Safety of New Nuclear Reactors

Pavel Kudinov

Nuclear Science and Engineering
Royal Institute of Technology (KTH)
Stockholm, Sweden

Hazard, Uncertainty, and Risk

- Hazard – source of potential danger.

- Uncertainty is a result of complexity.
  - Complexity – fundamentally limits our ability to understand and predict system behavior.

- Risk – possibility (uncertainty) of damage.
  - Likelihood of conversion: Hazard => injury.
    - No potential damage => no risk
    - No uncertainty => no risk

- Risk is never zero,
  - but can be made as small as we like by increasing safeguards.
    - Risk ~ Hazard / Safeguards.

  - Awareness of a hazard is a safeguard
    - Helps to reduce the risk by avoiding the hazard.

Risk and Knowledge

- If all threats are known, then safeguards can be applied effectively.

  - *If you know your enemies and know yourself, you can win a hundred battles without a single loss.*
  - *if you only know yourself, but not your opponent, you win one and lose one.*
  - *If you know neither yourself nor your enemy, you will always endanger yourself.*

Sun Tzu, ~6th century BC

Relativity of Risk

- Risk is relative to the observer's (knowledge)
  - "Perceived risk"
    - "Absolute" or "Objective" risk
      - is risk perceived by someone else with different knowledge.

- Is it risky to reach with your hand into the bag?
  - (with a rattlesnake in it)?

- The answer depends on the knowledge available to the observer.
  - if the observer doesn't know about the rattlesnake in the bag, the answer is most probably "No".

Risk and Decision making

- Safety = Risk Management
- It is not possible to avoid risk but only to choose between different risks.
  - Doing “nothing” is not “risk free”.
- Rational decision-making requires a **quantitative way of expressing risk**
  - so that it can be properly weighed,
    - along with all other costs and benefits,
- in the process of making “risk informed” decisions.

Probability and Frequency

- “Frequency” refers to the outcome of an experiment of some kind involving repeated trials.
  – Frequency is a measurable value.
    - This is so even if the experiment is only a thought experiment or an experiment to be done in the future.

- “Probability” is a numerical measure of a state of knowledge, a degree of belief, a state of confidence in specific outcome.
  – Probability is a number used to communicate a state of mind
    - Subjective, not measureable
      – at least not in the usual way.
  – When one has insufficient statistical data, there is nothing else one can do but use probability.

Quantitative definition of Risk

1. What can go wrong?
   – Scenario s_i
2. How likely is that it will happen?
   – Frequency f_i
     • when statistical data is available
3. If it does happen, what are the consequences?
   – Measure of damage x_i

• Answers to the questions define the Risk quantitatively as a set of triplets:

$$R_i = \{s_i, f_i, x_i\}$$

• often we do not know exactly
  – the frequency with which scenario occurs $P_i(f_i)$
  – consequences of the scenario $P_i(x_i)$.

$$R_i = \{s_i, P_i(f_i, x_i)\}$$

Risk Curves

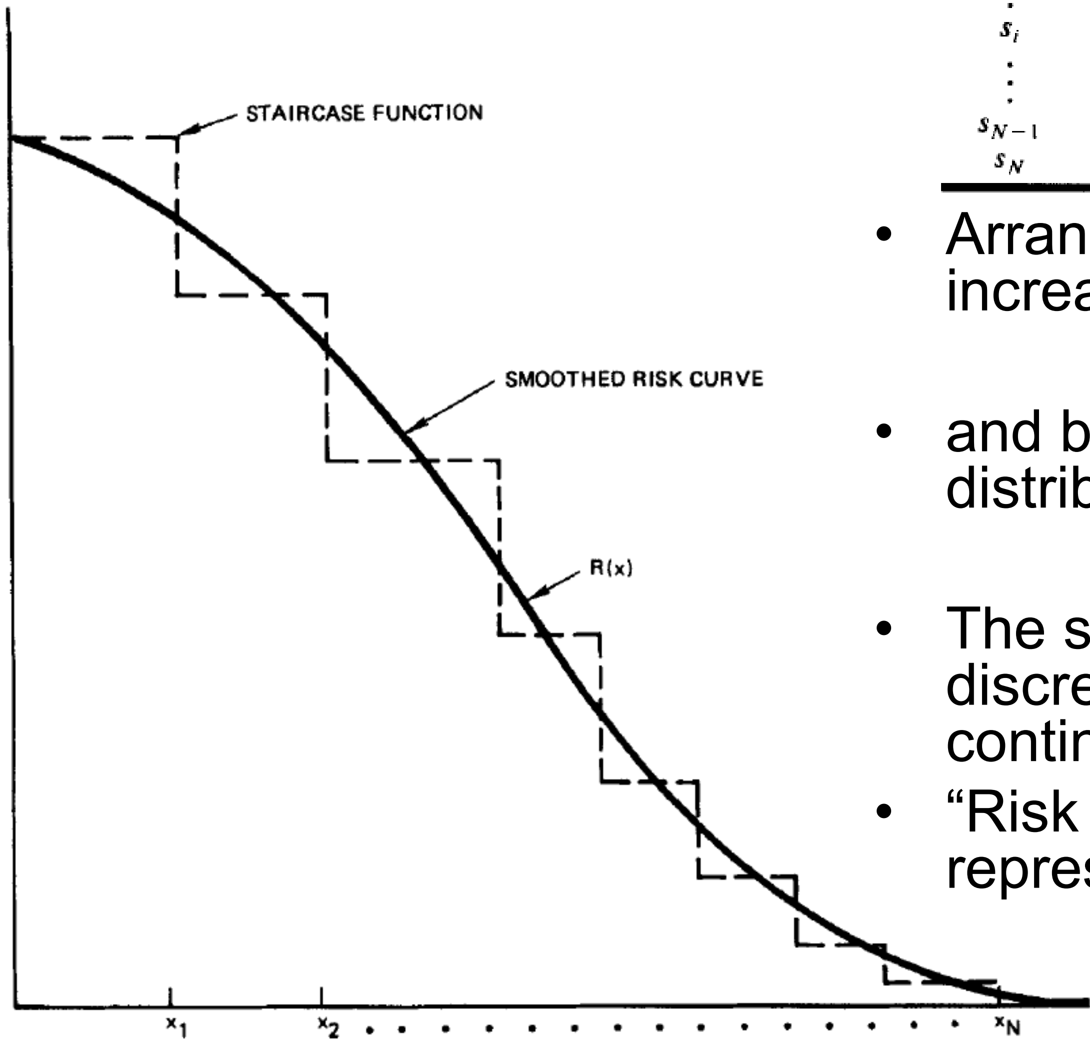
Scenario	Likelihood	Consequences	Cumulative probability
s_1	p_1	x_1	$P_1 = P_2 + p_1$
s_2	p_2	x_2	$P_2 = P_3 + p_2$
$\vdots$	$\vdots$	$\vdots$	
s_i	p_i	x_i	$P_i = P_{i+1} + p_i$
$\vdots$	$\vdots$	$\vdots$	
s_{N-1}	p_{N-1}	x_{N-1}	$P_{N-1} = P_N + p_{N-1}$
s_N	p_N	x_N	$P_N = p_N$

- Arrange scenarios in order of increasing severity of damage (x)

$$x_1 \leq x_2 \leq \cdots \leq x_N$$

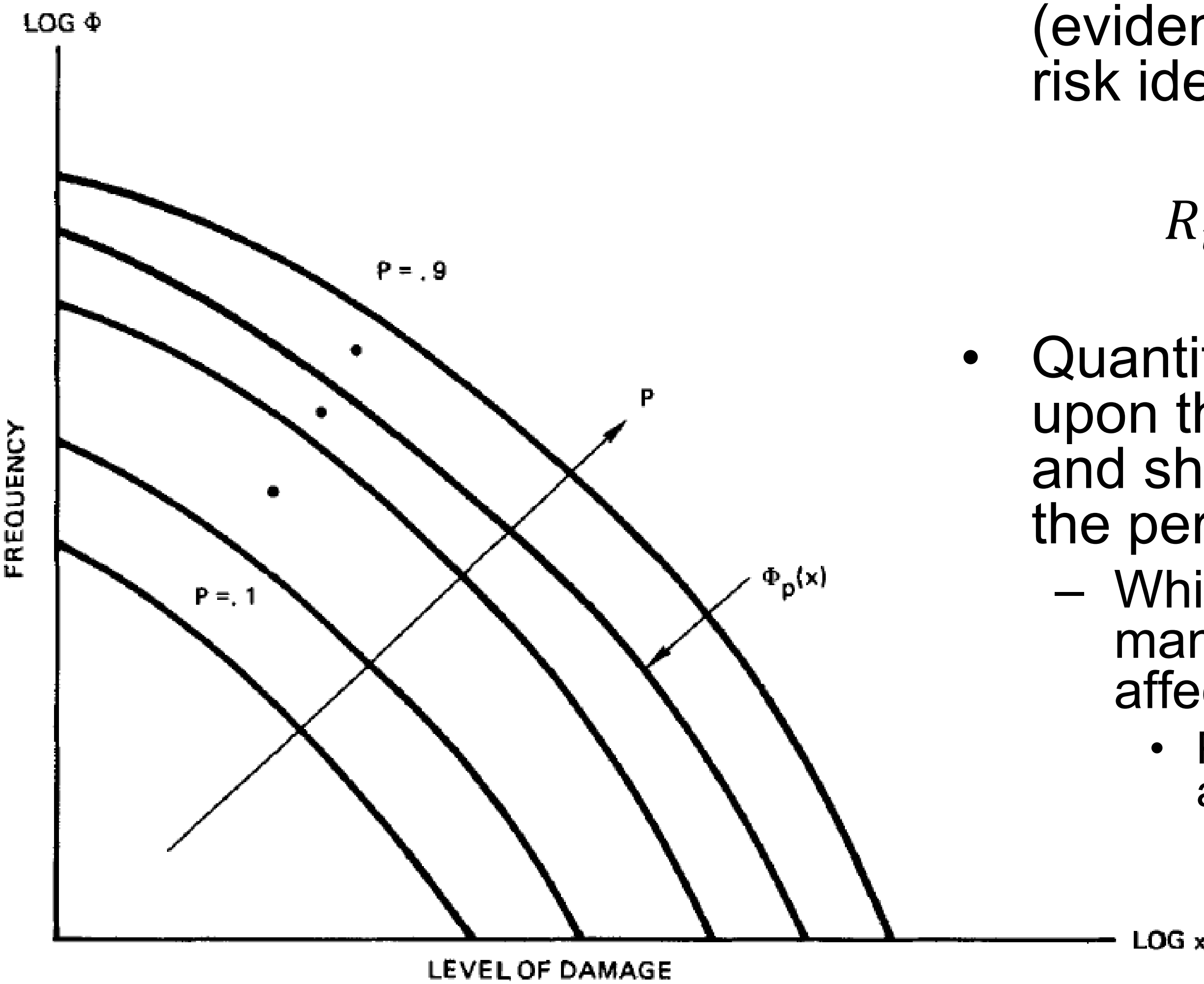
- and build a cumulative distribution of frequency

- The staircase function is a discrete approximation to a continuous reality.
- “Risk curve” can be used to represent the actual risk.



Risk Curves + Uncertainty

(Lack of) knowledge effect on the risk curve

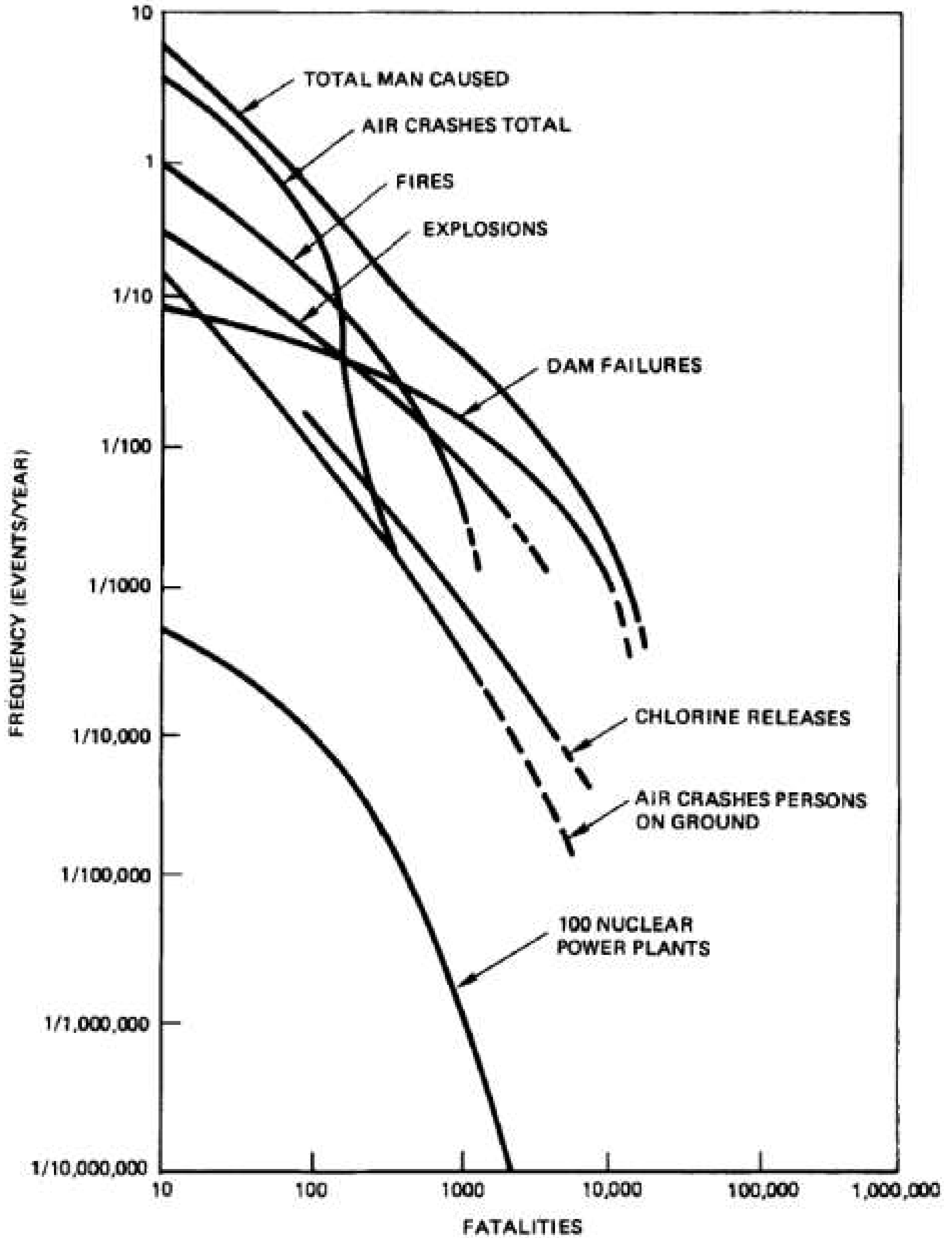


- While risk is relative to the observer's knowledge.
- Two rational beings given the identical totality of information (evidence) must assess the risk identically.

$$R_i = \{s_i, P_i(f_i, x_i)\}$$

- Quantitative risk depends upon the evidence at hand and should be independent of the personality.
  - While decisions on the risk management might be affected by the personality.
    - Personal degree of risk aversion/acceptance

Risk Curves



- ***Reactor Safety Study, Wash-1400, 1975.***
- Frequency of fatalities due to man-caused events
- The asymptotes have the interpretation of
  - "maximum possible damage" and
  - "probability of any damage at all."
- The effect of ~100 nuclear reactors on the total man caused mortality is negligible.

Risk comparison

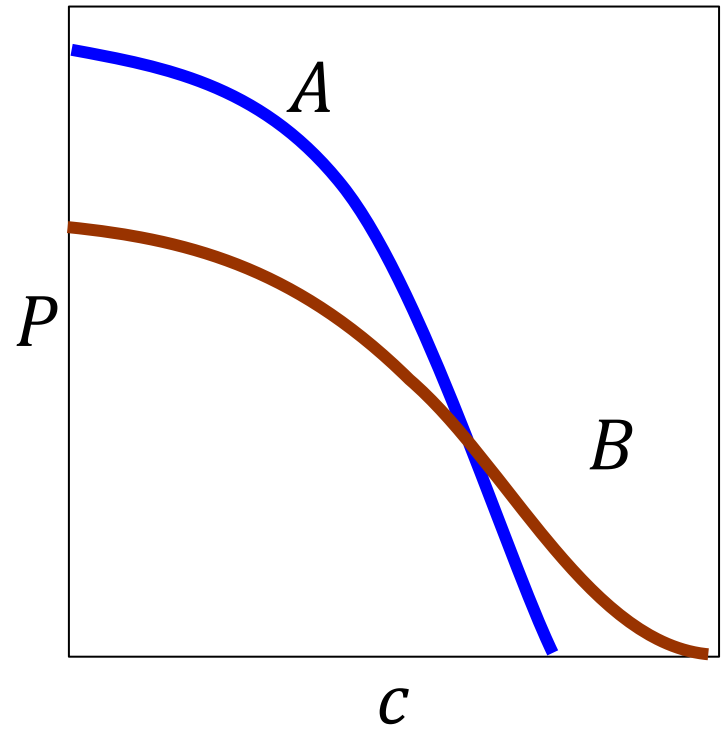
- Risk of A is clearly different from B.
  - Which option is better?

- It is possible to reduce risk curves to single numbers, for example by introducing a utility function and performing an expected value operation

$$\bar{U} = -\int_0^\infty U(c)\frac{dP(c)}{dc}dc$$

- These figures of merit are scalars and thus linearly comparable, but, only at a cost of great loss of information in the expectation operation.

