchboard
- Diesel Generators
- Battery Life
- MARK I Containment

SAFETY CULTURE

??

Safety Culture

Report of Japanese Government to the IAEA Ministerial Conference
Japan will Establish a Safety Culture …
Pursuing Defense-in-Depth by Constantly Learning Professional Knowledge on Safety

THOROUGHLY INSTIL A SAFETY CULTURE

A Safety Culture that Governs the Attitude and Behavior in Relation to Safety of all Organizations and Individuals Concerned must be Integrated in the Management System
(IAEA: Fundamental Safety Principles, SGF-1, 3.13)

Safety Culture

POST FUKUSHIMA WORLD

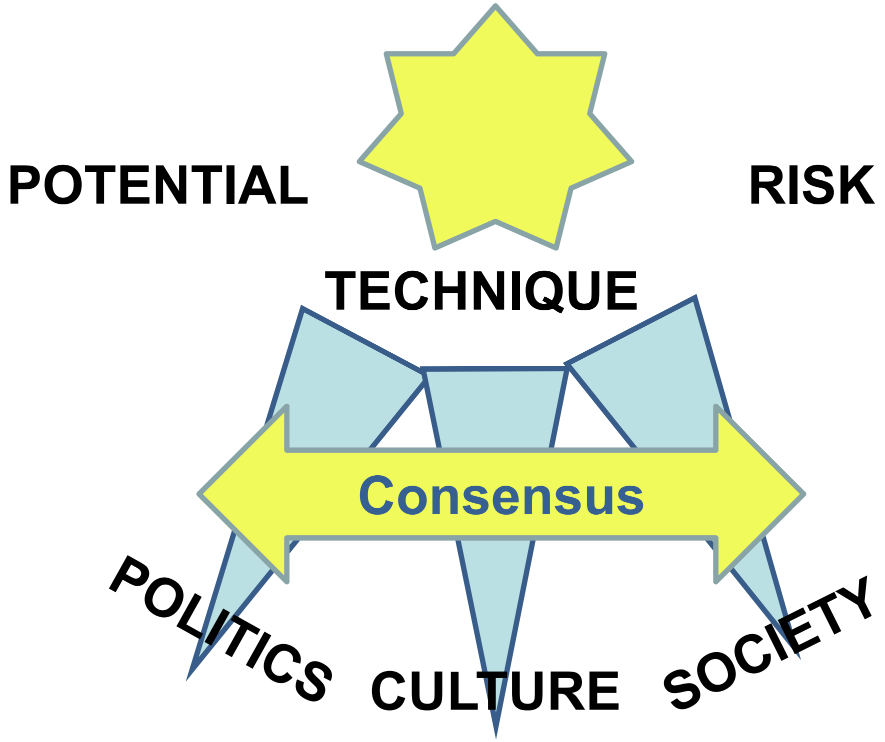
INTERNATIONAL CONVENTION ON NUCLEAR SAFETY:

NATIONAL OPERATIONAL TRANSPARENCY
- INDEPENDENT , EFFECTIVE NUCLEAR REGULATION
RE-VISITATION of THREATS of EXTERNAL HAZARDS
BINDING INTERNATIONAL SAFETY STANDARDS
Yukiya Amano, IAEA (June 21):
- Safety Checks on a regular basis by IAEA Inspectors -