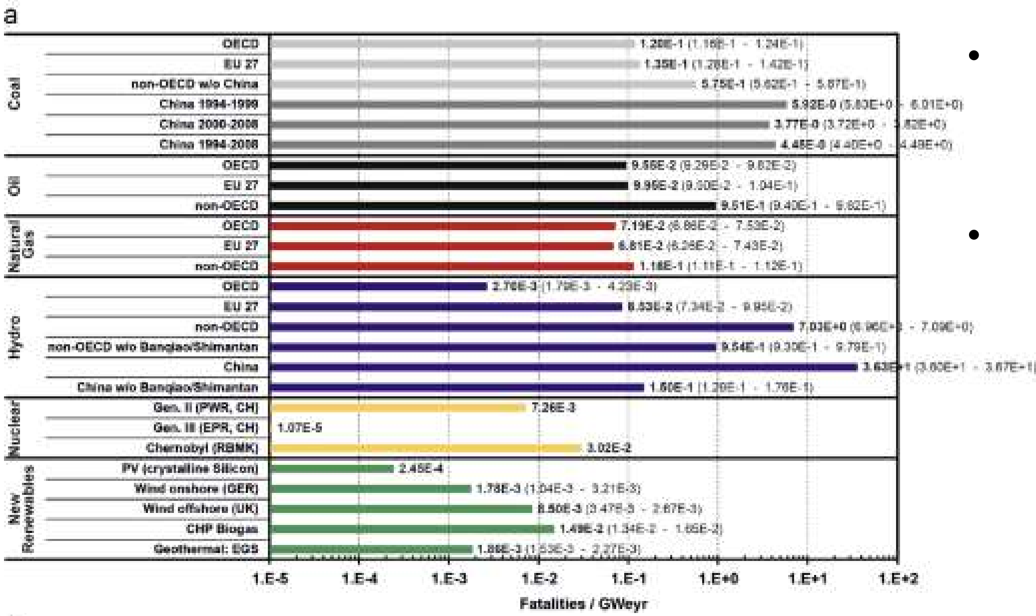
- E.g. $\bar{U}_A > \bar{U}_B$ but B can include a scenarios with extremely high consequences, that should be avoided, despite its very low probability.



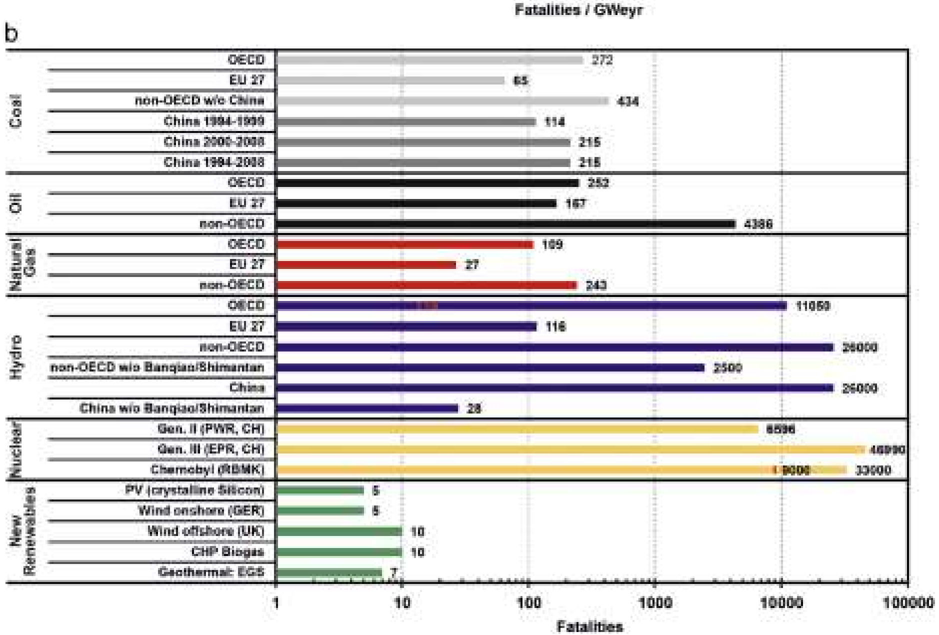
“Acceptable” Risk

- Risk cannot be spoken of as acceptable or not in isolation,
  - but only in combination with the **costs and benefits** that are attendant to that risk.
- **Considered in isolation, no risk is acceptable!**
- A rational person would not accept any risk at all except possibly in return for the benefits that come along with it.
- Even then, Risk is still not acceptable if it is possible to
  - obtain the **same benefit in another way with less risk**.
  - **reduce the risk** at small (compared to benefit) cost.
- A larger risk may be perfectly acceptable if it brings with it
  - a substantially reduced cost or
  - increased benefit.

Perception and acceptance of risks associated with energy production



- (a) Risk per GW electric year
  - Takes into account the benefit (power)
  - Likelihood of damage
- (b) Worst case scenarios (maximum fatalities)
  - No benefit
  - No likelihood
  - Yet, often the basis for policy decision



- Peter Burgherr, Stefan Hirschberg (2014):
  - Comparison of (a) fatality rates (with 5% and 95% confidence intervals) and (b) maximum consequences of a broad selection of energy technologies.
  - Fossil and hydropower is based on the ENSAD database (period1970–2008); for nucleara simplified level-3 PSA is applied; and for other renewable sources a hybrid approach using available data, modeling and expert judgment is used.
  - Abbreviations: PWR - pressurized-water reactor; EPR - European Pressurized Reactor; CH - Switerland; RBMK - reaktor bolshoy moshchnosty kanalny, a boiling water-cooled graphite moderated pressure tubetypereactor; PV - photovoltaic; CHP - combined heat and power; and EGS - Enhanced Geothermal Systems.

Perception and acceptance of risks associated with energy production

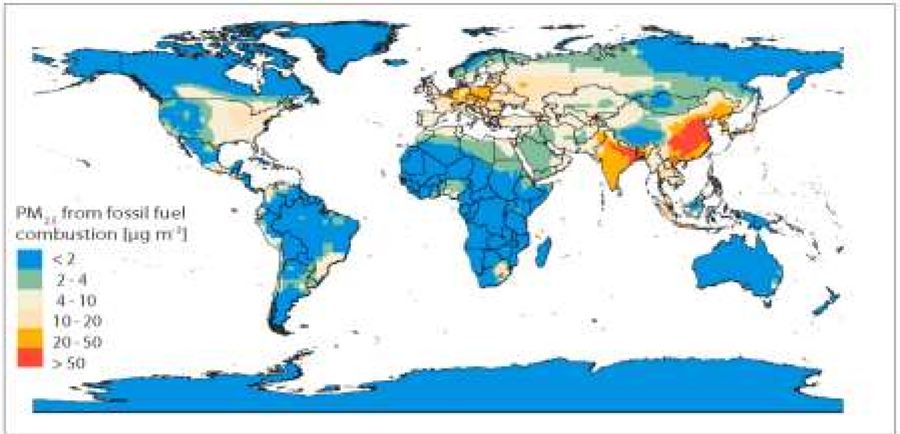


Fig. 1. Contribution of fossil fuel combustion to surface $PM_{2.5}$, as calculated by the chemical transport model GEOS-Chem. The plot shows the difference in surface $PM_{2.5}$ concentrations from GEOS-Chem with and without fossil fuel emissions.

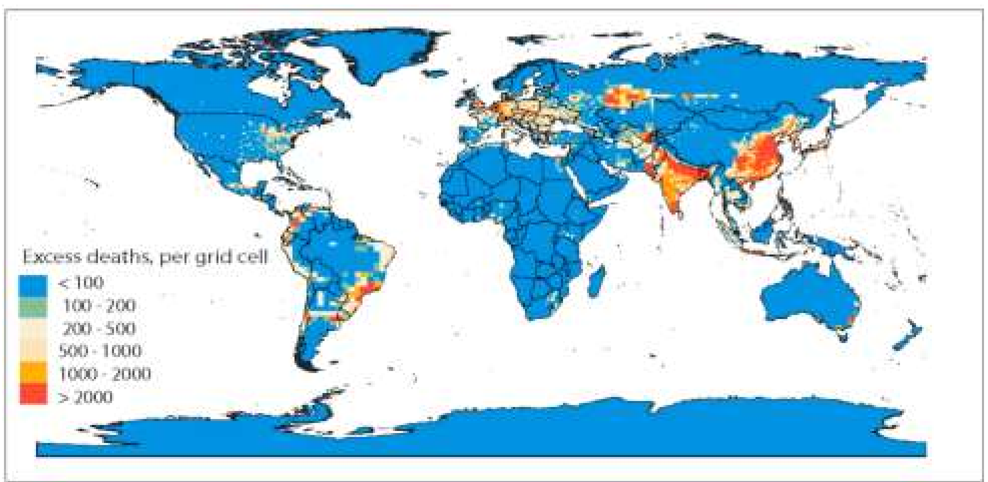


Fig. 2. Estimated annual excess deaths due to exposure to ambient $PM_{2.5}$ generated by fossil fuel combustion.

- Karn Vohra, Alina Vodonos, Joel Schwartz, Eloise A. Marais, Melissa P. Sulprizio, Loretta J. Mickley (2021) Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem

- The burning of fossil fuels – especially coal, petrol, and diesel – is a major source of airborne particulate matter with an aerodynamic diameter < 2.5 µm (PM2.5).

- **A global total of 10.2 million premature deaths annually attributable to the fossil-fuel component of PM2.5.**
  - The greatest mortality impact is estimated over regions with substantial fossil fuel related PM2.5, notably China (3.9 million), India (2.5 million) and parts of eastern US, Europe and Southeast Asia.

- **What would be a rational decision on selection of the energy source?**

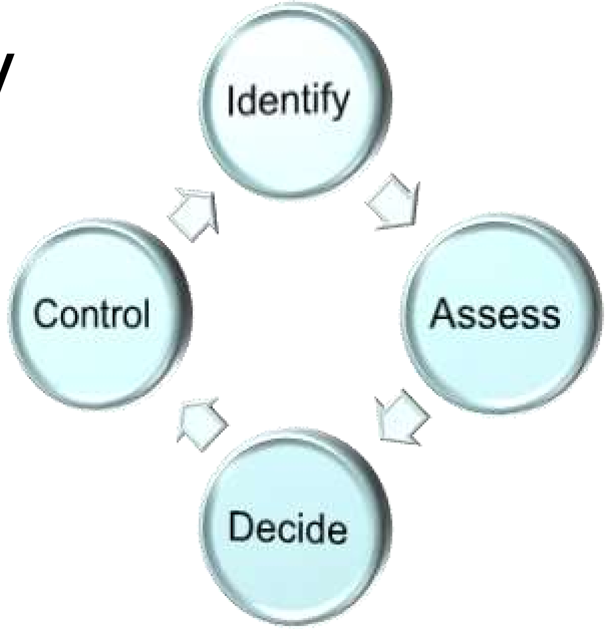
Nuclear power: benefits

- Nuclear power is a source of energy capable to provide base-load demand without negative impact on the climate
  - CO_2 and air pollution free.
    - Nuclear energy provides about 30% of the base-load electricity in the EU and is considered a strategically important source of the future energy mix by the European Strategic Energy Technology Plan (SET-plan).
- Nuclear energy can be used to actively reduce the concentration of greenhouse gases in the atmosphere.
  - to prevent the climate catastrophe.

Uncertainty and Risk

- **Managing the Risk is about dealing with uncertainty.**
  - Nuclear power safety aims to bound the uncertainties and provide adequate protection despite the unavoidable “unknown unknowns”

- We can reduce **uncertainty** by
  - Changing the system
    - design,
    - procedures,
    - training…
  - Improving knowledge
    - Research

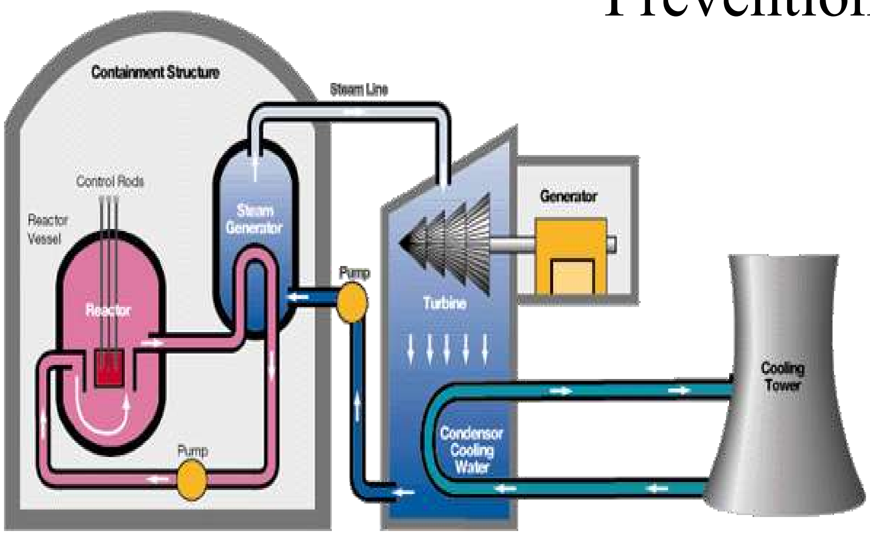


Safety ~ Risk Management

Perceiving, Assessing and Managing ***Risk of***
Rare, High-Consequence Hazards

Risk = { Frequency , Consequence }

Prevention   Mitigation



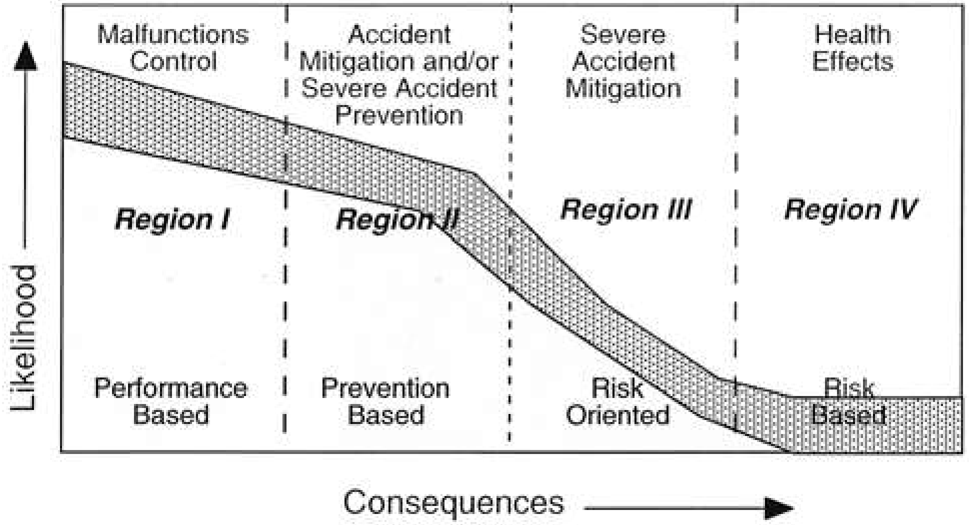
VS.

- Statistics Available.
- Trials-and-Errors
- Full-Scale Testing

- Physics-Based and Engineering Judgment.
- Simulation-Based Prediction.
- Synthesis

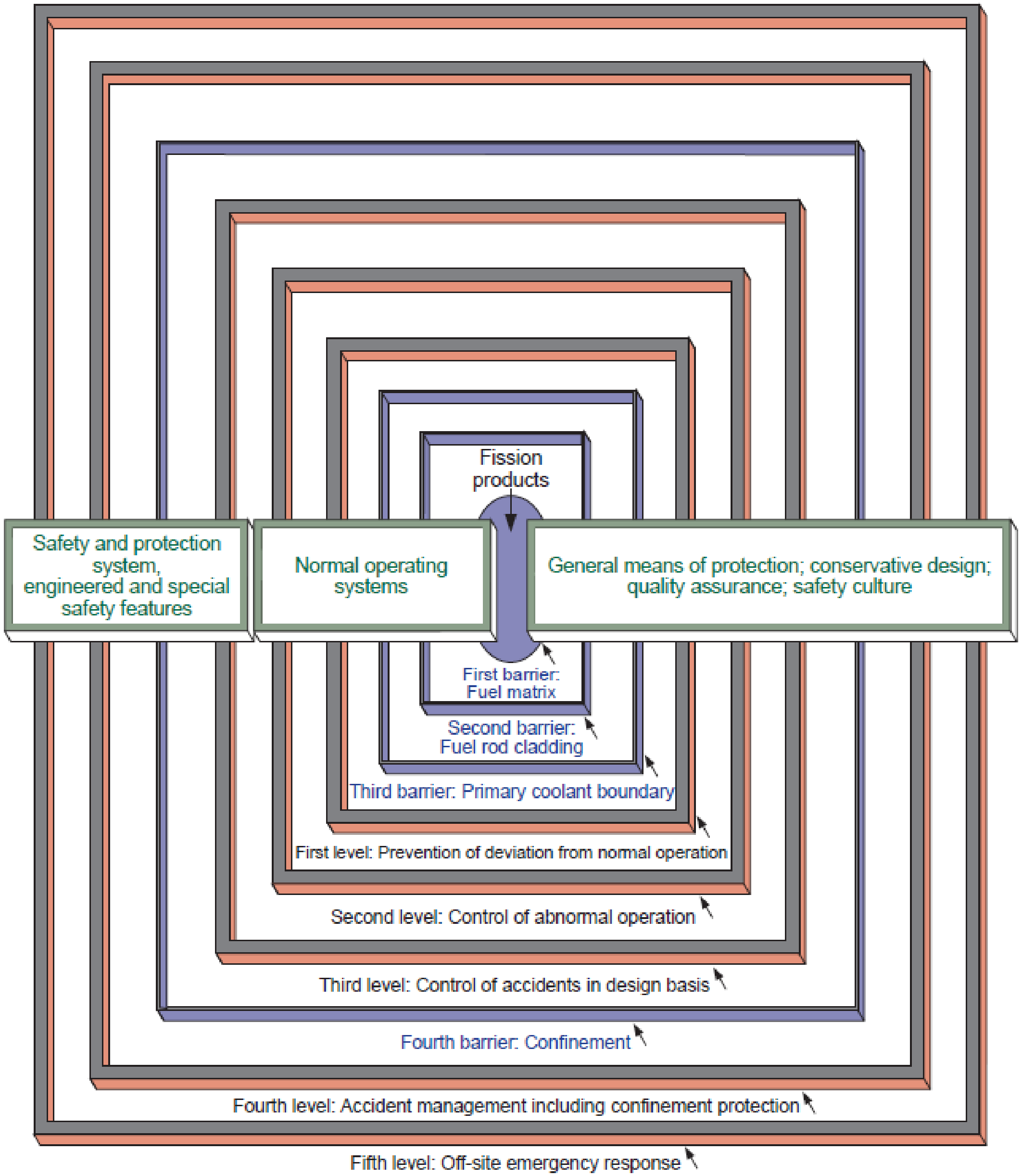
Dealing with Very High Consequence Hazards

Theofanous (1996)



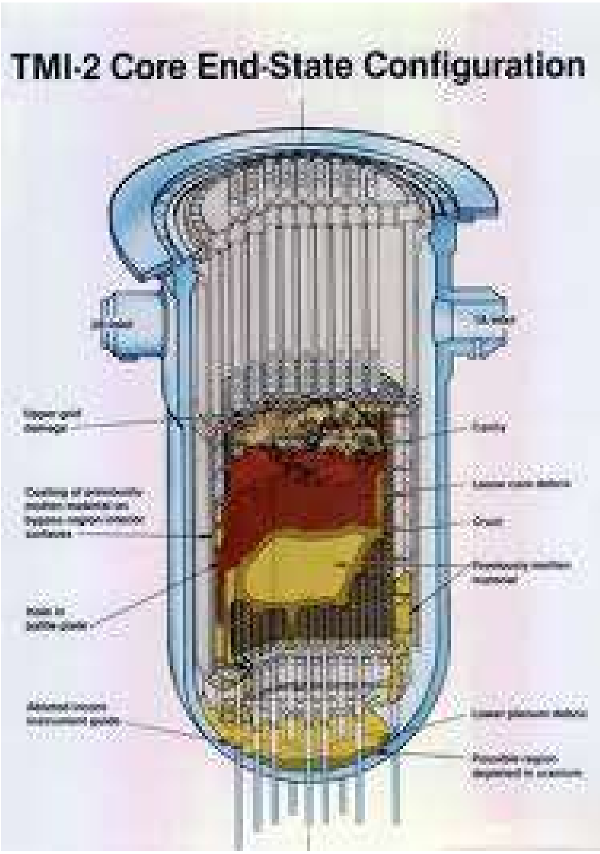
- When consequences are extremely high (e.g. severe accident), low probability is insufficient to satisfy public risk aversion
  - Fukushima (and previously TMI-2 and Chernobyl) accident shows that public has near-zero tolerance to significant release of fission products,
    - even if there are few or no fatalities which can be directly linked to the release.

Safeguards: Defence in Depth: Physical barrier and levels of protection



- Defence in depth provides the basic framework for nuclear power plant safety.
- There are many layers of protection of people and the environment against
  - the possibility and
  - the effects
- of accidents.

What if risk management fails?

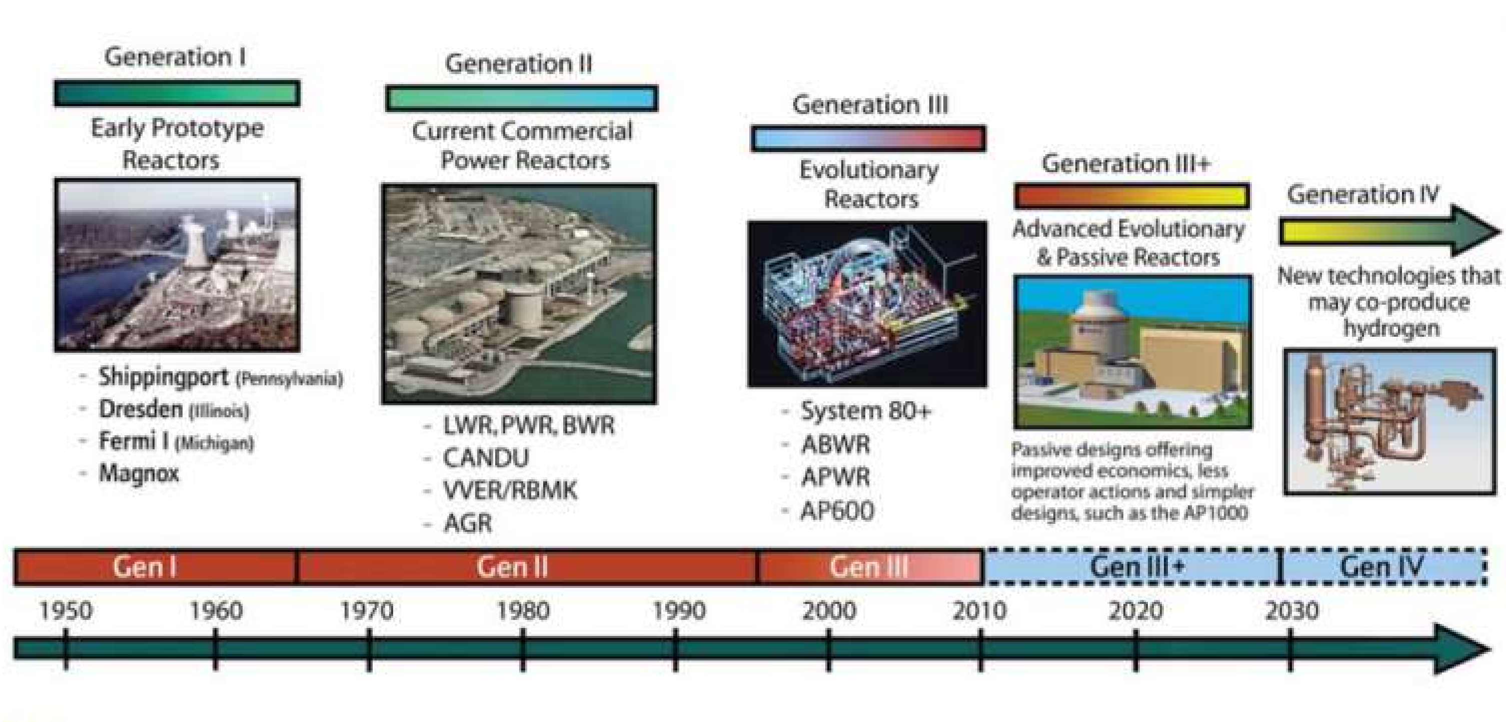


- According to Murphy's law:

  If anything ***can*** possibly go wrong, ***it will***.

- TMI-2, Chernobyl – when design allows, human operator is the weakest link.
- Fukushima – likelihood of extreme external hazards can be severely underestimated

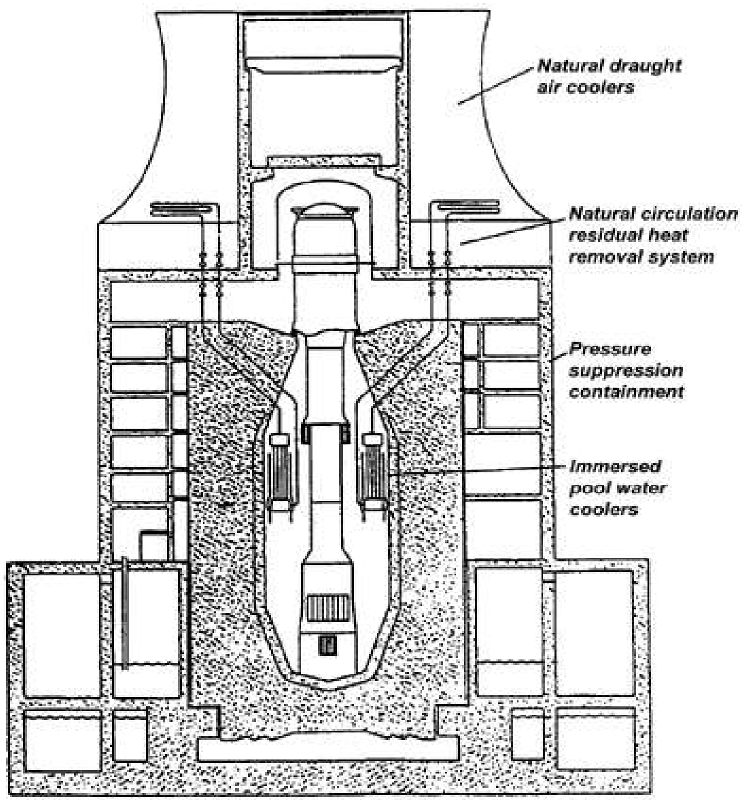
Evolution of the safety design

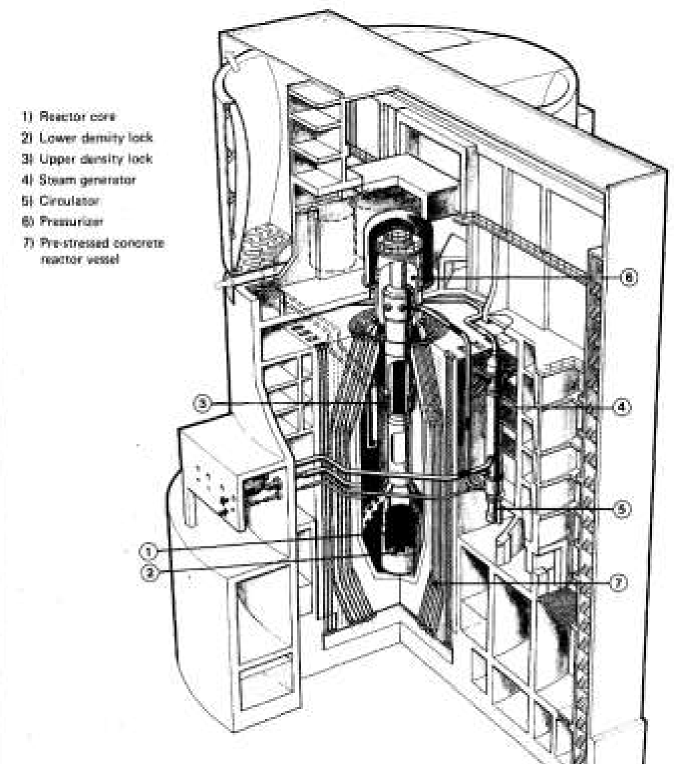


- Gen III+ reactor designs are an evolutionary development of Gen III reactors, offering significant improvements in safety.
- Examples of Gen III+ (stands for +passive systems) designs include:
  - AP1000:
    - Heavily influenced by ideas of Process Inherent Ultimate Safe Reactor (PIUS)
  - European Pressurized Reactor (EPR):
    - evolutionary descendant of the Framatome N4 and Siemens Power Generation Division KONVOI reactors
  - Economic Simplified Boiling Water Reactor (ESBWR):
    - based on the ABWR

Process Inherent Ultimate Safe Reactor (PIUS)

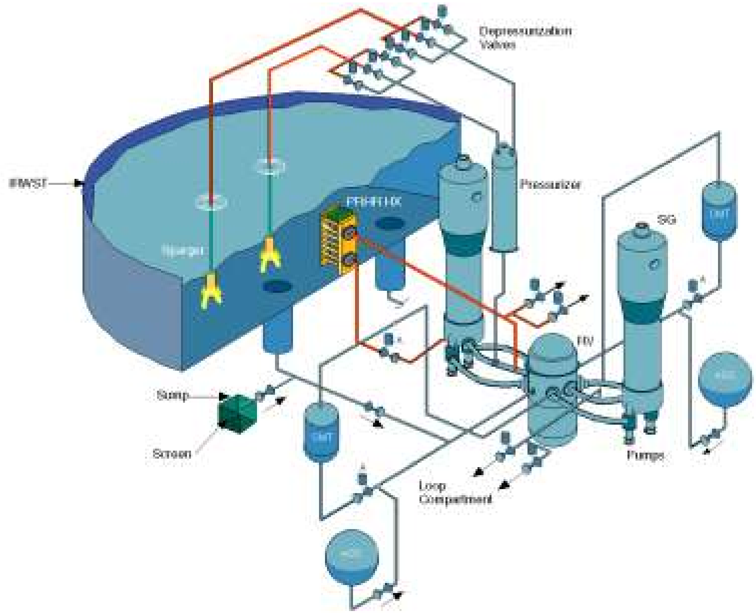
- The Process Inherent Ultimate Safe reactor is a 640 MWe advanced pressurized water reactor designed by ABB-Atom of Sweden that uses natural physical phenomena to accomplish control and safety functions.
- The PIUS design consists of a vertical pipe, called a reactor module, that contains the reactor core and is submerged in a large pool of highly borated water.
- The borated pool water is provided to shut down the reactor and to cool the core by natural circulation.
- Unlike most reactors, PIUS does not use control rods for controlling the nuclear chain reaction.
  - The reaction is controlled by the boron concentration and temperature of the primary loop reactor water.

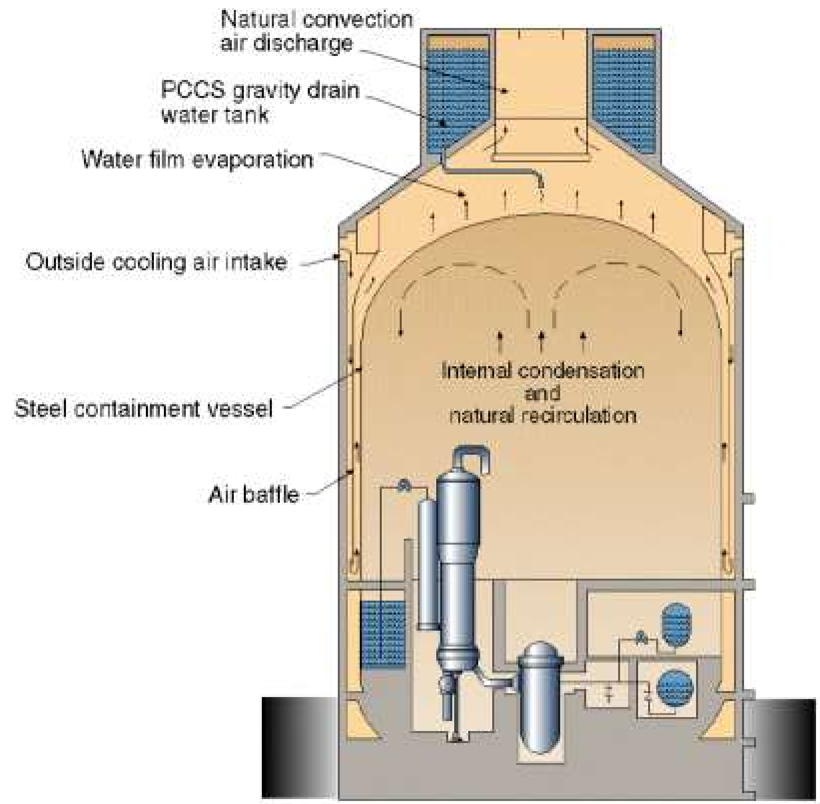




Basic arrangement of the PIUS-600 nuclear system

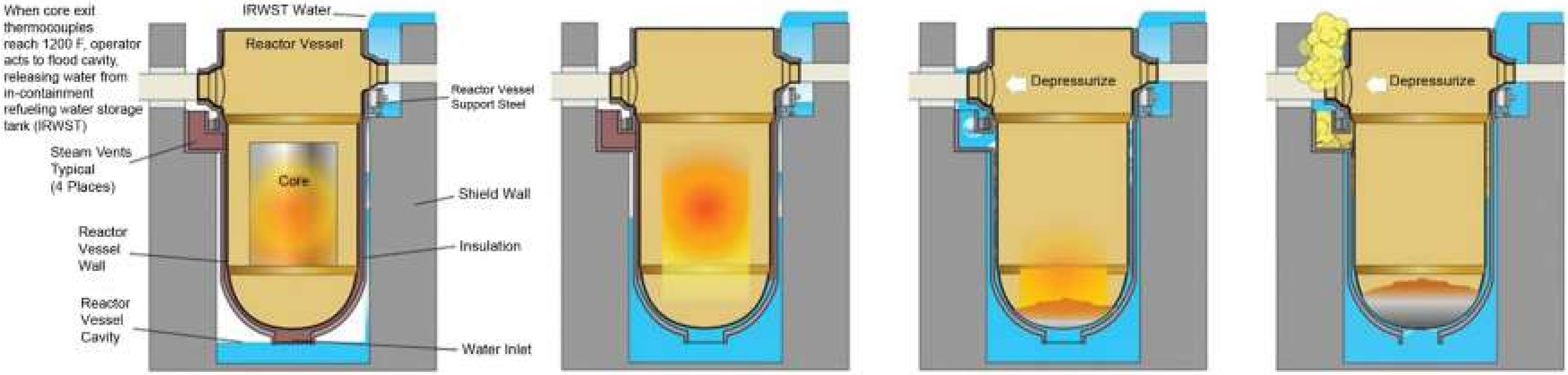
AP1000 Active plant with passive safety systems





- Active Non-Safety Systems
  - Reliably support normal operation
  - Minimize challenges to passive safety systems
  - Not required to mitigate design basis accidents or meet safety goals
  - Provide plant investment protection
- Passive Safety Systems (reduced dependency on operator actions)
  - Use “passive” processes only; no safety-grade active pumps, diesels….
  - Dedicated systems; not used for normal operations
  - Mitigate design basis accidents
  - Meet regulatory safety goals

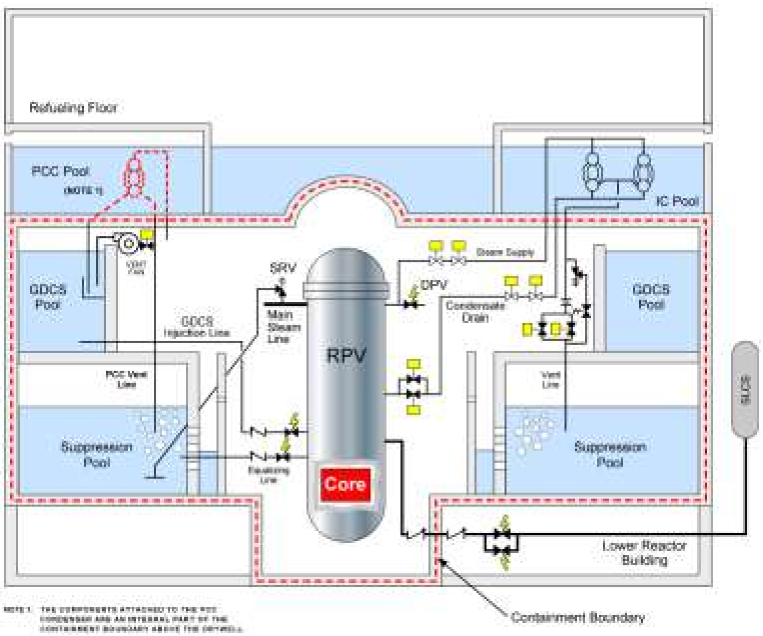
AP1000
In-vessel Severe accident management

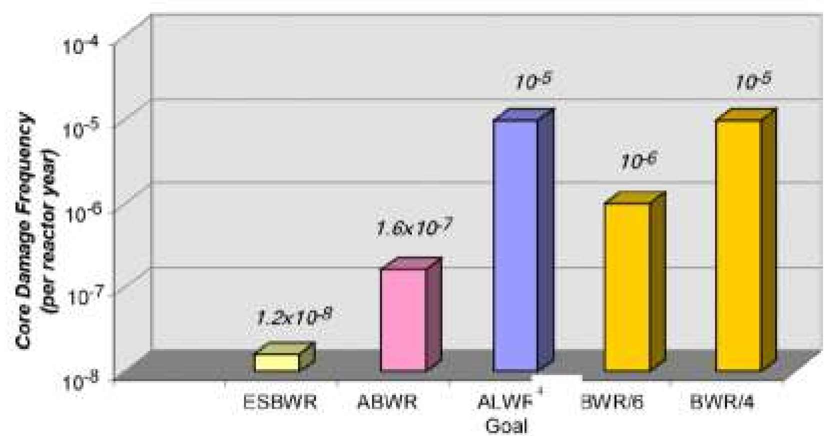


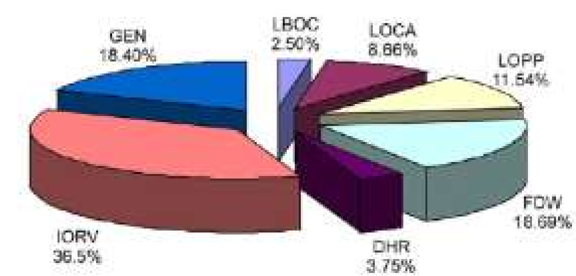
- In-Vessel Retention passively provides sufficient external cooling of the reactor vessel to retain a molten core inside vessel in the unlikely event of a severe accident.
- This concept was proven by a series of tests and offers numerous advantages over other severe accident core management designs.