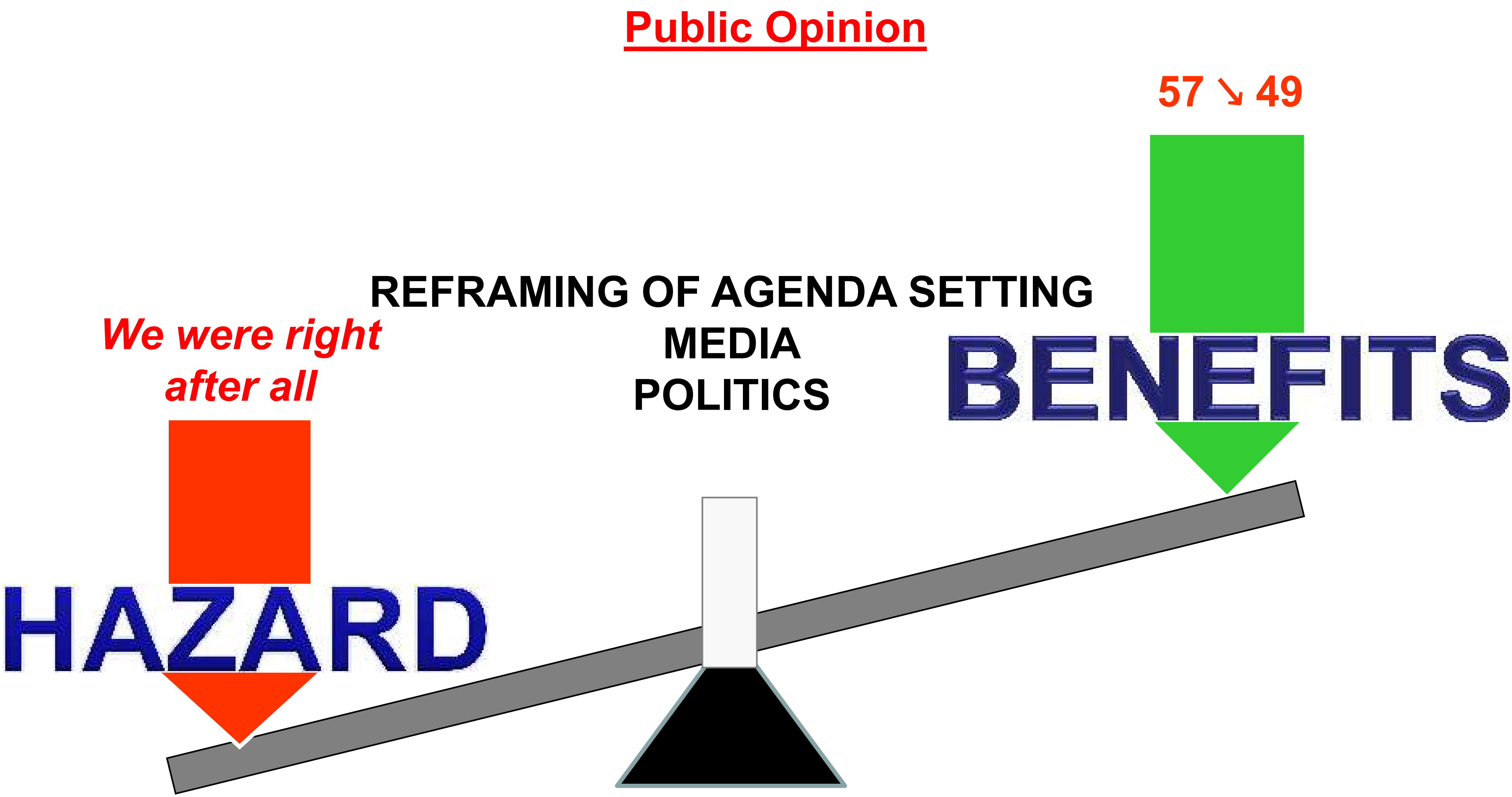
Public Opinion

Respect for the negative Stance on Nuclear Power

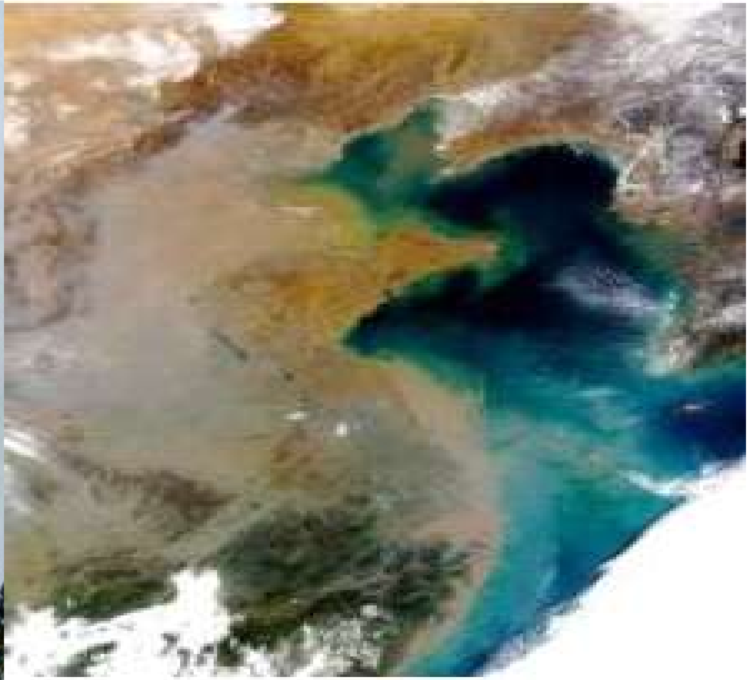
We all feel the task of mastering the future