ESBWR
Economic, Simplified Boiling Water Reactor

- Natural circulation in normal operation
- Passive safety systems for accident management.
- Station blackout doe has no significant contribution to core damage frequency



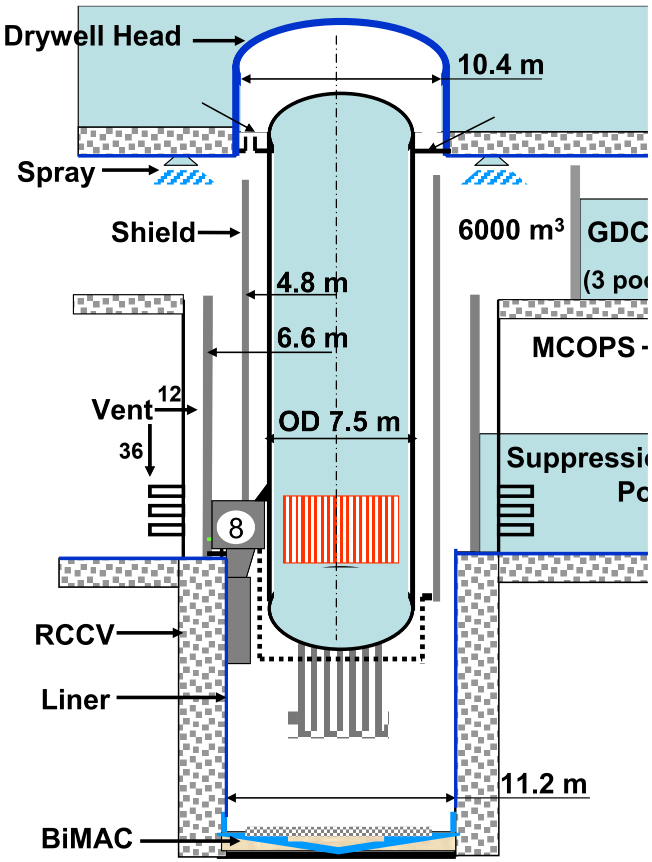


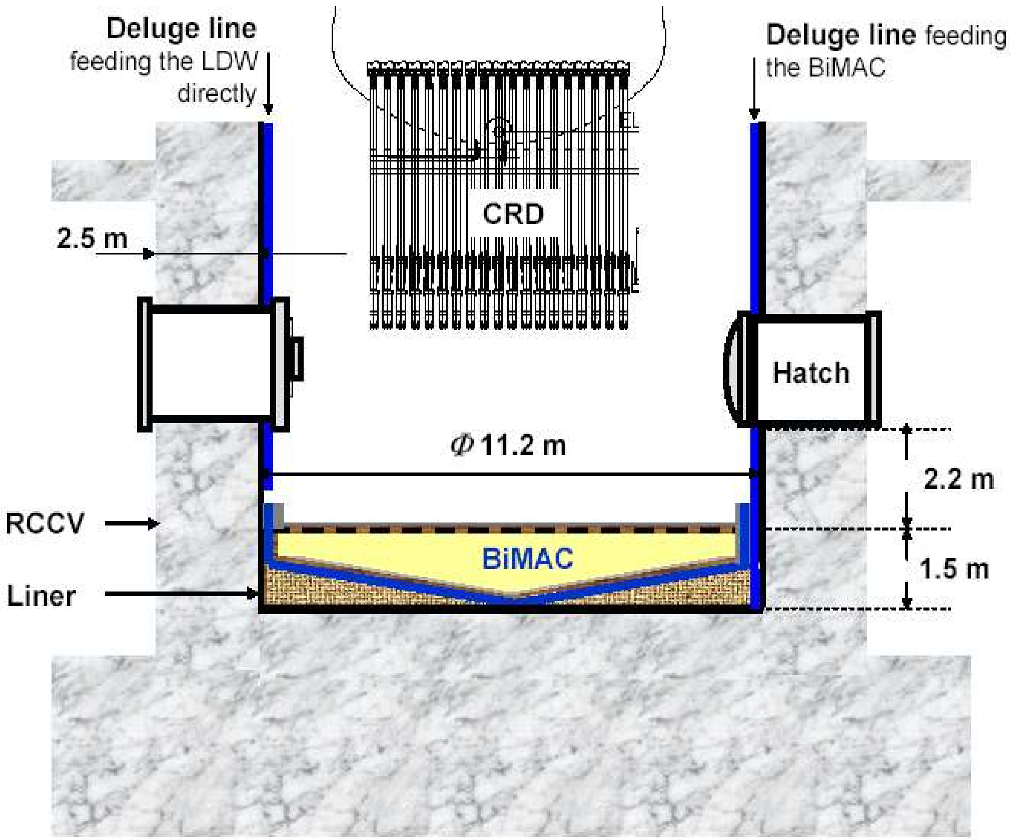


IORV: Transient with an Inadvertent Opening of a Safety Relief Valve
GEN: General Transient
LBOC: Line Break Outside of Containment
LOCA: Loss of Coolant Accident
LOPP: Loss of Preferred (Off-site) Power
FDW: Transient with Loss of Feedwater and Condensate
DHR: Loss of Decay Heat Removal

ESBWR
Ex-vessel Coolability Strategy

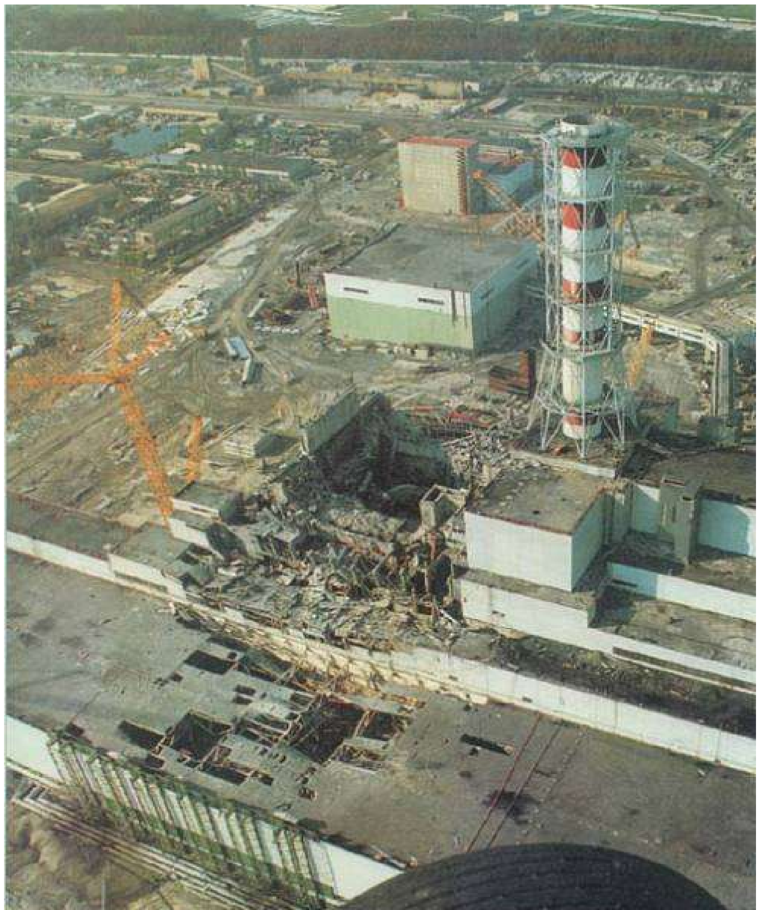
- Ex-vessel coolability was addressed inclusive of all possible ex-vessel scenario evolutions.

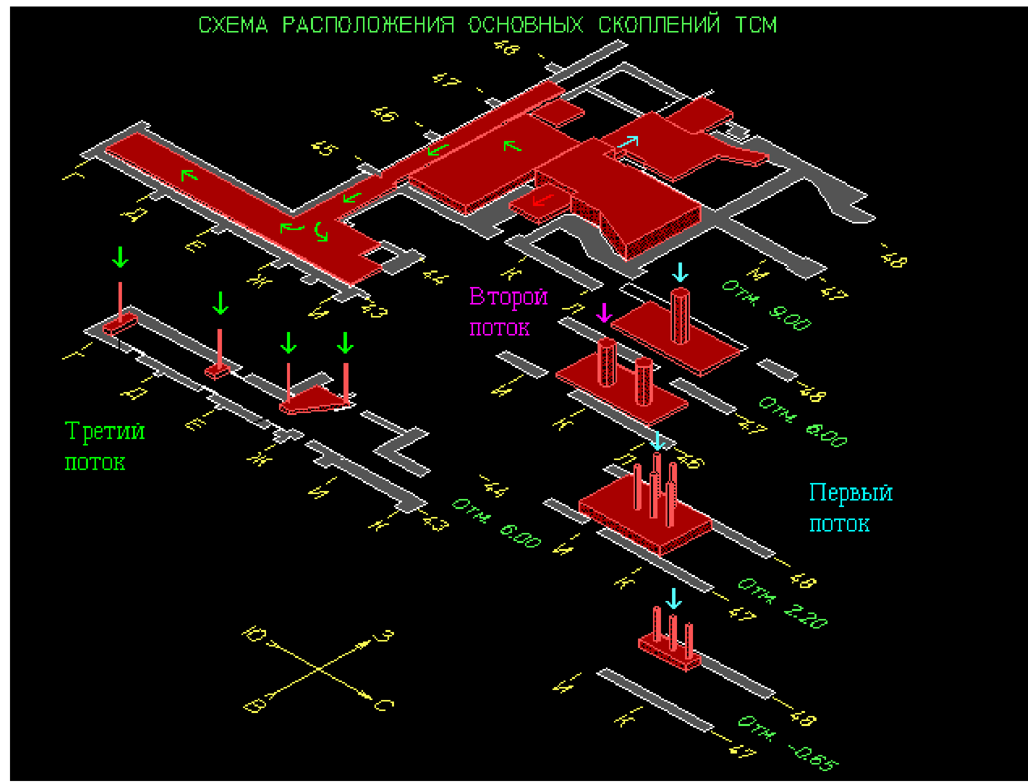




Chernobyl-4 Plant Accident (1986)

- Lessons from Chernobyl:
  - Core melt can spread in liquid state





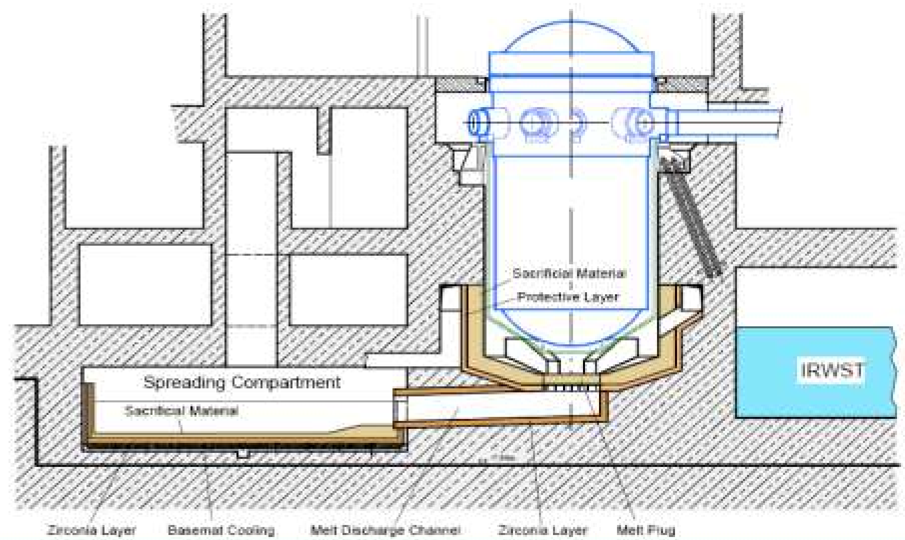
EPR
Severe Accident Management

- Accumulation in the crucible and one-shot melt release with high flow rate and superheat

VULCANO VE-U7 test with prototypic corium (CEA Cadarache)

ig. 4. Post mortem views of the spread (right: zoom of the spread front over concrete).

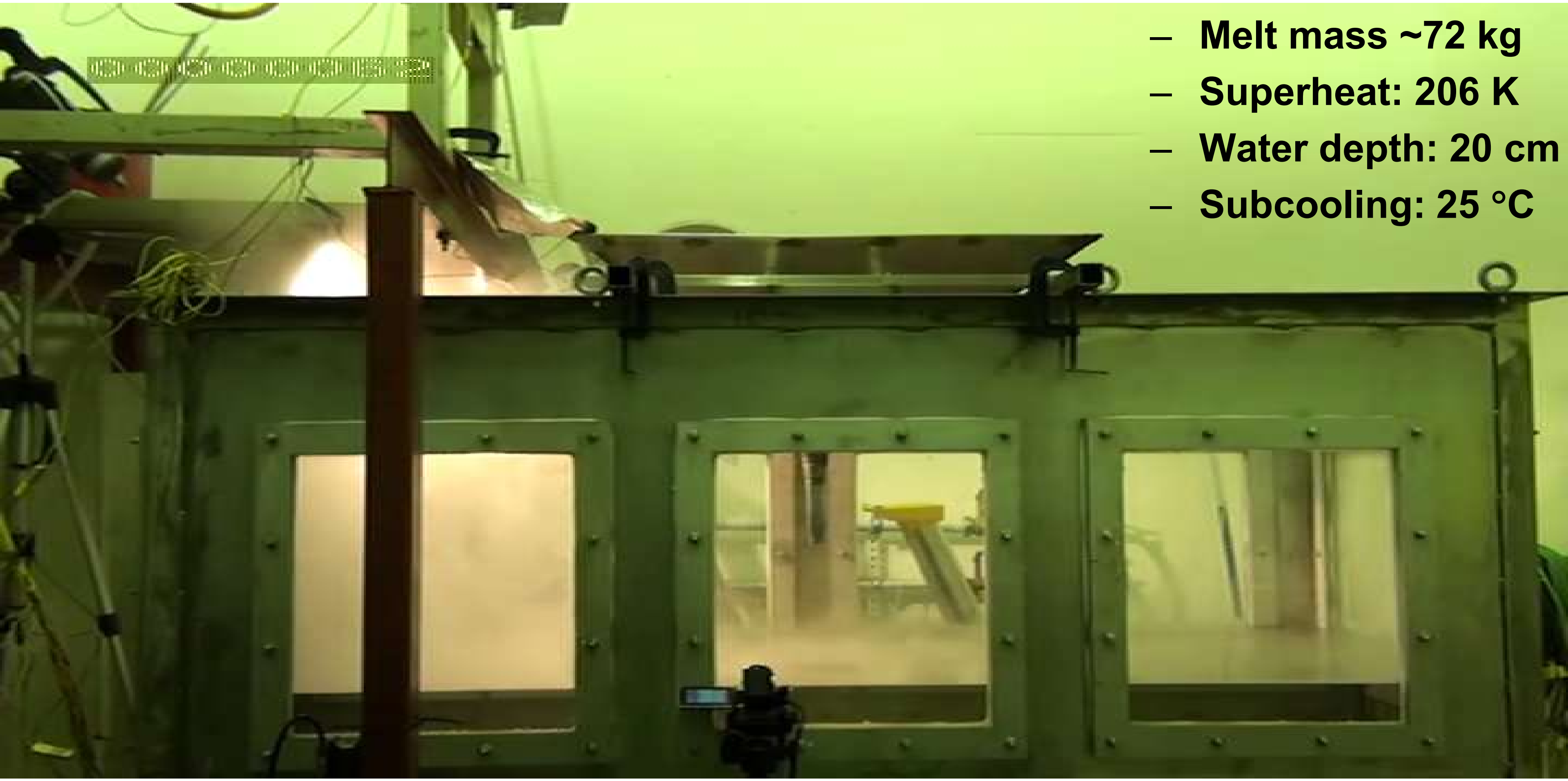
EPR Core-Catcher



Main elements of the core-melt stabilization concept of the EPR

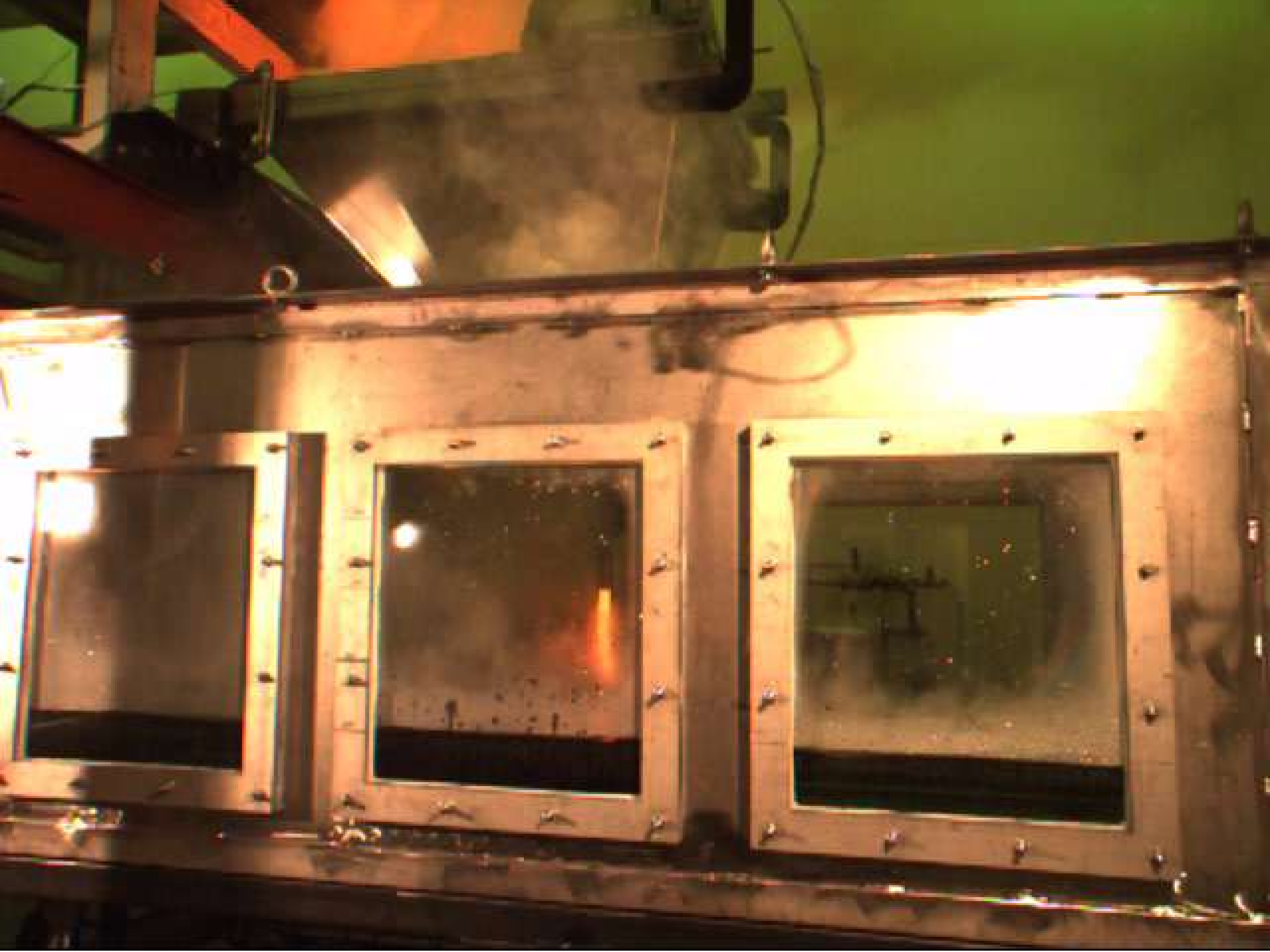
PULiMS-E3 test at KTH

- Melt: WO_3-Bi_2O_3
- Melt temp.: 1076 °C
- Melt mass ~72 kg
- Superheat: 206 K
- Water depth: 20 cm
- Subcooling: 25 °C



PULiMS-E5 test

- Melt: WO_3-ZrO_2
- Melt temp.: 1531°C
- Superheat: 300 K
- Melt mass ~15 kg
- Water depth: 20 cm
- Subcooling: 25 °C



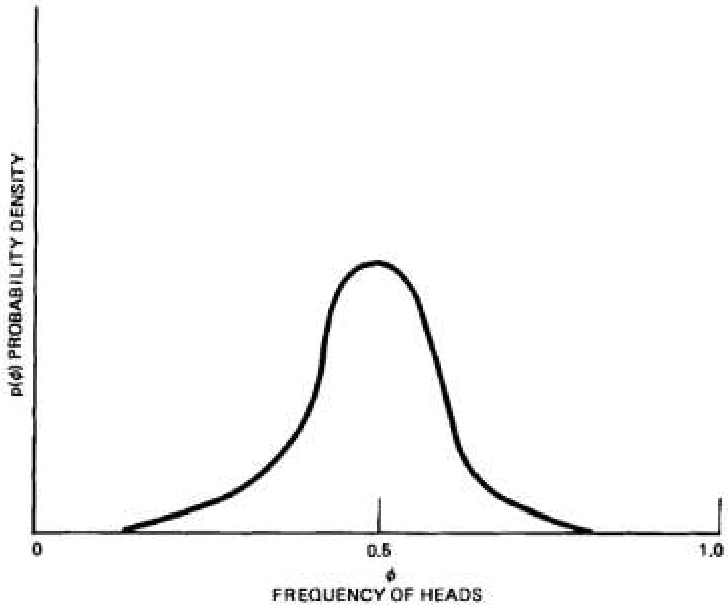
Summary

- There is no way to avoid risk but only to choose between risks.
- Rational decision-making requires a quantitative way of expressing risk.
  - "Intuitive" Risk perception is almost always wrong.
- Risk can be defined quantitatively as a set of triplets
  - Risk = (Scenario, Probability, Consequences)
- Decisions on risk acceptance should consider in quantitative manner
  - other risk sources,
  - costs and benefits.
- Modern reactors manage the risk by developing both
  - Prevention
    - reduction of failure probability by reducing reliance from human operator and electricity supply to passive safety systems
  - Mitigation
    - Expressly designed measures to arrest accident progression and prevent containment failure
- Yet, the systems are complex
  - risk management (i.e. "safety") is a **continuous process**!

Probability and Frequency

- Probability
  - What is the probability of a head on the next toss?
    - Our state of confidence on the prospect of a head on the next toss.
    - Odds we would take in a bet.

- Probability of Frequency:
  - I am going to toss the coin 10,000 times.
  - What is the frequency, i.e., the percentage of heads going to be?
    - Since we do not know outcome of experiment that will be done in the future
    - we can express our prediction in the form of a probability curve against frequency
      - our confidence / believe about frequency



“Acceptable” Risk

- Decision theory point of view:

- What are my options?

- What are the
  - costs,
  - benefits, and
  - risks
- of each option?

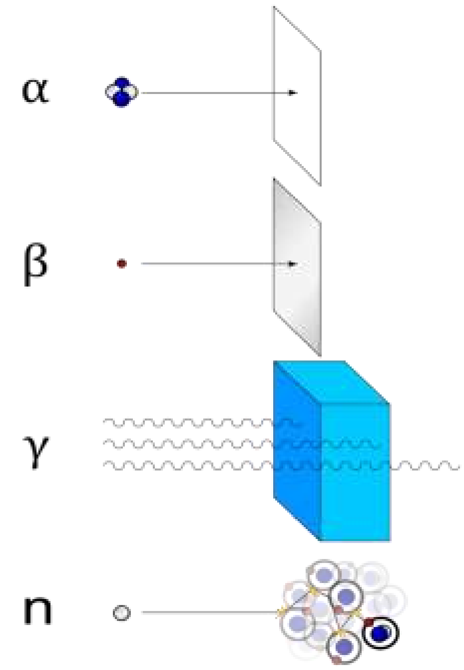
- That option with the optimum mix of cost, benefit, and risk is selected.

- The risk associated with that option is acceptable.

- All others are unacceptable.

Hazard: Ionizing Radiation

- Radioactive **fission products (FP)** in nuclear reactor are the source of ionizing radiation
- ***Ionizing radiation*** is radiation composed of particles that individually have sufficient energy (or can liberate sufficient energy) to remove an electron from an atom or molecule.
- This ionization produces ***free radicals***, which are atoms or molecules containing unpaired electrons.
- ***Free radicals*** tend to be especially chemically reactive, and they account for most of the ***biological damage of ionizing radiation***.



Alpha (α) radiation consists of a fast moving nucleus and is stopped by a sheet of paper.

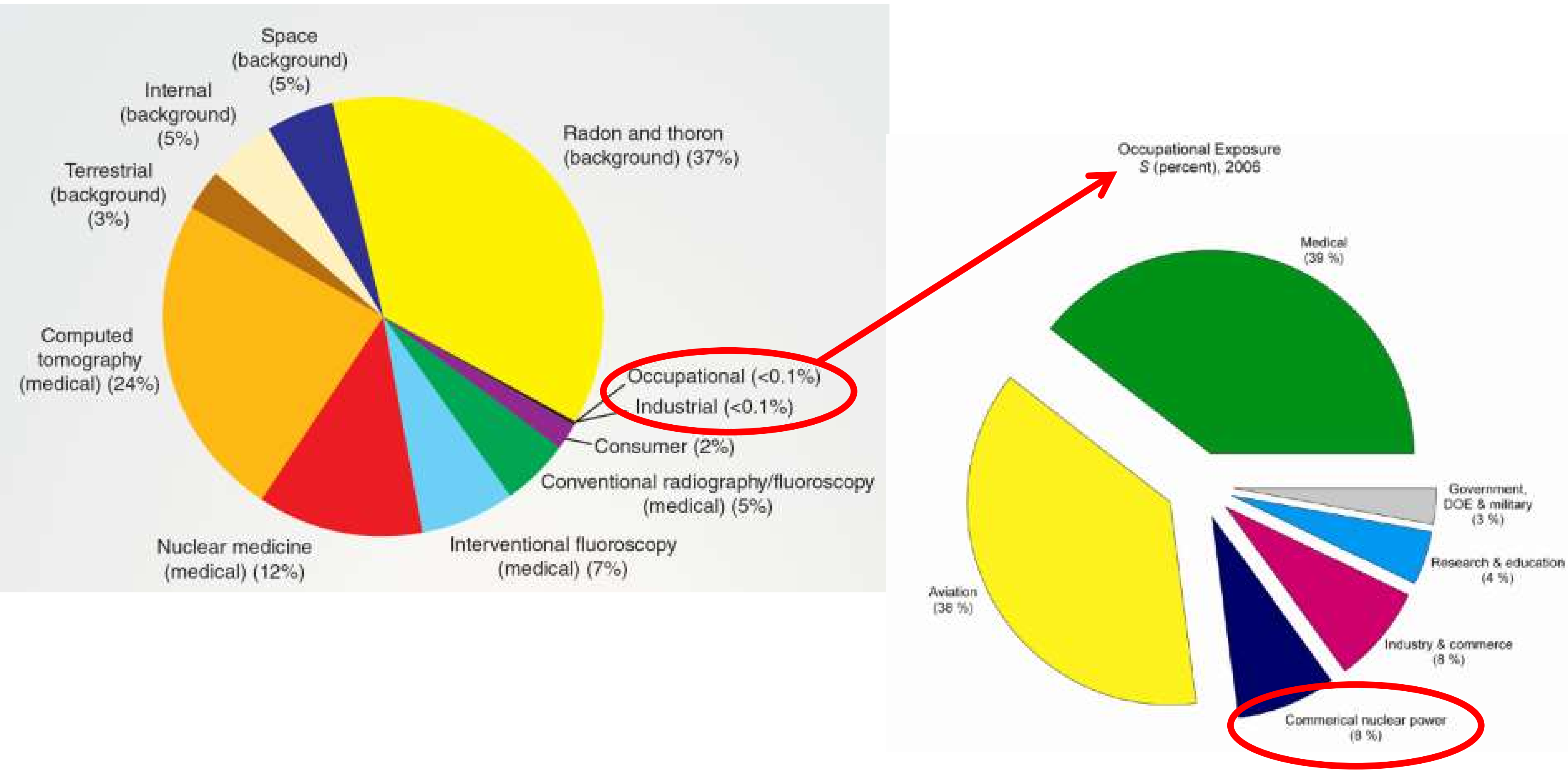
Beta (β) radiation, consisting of electrons, is halted by an aluminium plate.

Gamma (γ) radiation, consisting of energetic photons, is eventually absorbed as it penetrates a dense material.

Neutron (n) radiation consists of free neutrons that are blocked using light elements, like hydrogen, which slow and/or capture them.

Sources of Radiation Exposure

- Sources of radiation exposure to the US population (NCRP, 2009 (National Council on Radiation Protection and Measurements, http://NCRPonline.org).



Consequences: Dose Units

- ***Absorbed dose*** (amount of energy deposited by ionizing radiation).
  - The gray (Gy), represents the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter.
  - 1 Gy of alpha radiation causes about 20 times as much damage as 1 Gy of X-rays

- ***Equivalent dose*** (dose of a given type of radiation in Gy that has the same ***biological effect*** on a human as 1 Gy of x-rays or gamma radiation.
  - The **sievert (Sv)** J/kg. Equivalent dose that has the same biological effect on a human as 1 Gy of x-rays or gamma radiation.
  - The rem (Roentgen equivalent man)
    - 1 rem = 0.01 Sv = 10 mSv
    - 1 Sv = 100 rem

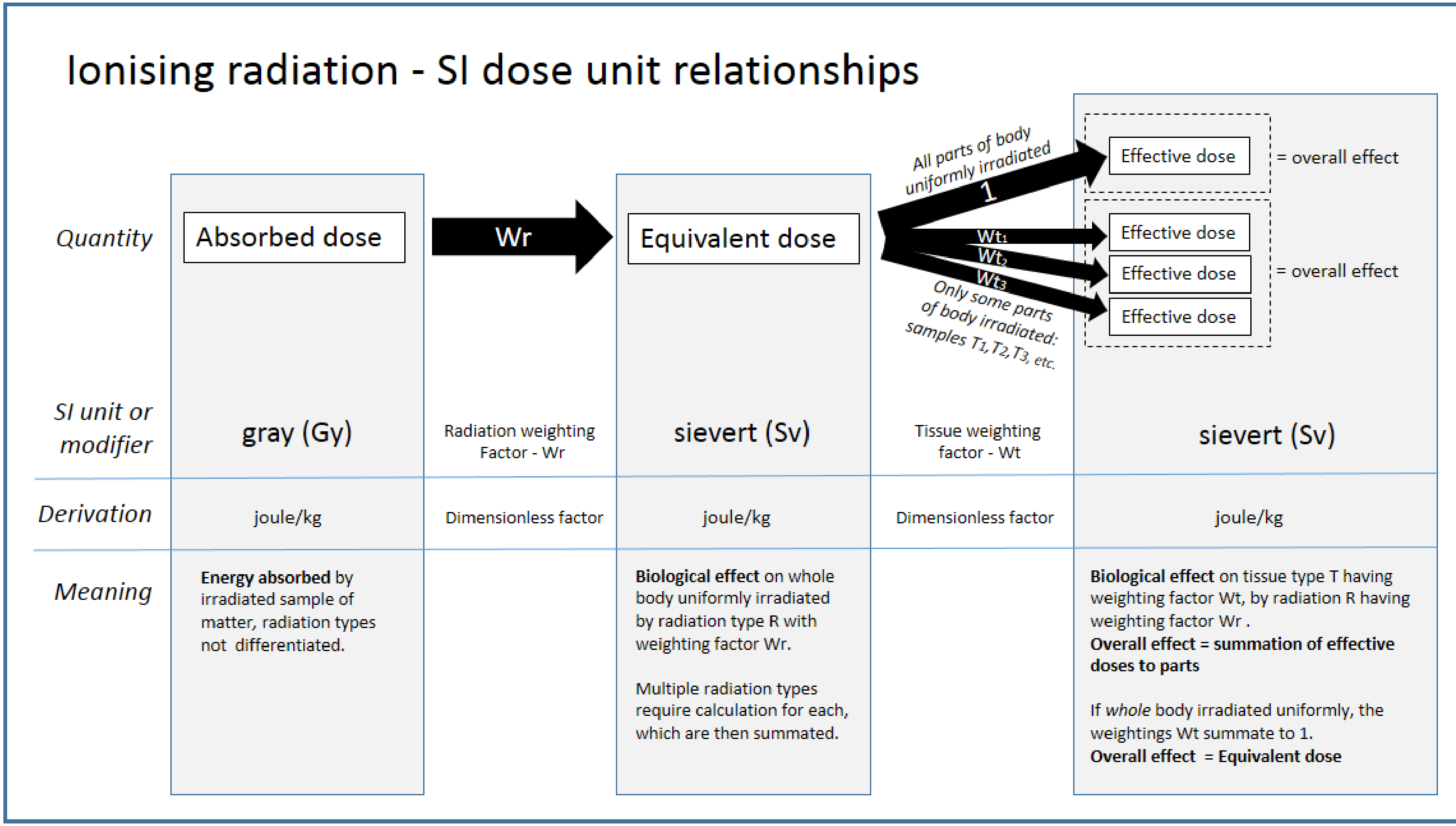
Becquerel: one nucleus decays per second

Average human body produces 4400 becquerels from decaying potassium-40

Dose, mSv

0.025	5-hour jet airplane ride
0.08	Chest x-ray
1.4	Mammogram.
6.2	USA annual average dose from all sources.
12	Whole body CT scan.
100	5 years occupational limit for designated Nuclear Energy Workers in Canada.
160	annual dose from smoking 30 cigarettes per day.
250	Maximum allowed dose for emergency workers at Fukushima plant.
500	Occupational limit for workers carrying out urgent work during an emergency.
1000	Nausea, no immediate death. Few percent increase in probability to have cancer years later. Doses to some workers on sight in Chernobyl.
10000	Rapid death for firefighters in Chernobyl. Most commercial electronics can survive this radiation level

Radiation and Dose



Radiation and Dose

- The probability of ionizing radiation causing cancer is dependent upon
  - the ***absorbed dose*** of the radiation, as adjusted for the damaging tendency of the type of radiation (***equivalent dose***) and
  - the sensitivity of the organism or tissue being irradiated (***effective dose***).