Fukushima – Lessons to be learned



Public Opinion

DEVIL'S BARGAIN

THE BEST LESSON

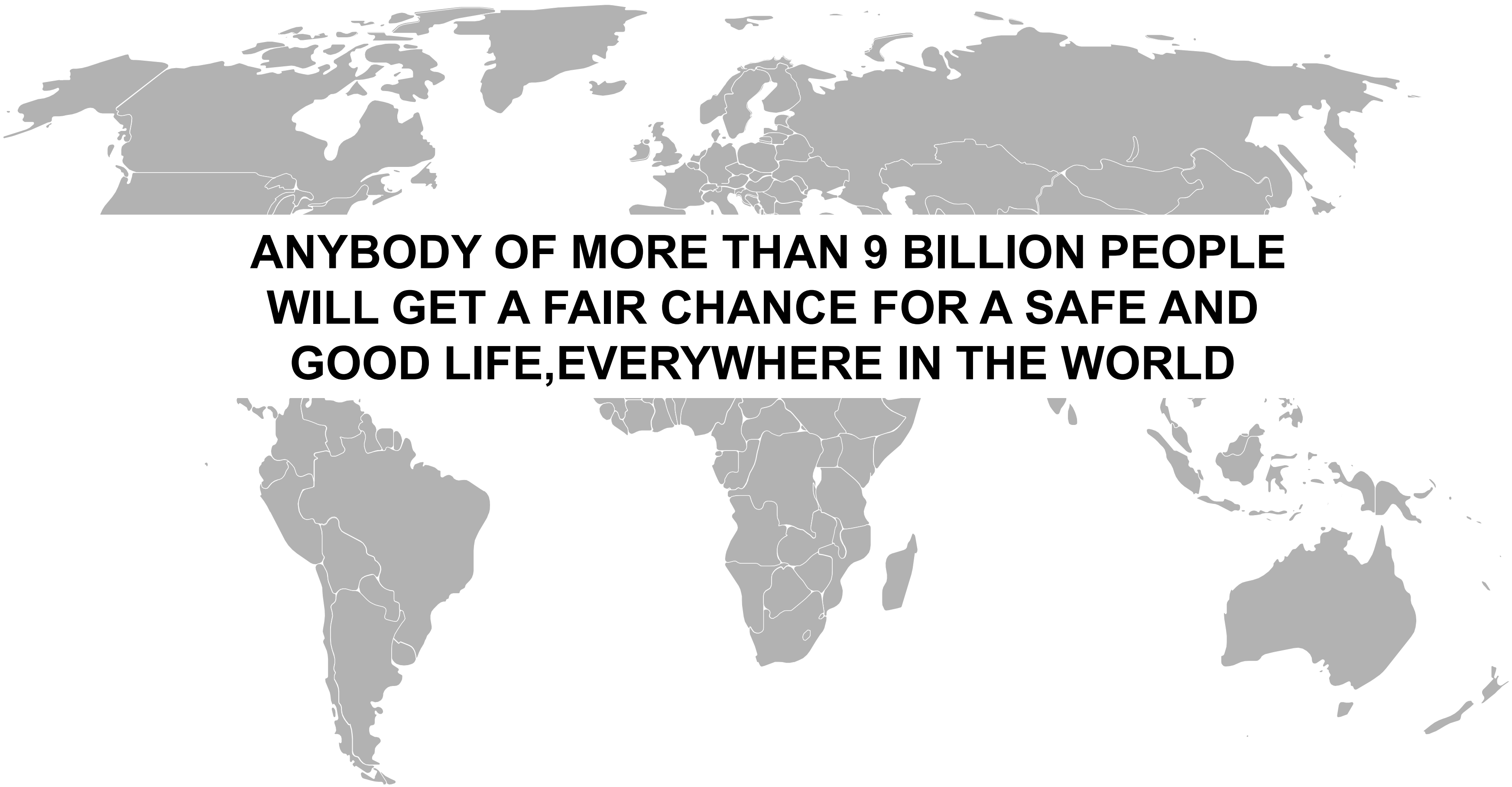
LET US WORK TOGETHER FOR ONE WORLD

THANK YOU VERY MUCH FOR YOUR ATTENTION

ENJOY THE CONFERENCE AND THE CHARM OF VALENCIA

Fukushima – Lessons to be learned

The Best Lesson: Let Us Work Together for One World



ANYBODY OF MORE THAN 9 BILLION PEOPLE WILL GET A FAIR CHANCE FOR A SAFE AND GOOD LIFE,EVERYWHERE IN THE WORLD