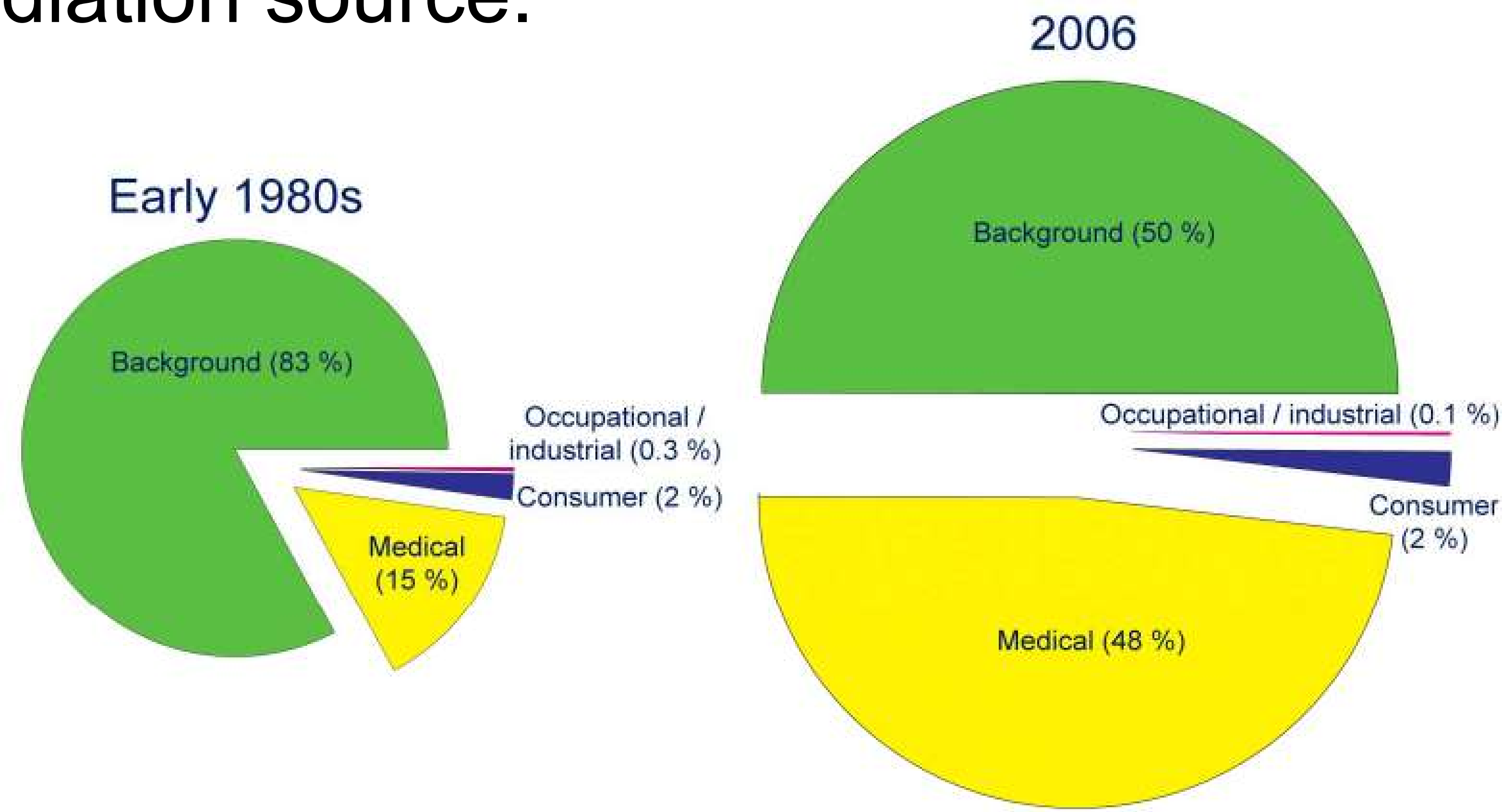
$$E = \sum_T W_T H_T = \sum_T W_T \sum_R W_R D_{T,R}$$

where $D_{T,R}$ is the absorbed dose in tissue T by radiation type R,
W_R is the weighting factors for different types of radiation,
H_T is the equivalent dose absorbed by tissue T,
W_T is the weighting factor for different tissues.

  - The International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiation Protection (ICRP) have the overall responsibility for values for the weighting factors, and other technical guidance on how radiation should be measured.

Sources of Radiation Exposure

- Almost double growth, due to medical radiation source.



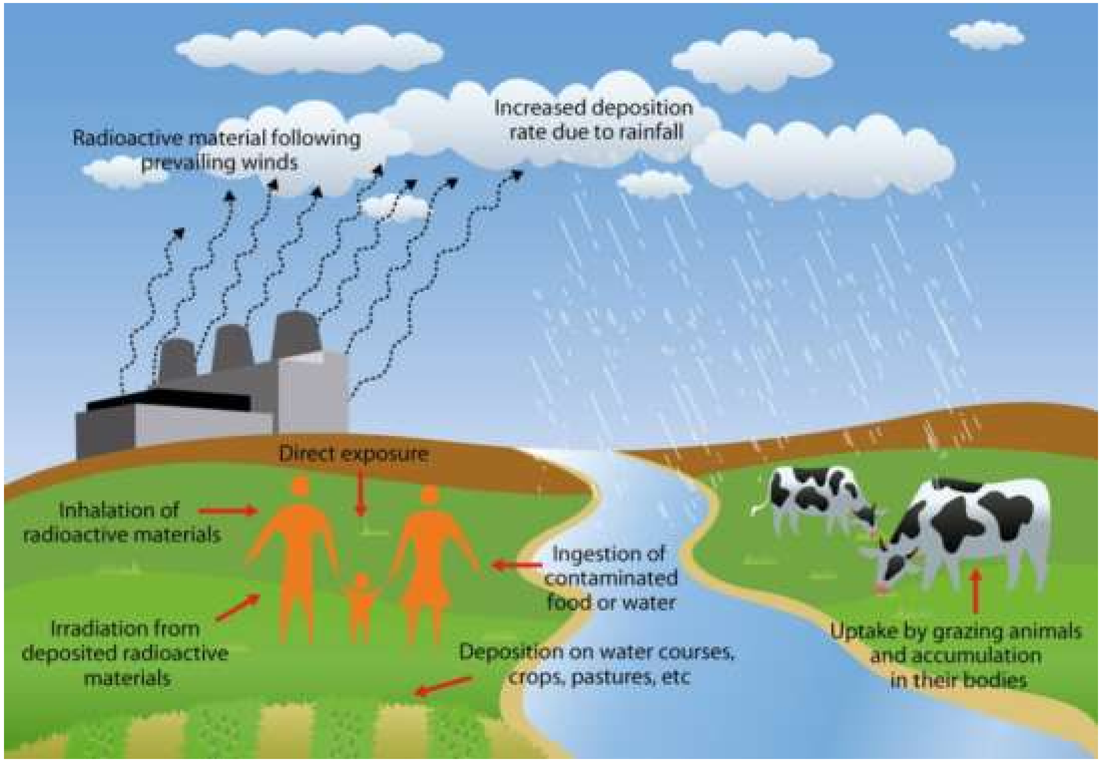
	Early 1980s	2006
Collective effective dose (person-Sv)	835,000	1,870,000
Effective dose per individual in the U.S. population (mSv)	3.6	6.2

Radiation Exposure Mechanisms (scenarios) in case of Nuclear Accident

- In case of an accident fission products (FP) can be released to environment.
- Land can be contaminated and population can be irradiated.

Population exposure to radiation:

- Form FP in a plume
  - cloud-shine
- From FP on ground
  - ground-shine
- Inhaled FP
- Ingest FP



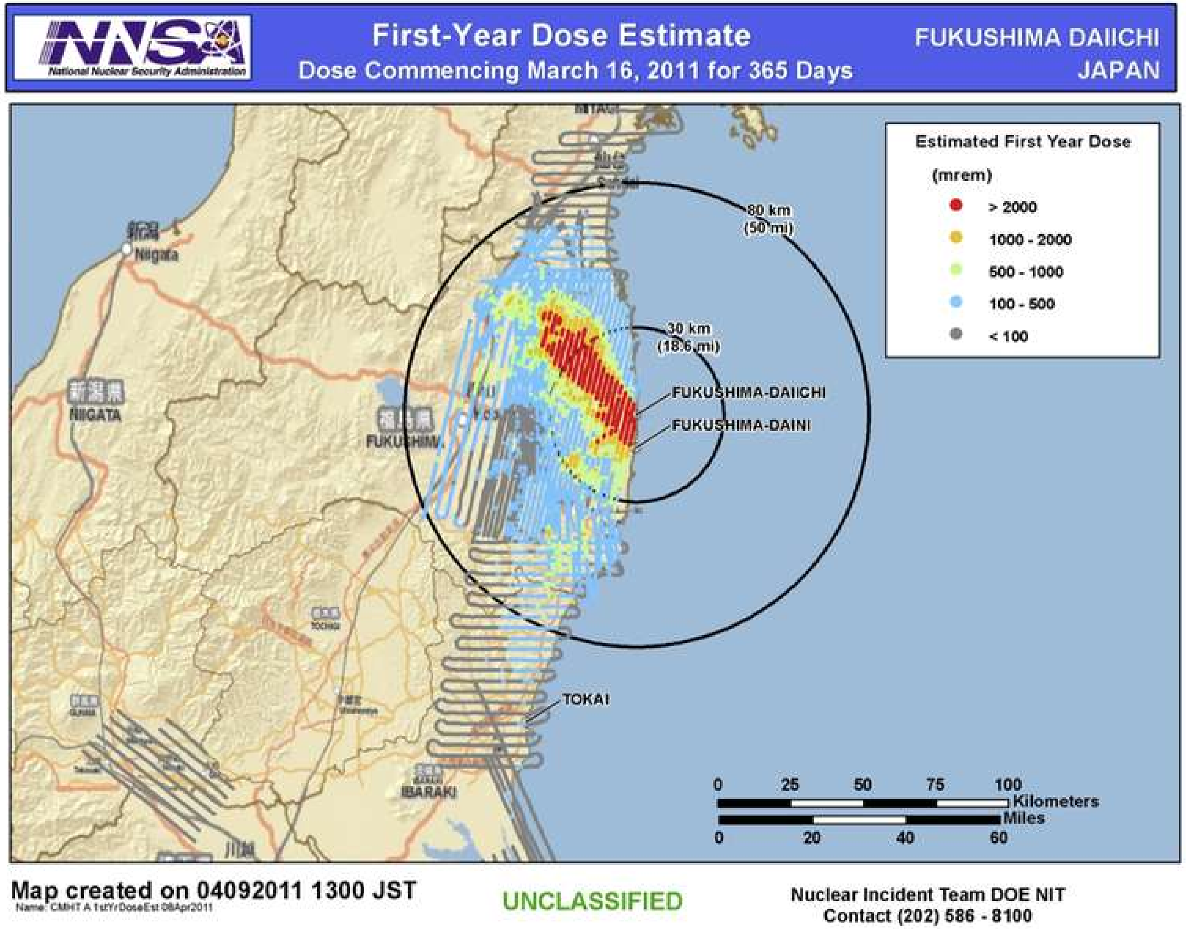
Consequences of FP release (Fukushima)

- **Fukushima:** Residence is prohibited in the areas with accumulated annual does more than
  2 Rem = **20mSv/year**
  - ~2 x Whole body CT scan

- **USA annual average** dose from all sources.
  up to **6.2 mSv/year**

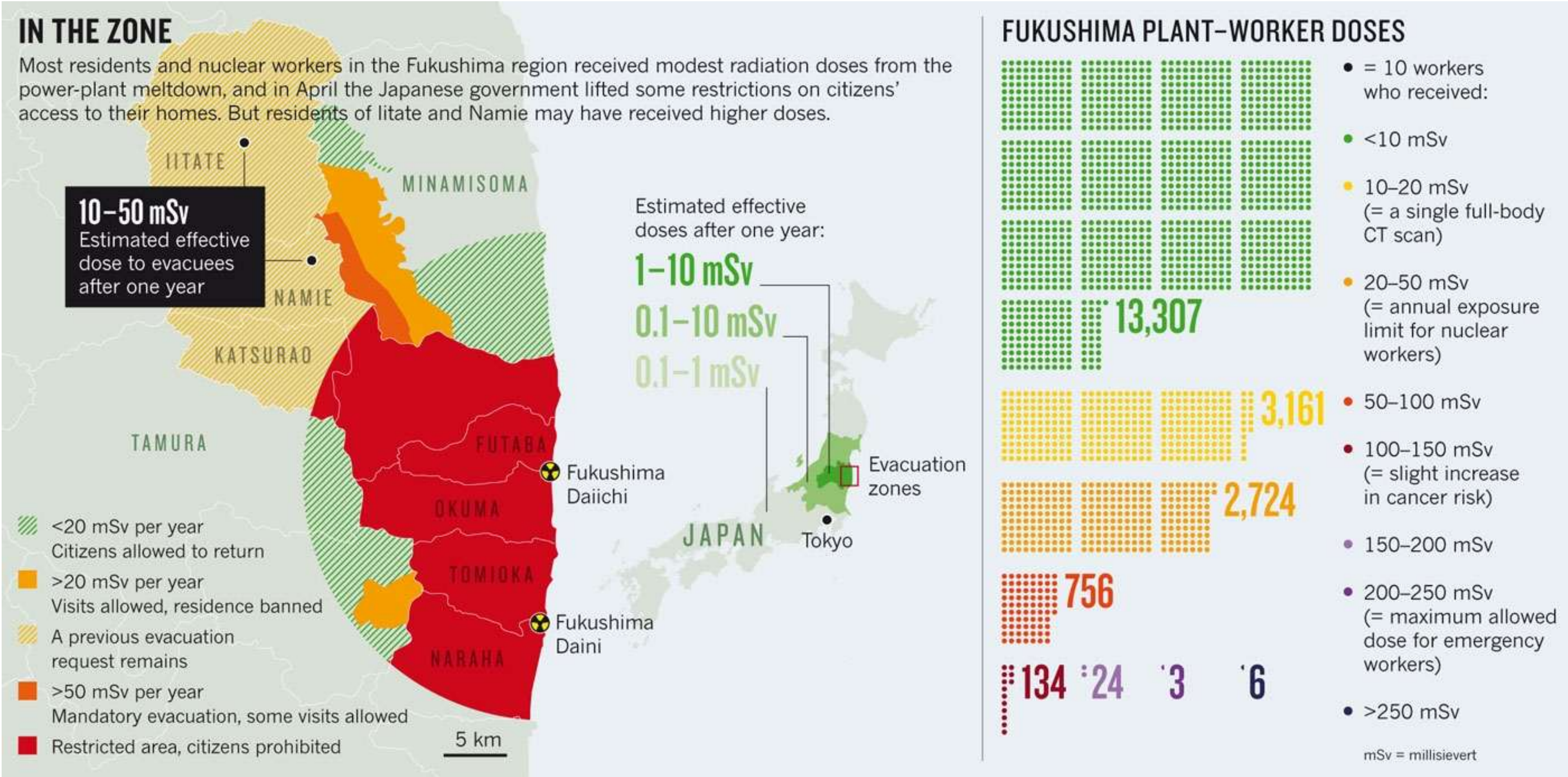
- **Guarapari, Brazil**, a city of ~80 000 inhabitants and tourist destination. Background natural radiation
  ~ **175 mSv/year**.

- **Ramsar, Iran**, a city of ~32 000. Background natural radiation
  ~**10-260 mSv/year**.



Consequences of FP release (Fukushima)

- 146 employees and 21 contractors received a dose of more than 100 millisieverts (mSv).
- Six workers received more than the 250 mSv allowed by Japanese law for front-line emergency workers
- 2 operators in the control rooms for reactor units 3 and 4 received doses above 600 mSv,
  - because they had not taken potassium iodide tablets to help prevent their bodies from absorbing radioactive iodine-131.
- *Nature* **483,** 138–140; 2012
- Japan's government acknowledged that radiation caused illness in four workers one death due to lung cancer in September 2018.



Consequences of FP release (Fukushima)

- According to a June 2012 Stanford University study by John Ten Hoeve and Mark Z. Jacobson, based on linear no-threshold (LNT) model, the radioactivity released could cause
  - 130 deaths from cancer (the lower bound for the estimate being 15 and the upper bound 1100) and
  - 180 cancer cases (the lower bound being 24 and the upper bound 1800), mostly in Japan.

- Radiation exposure to workers at the plant was projected to result in 2 to 12 deaths.

- Preventive actions taken by the Japanese government may have substantially reduced the health impact of the radioactivity release.
- Evacuation procedures after the accident may have potentially reduced deaths from radiation by 3 to 245 cases, the best estimate being 28
  - even the upper bound projection of the lives saved from the evacuation is lower than the number of deaths already caused by the evacuation itself.
    - An additional approximately 600 deaths have been reported due to non-radiological causes such as mandatory evacuations.

- These numbers are very low compared to the estimated 20,000 casualties caused by the tsunami itself, and it has been estimated that if Japan had never adopted nuclear power, accidents and pollution from coal or gas plants would have caused more lost years of life.

AP1000 Approach to Safety

Passive Safety Systems

- Use "passive" processes only; no safety-grade active pumps, diesels….
- Dedicated systems; not used for normal operations
- Reduced dependency on operator actions
- Mitigate design basis accidents
- Meet regulatory safety goals

Active Non-Safety Systems

- Reliably support normal operation
- Minimize challenges to passive safety systems
- Not required to mitigate design basis accidents or meet safety goals
- Provide plant investment protection

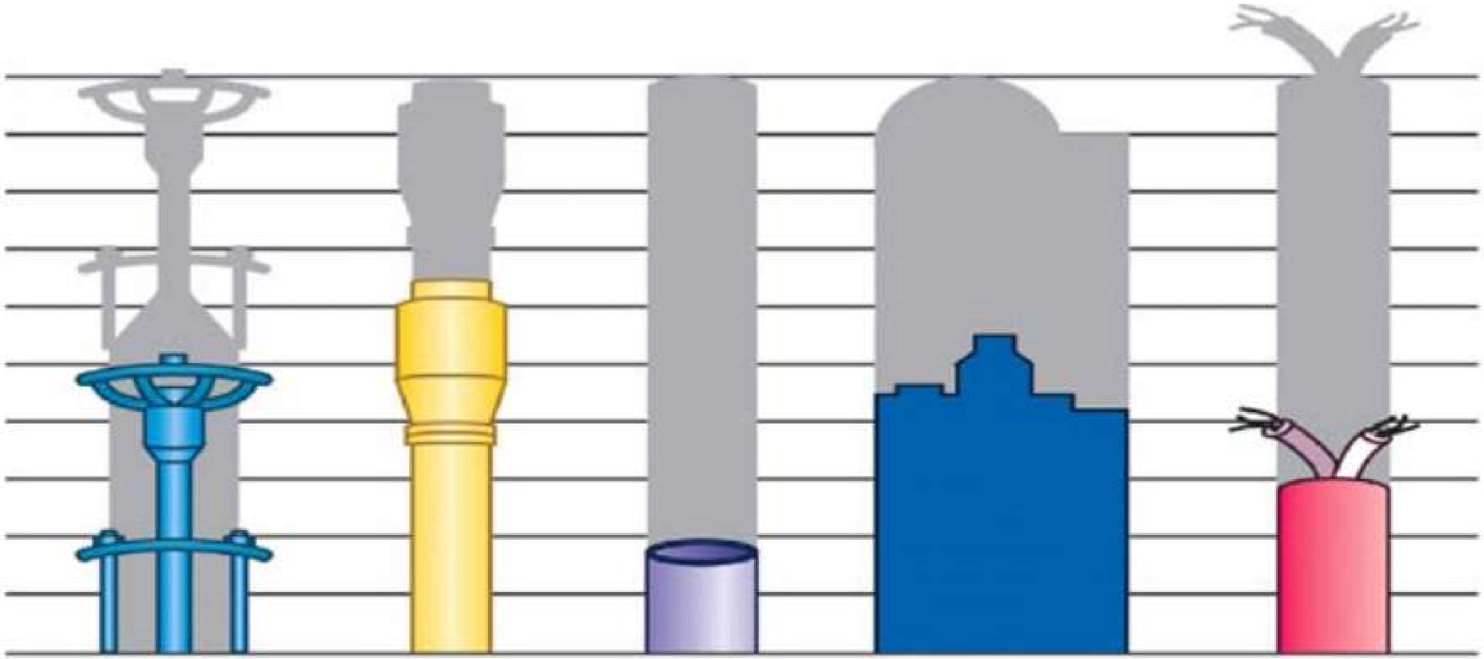
Multiple Levels of System Defense In Depth

- First action is usually by non-safety grade active system
    - High quality industrial grade equipment
- Second action is by safety grade passive system
    - Provides safety case for SAR
    - Highest quality nuclear grade equipment
- Other passive systems provide additional defense-in-depth
    - Example: passive feed/bleed backs up PRHR HX
- Available for all shutdown conditions as well as at power
- More likely events have more levels of defense

AP1000 Reactor Coolant System

- Canned motor pumps mounted in steam generator lower vessel head
- Elimination of RCS loop seal
- Large pressurizer
- Top-mounted, fixed in-core detectors
- All-welded core shroud
- Ring-forged reactor vessel

AP1000 Reactor Coolant System



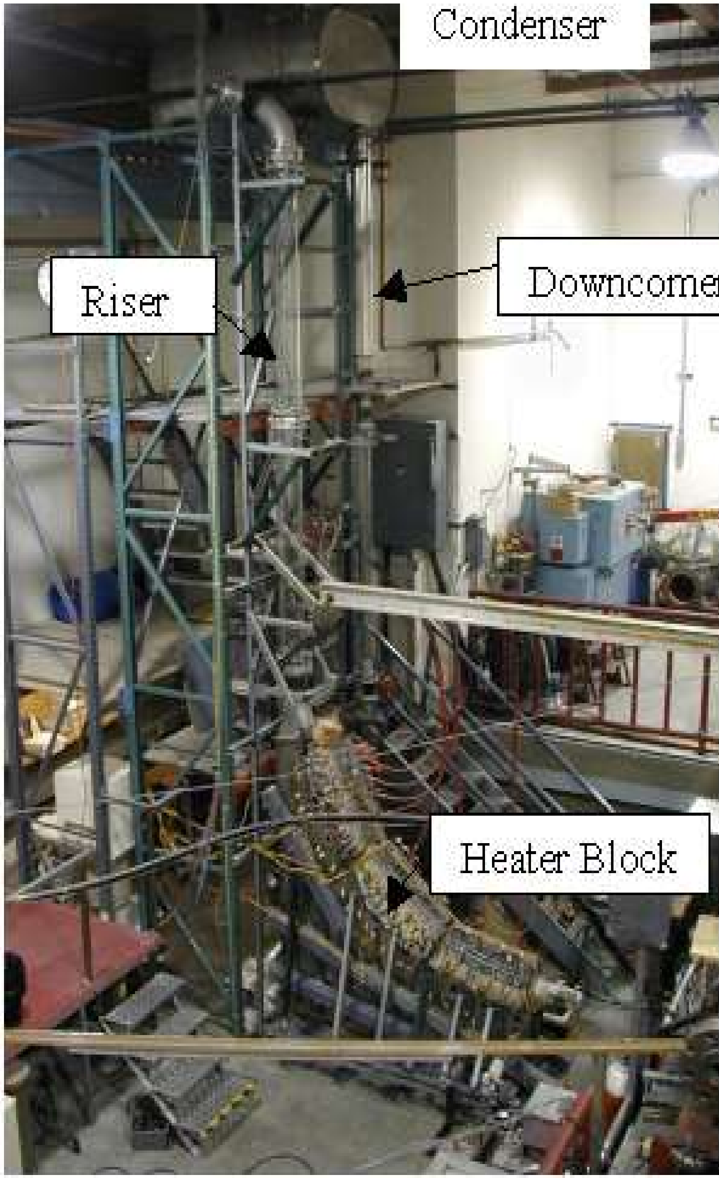
Reduced Number of Components:

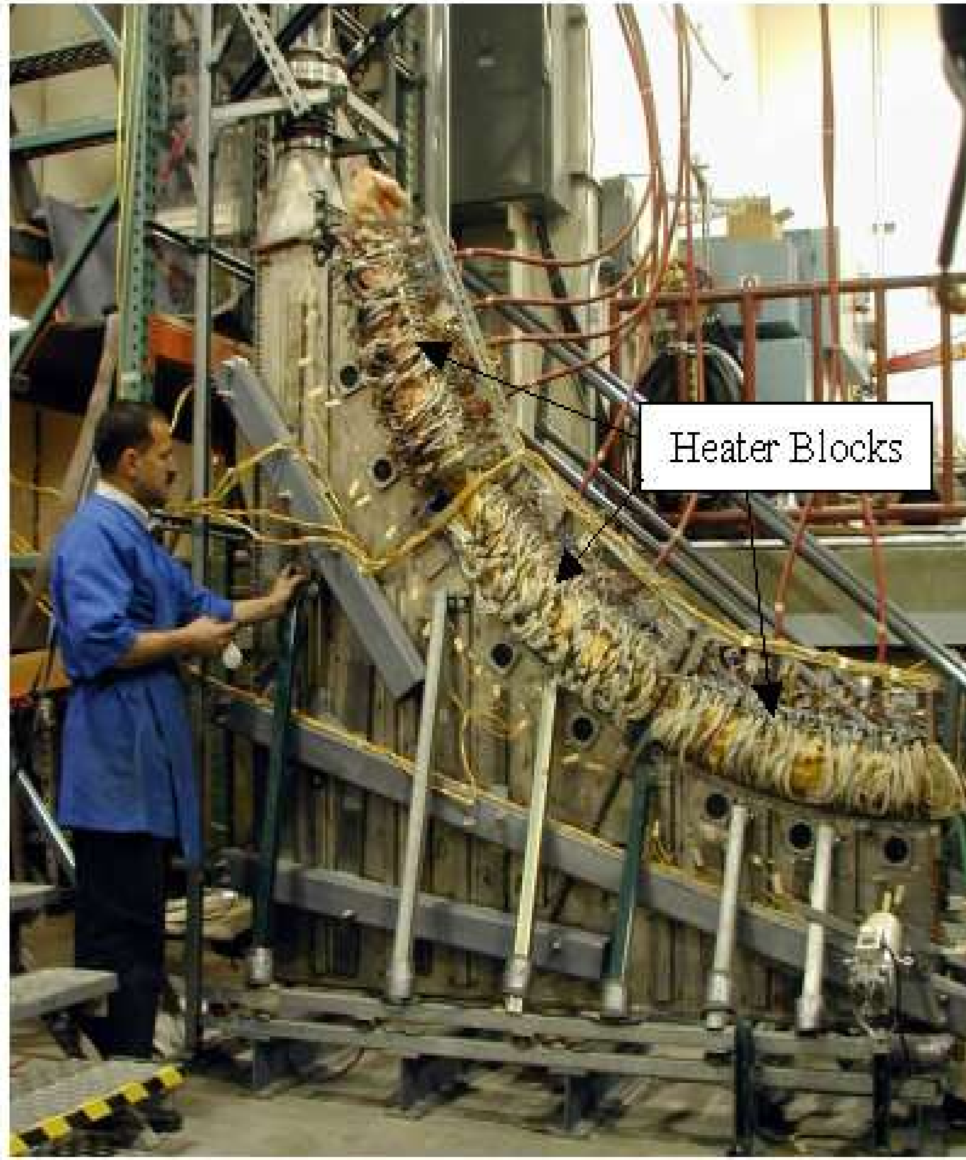
	1000 MW Reference	AP1000	Reduction
- Safety Valves	2844	1400	51%
- Pumps	280	184	34%
- Safety Piping	11.0×10^4 feet	1.9×10^4 feet	83%
- Cable	9.1 mil. feet	1.2 mil. feet	87%
- Seismic Building Volume	12.7 mil. ft^3	5.6 mil. ft^3	56%

IVR Phenomenology

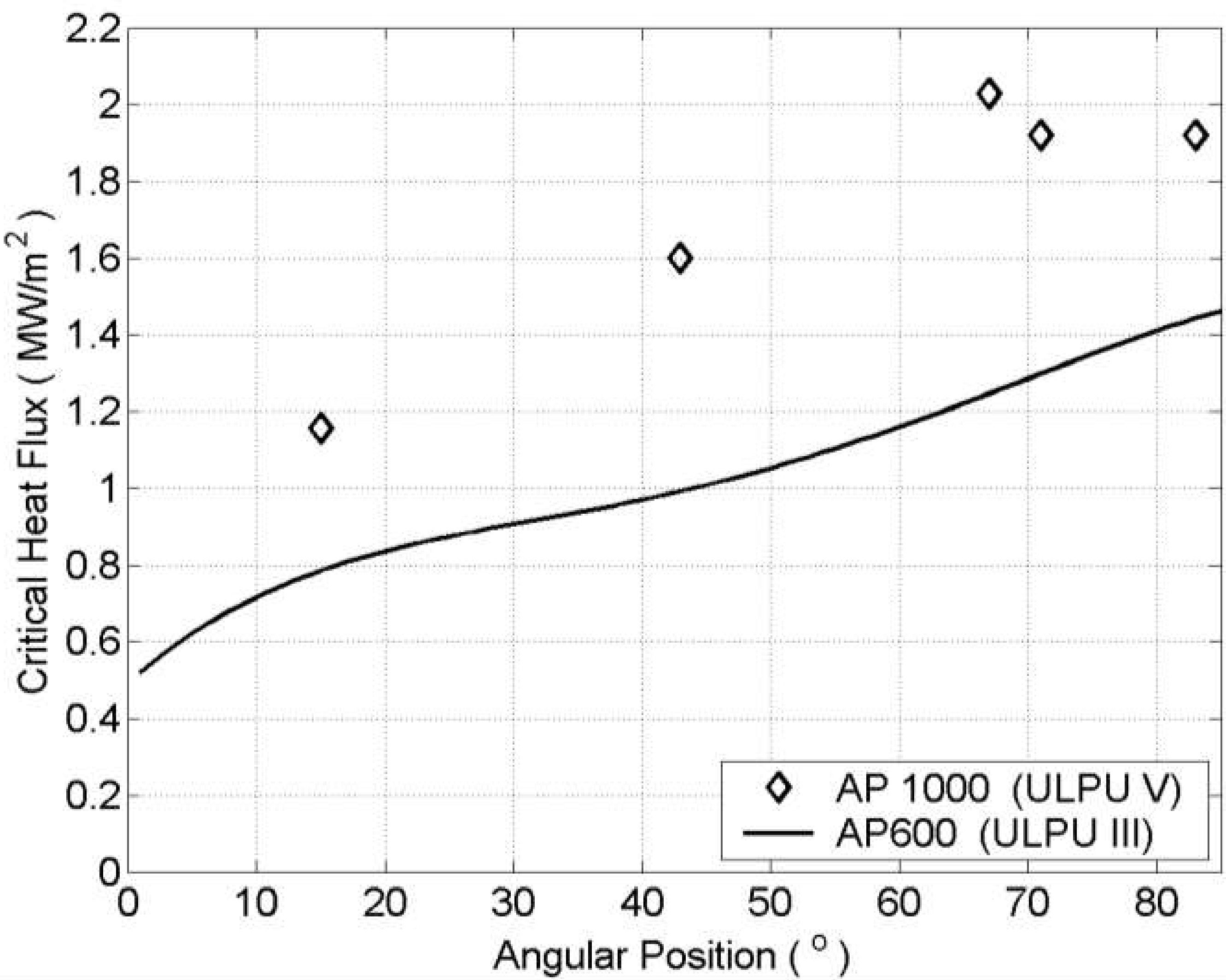
- The IVR required the development of phenomenology for:
  - The scenario descriptions, in particular, how the melt relocates from the core region to lower head.
  - Further, the determination of the possibility of vessel failure due to
    - (i) the **melt jet attack** on some particular vessel location and
    - (ii) a **steam explosion** generated by the melt entry into the water contained in the lower head.
  - The determination (or assumption) of the magnitude of core melt in the vessel lower head.
  - The determination of the melt pool composition, configuration (e.g. stratification, etc), since they affect the heat loading on the vessel wall. This includes
    - (i) the **separation and stratification of steel** above the oxide pool to pose the danger of **focusing of heat flux**, and
    - (ii) the **stratification of the oxide pool**, which decreases the heat flux to top
  - The determination of the magnitude and polar distribution of the heat flux imposed by the assumed melt mass on the vessel wall.

The ULPU facility





ULPU-V Reference Data for AP1000 IVR Conditions



THE CASE FOR AP-1000

- The AP-1000 case, in terms of the focusing effect is similar to the case for AP-600,i.e. a large amount of steel will melt for the bounding configuration and provide not an extremely large focusing effect.
- The maximum thermal load for AP-1000 was estimated to be 1.3Mw/m^2 which is too close for comfort to the maximum CHF value of 1.4Mw/m^2 as measured in ULPU-2000, i.e. without any special shaping of the flow.
- The AP-1000 case, with sufficient margin to CHF could only be made after establishing that the CHF could be increased to 1.9 to 2Mw/m^2 , with baffling to shape the two phase flow field on the vessel external surface, removing the paint on the surface, reducing the pressure drop in the flow circuit, etc.
- The AP-600 and AP-1000 designs, both have been certified by USNRC, without specifically mentioning that the IVMR cases are acceptable, However, the SAM IVMR in AP-1000 is now being offered for sale by Westinghouse.

ESBWR

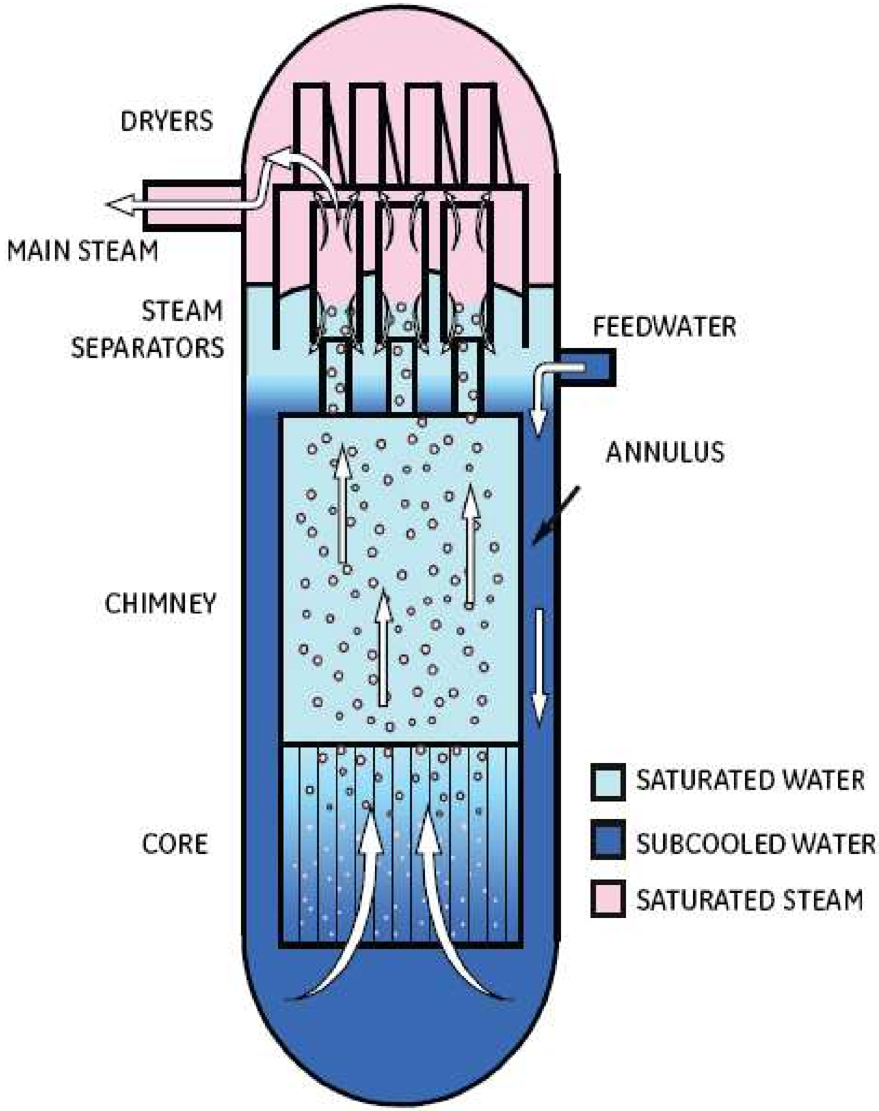
- As in the most recent ABWR design, the ESBWR features
  - an inert containment atmosphere to prevent deflagration or detonation of combustible mixtures,
  - a containment over-pressurization protection system (COPS) (but here it is manually operated MCOPS) to guard against slow buildup of pressure due to non-condensable gas generation and/or heat up of the suppression pool water, and
  - a drywell spray system in support of accident recovery operations.

ESBWR

- Unlike the ABWR, or any other previous GE BWR, the ESBWR containment design includes
  - the passive containment cooling system (PCCS) to remove decay heat from the containment, and
  - the (also passive) Basemat internal Melt Arrest and Coolability (BiMAC) device (Theofanous and Dinh (2005)) to essentially eliminate the possibility of extended corium-melt interactions, noncondensable gas generation, and basemat penetration.

- In addition, the ESBWR is equipped with isolation condensors (ICs), a system for ensuring decay heat removal from the RPV in sequences where the reactor is at high pressure.
  - This is an improved version of a system employed in some of the earlier BWR designs.

ESBWR Reactor Design



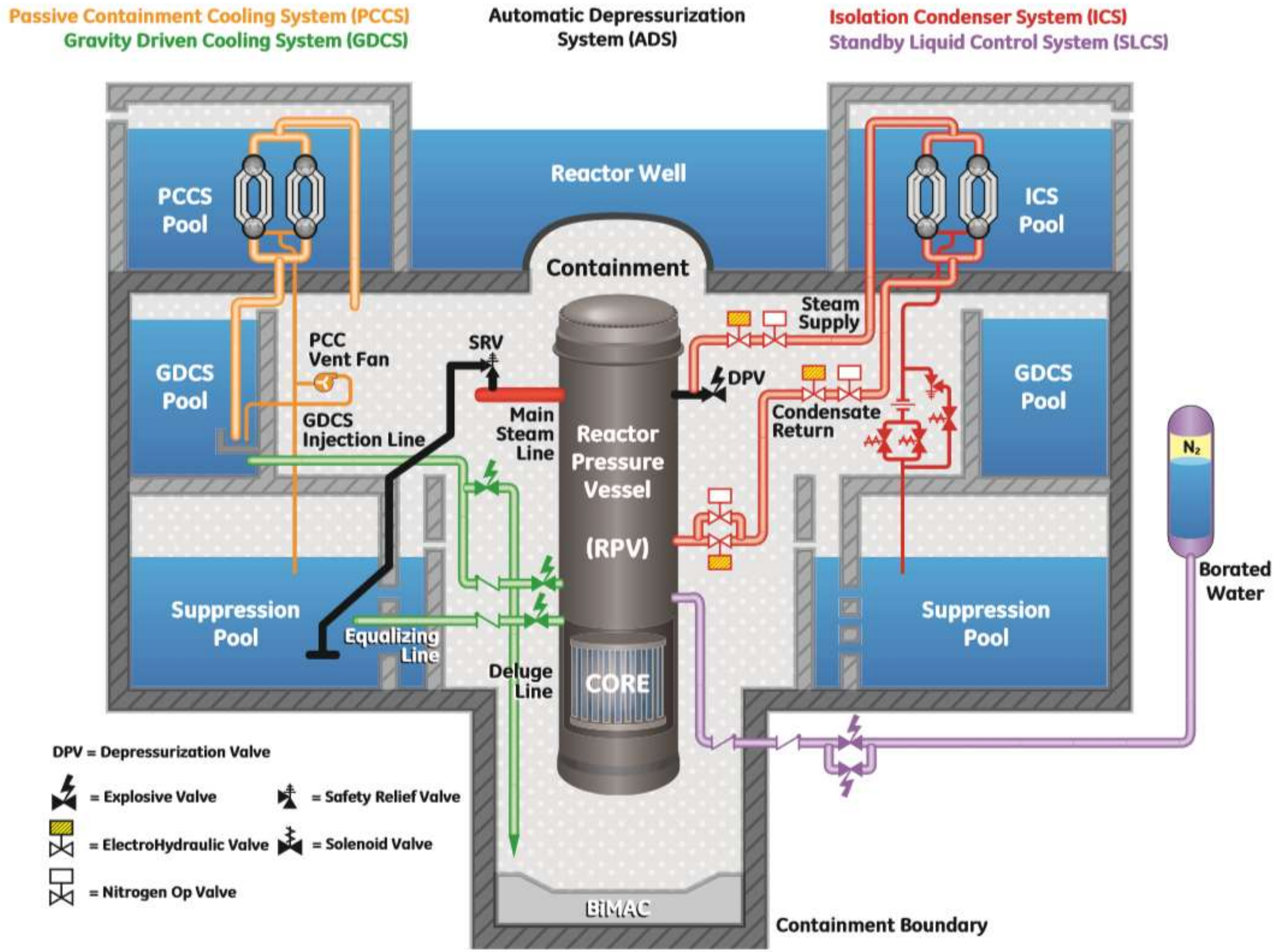
Natural Circulation

Because hot water is less dense, it rises through the core while the cool water flows down to the bottom of
the core. These natural differences in density create circulation.

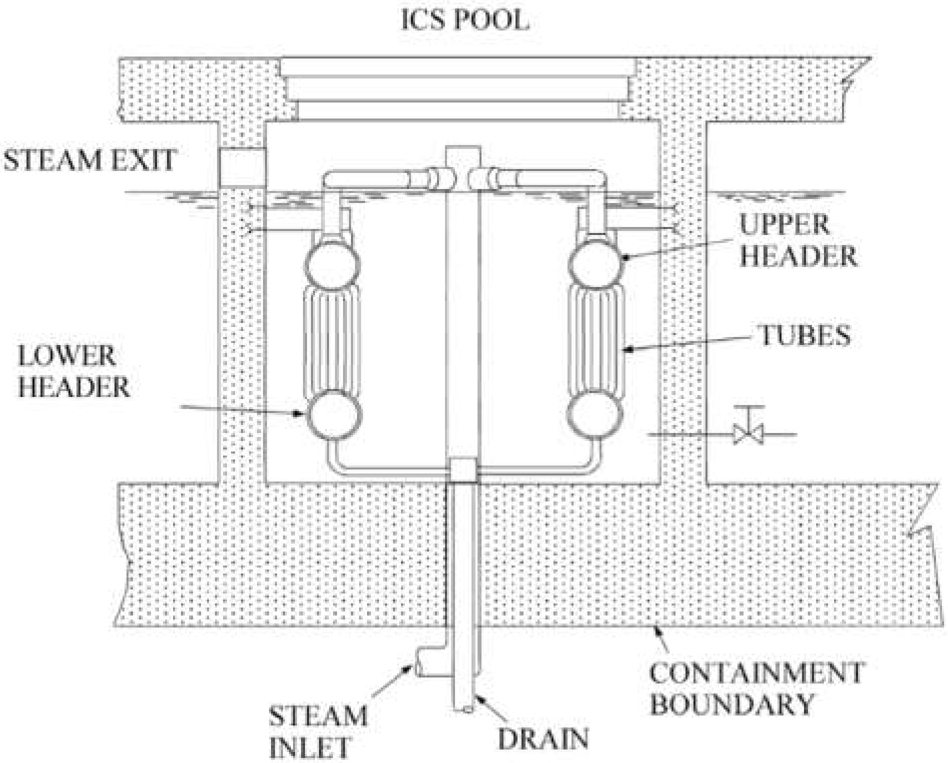
Reduced flow restrictions
- larger downcomer area
- shorter core
- improved separator

Higher driving head
- chimney
- taller vessel

Containment Systems (Note: Water!)



PCC heat exchanger unit



Isolation Condenser System
Heat Exchanger Unit

Treatment of Severe Accidents

- Severe Accidents in ESBWR……CDF ~ 10^{-8} per year
  - That is, they are Remote & Speculative
  - Could be treated as Residual Risk

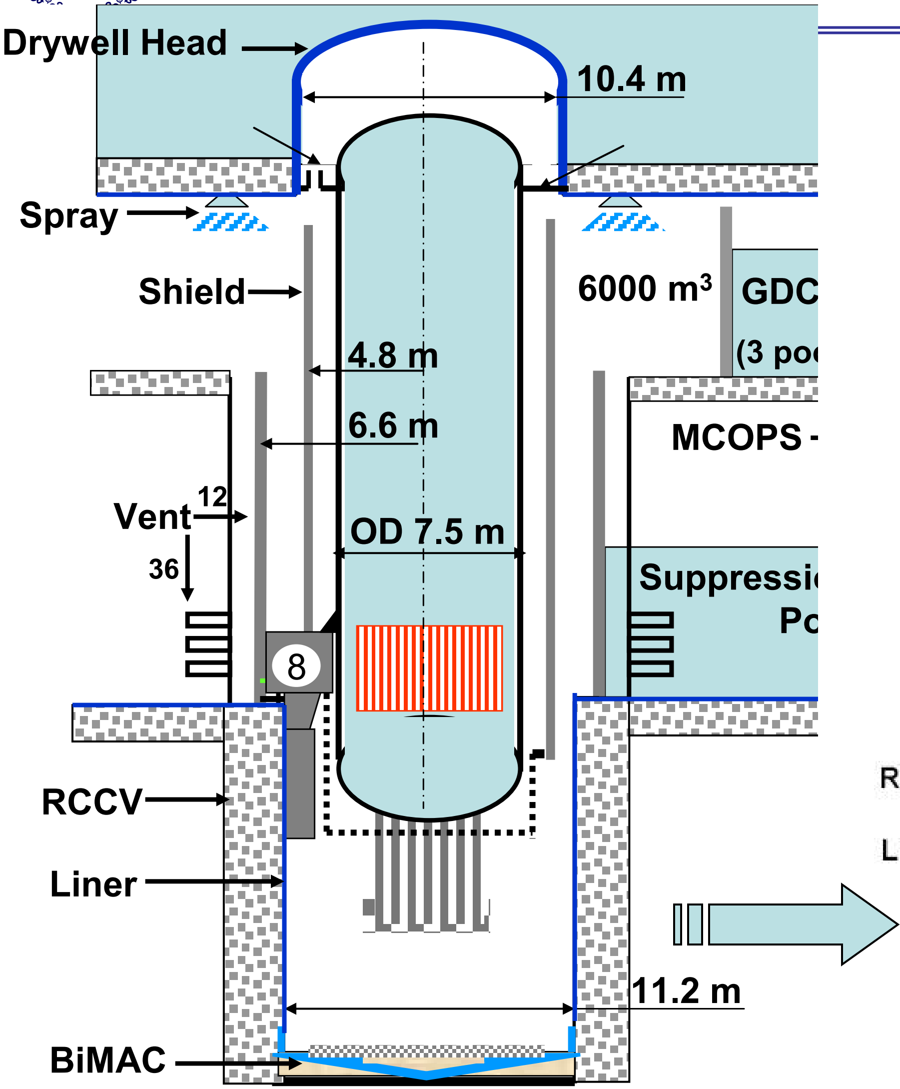
- GE Designs for Defense-In-Depth
  - Assess full compliment of severe accident threats
  - Determine and Enhance ESBWR capabilities
  - Verify by a full ROAAM treatment

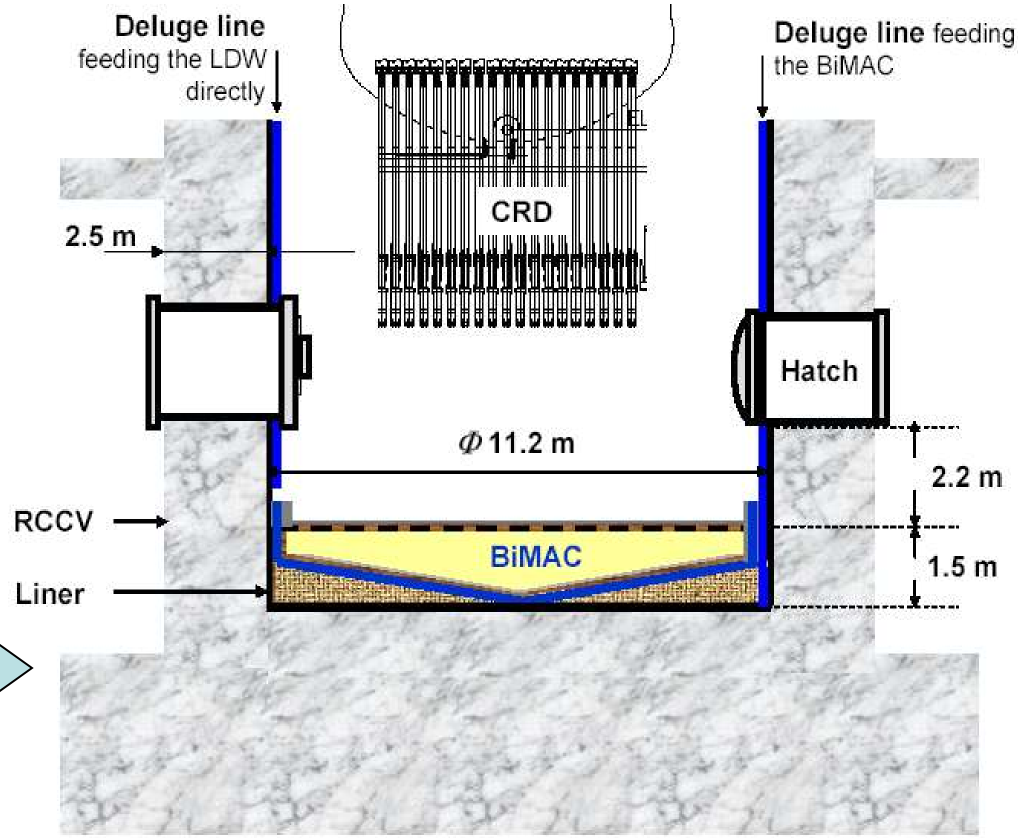
Adopted from publicly available materials on ESBWR
www.nrc.gov/public-involve/conference-symposia/ric/past/2006/slides/t2bc-**wachowiak**.pdf

Ex-vessel Coolability Strategy

- A principal strategic decision for severe accident management (SAM) in the ESBWR was in regard to arresting the melt propagation process and ensuring long-term coolability within the containment boundary.
- Applicability and effectiveness of in-vessel retention (IVR) (Theofanous et al., 1997) was assessed and concluded that this could be a highly effective approach for the ESBWR, however, only if all equipment found hanging from the lower head penetrations were to be supported from the outside. This proved unworkable from the operational perspective, and the option was rejected by the design managers.
- Therefore the ex-vessel coolability question was addressed. Threats to containment integrity were addressed in a manner that is inclusive of all possible ex-vessel evolutions.

ESBWR SA Containment Threats





Motivation: New Evidences PULiMS and SES tests observations

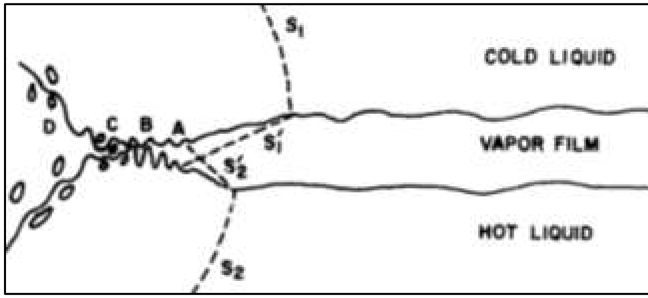
- PULiMS – Pouring and Underwater Liquid Melt Spreading.
- SES – Steam Explosion in Stratified configuration.

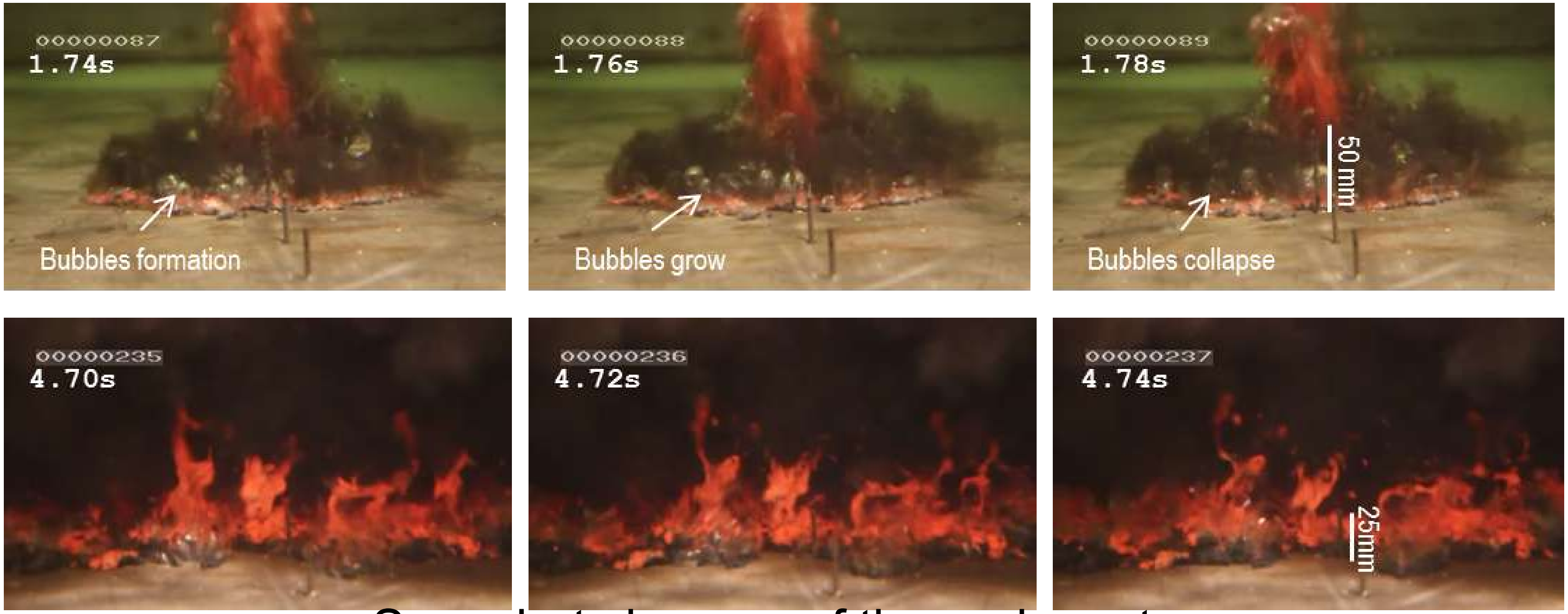
- In total 6 exploratory tests have been carried out in PULiMS and SES facilities with
  - pouring of superheated (about 200K) melt
  - into a shallow (about 0.2 m) pool of water.
- **5 tests with water subcooling higher than 13K** resulted in spontaneous steam explosions.
  - One test (SES-E3) was carried out with low water subcooling (about 5K) and yielded no spontaneous steam explosion.

- More than **30 experiments in DEFOR** facility with a **deep pool (0.6 – 1.5 m)** and fragmented melt jet-coolant pool configuration with the same:
  - simulant materials
  - high melt superheat (up to 320K)
  - jet diameters (10-30 mm)
  - water subcooling (10 – 30K)
- have **never resulted in spontaneous steam explosion.**

New Evidences
Stratified steam explosion in PULiMS and SES

- The most important experimental finding is that the assumption about stable interface in stratified melt-coolant configuration is in apparent contradiction with the observations from PULiMS and SES tests.
- The interface instability and formation of premixing zone is clearly visible in video records.
- Such premixing layers can be triggered yielding quite strong explosions (see previous section).





Snapshots images of the underwater melt spreading in PULiMS

Melt premixing in PULiMS-E4