SH2705 Simulation Course

Evolution of Nuclear Power Safety

Sean Roshan

Time line for the course

- Before the first seminar, each group will turn in a theoretical report, explaining the nuclear power safety concepts. You choose a past event and explain how the event started and progressed and how it could be prevented considering the nuclear power safety concepts.
- Results of exercises and project work are presented during the first seminar to receive feedbacks.
- Each group will turn in a lab-report about the excercises and project work before the final presentation
- The final presentation is presented at the 2:nd seminar during which, each students shall also answer two questions regarding the theoretical part.
- See the examination instructions on the canvas!

Grading requirements

Grade	Theoretical Part
A	To comprehensively and in detailed describe: - Correctly all of the concepts discussed during the course and explain their relevance to the example event
B	To comprehensively describe: - Correctly all of the concepts discussed during the course and explain their relevance to the example event
C	To describe: - Correctly all of the concepts discussed during the course and explain their relevance to the example event
D	To describe: - Correctly Most of the concepts discussed during the course and roughly explain relevance to the example event
E	To describe: - Some of the concepts discussed during the course correctly and roughly explain relevance to the example event
F	Do Not fulfil the above requirements

Nuclear Power Timeline

- The Greeks theorized that everything was made up of simple, indivisible particles they called atoms - they were correct partly!
- 1895 ⇒ Wilhelm Conrad Roentgen discovers the X-RAYs
- 1896 ⇒ Antoine-Henri Becquerel discovers the radiation
- 1897 ⇒ Joseph John Thomson, a British physicist and Nobel Laureate discovers electrons.
- 1905 ⇒ Einstein's Special Theory of Relativity, $E = mc^2$
- 1919 ⇒ Ernest Rutherford discovers the proton and develops a crude model of atom
- 1932 ⇒ James Chadwick discovers the neutron
- 1939 ⇒ Otto Hahn and Fritz Strassmann discover fission; Lise Meitner and Otto Robert Frisch explain uranium fission and validate Einstein's theory
- 1942 ⇒ Enrico Fermi and his team achieve the first self-sustaining chain reaction in a reactor built under the football stadium stands at the University of Chicago.
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- 1948 ⇒ US gov't plans to commercialize nuclear power

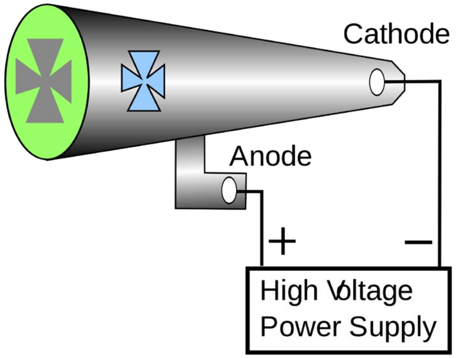
Discovery of X-Ray, 1895

Wilhelm Conrad Röntgen

In 1895, Wilhelm Conrad Röntgen was working on the effects of cathode rays by passing an electric current through gases at extremely low pressure.

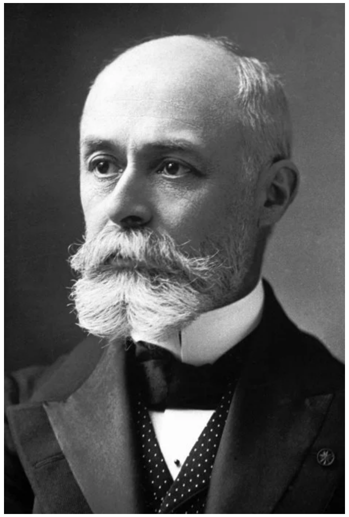
In November 1895 he was performing the experiment in a dark room with a fully covered discharged tube. He observed that certain rays were emitted during the passing of the electric current through the discharge tube.

He continued his experiments to capture the images of different objects of different thickness placed in the path of the rays, using a photographic plate. One of Roentgen's experiments was a film of his wife, Bertha's hand with a ring on her finger.



Bertha Röntgen

Discovery of Radiation, 1896



Antoine-Henri Becquerel

After the discovery of X-Ray, the French Academy commissioned Henri Becquerel to study the fluorescence of some minerals. Henri accidentally discovered that a mineral containing uranium was emitting rays of unknown origin that fogged a photographic plates stored in a dark drawer next to the minerals, even though they had not been exposed to light.

Becquerel realized that the uranium was emitting some kind of invisible rays that were capable of passing through solid objects and leaving an impression on photographic plates.

Henri studied this phenomena together with his PhD student Marie Curie, née Sklodowska and her husband Pierre Curie, which resulted in discovery of Polonium and Radium by Marie and Pierre.

The Nobel Prize in Physics 1903

Marie Curie,
née Sklodowska

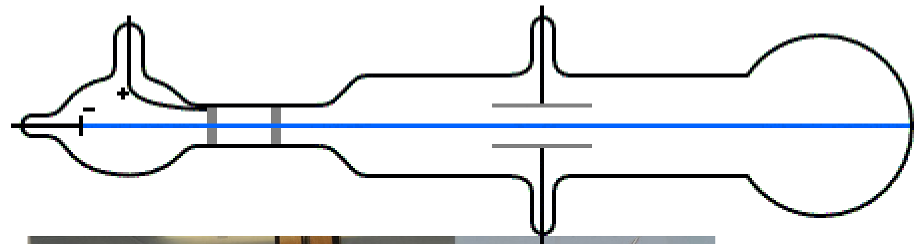
Pierre Curie

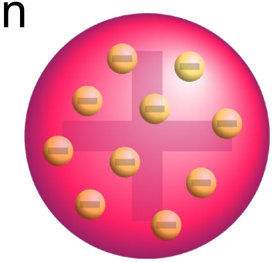
Discovery of Electrons, 1897

Joseph John Thomson

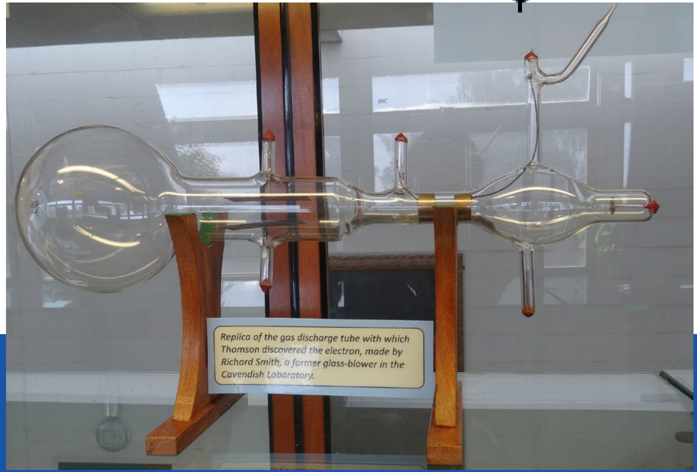
As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter.

— J. J. Thomson

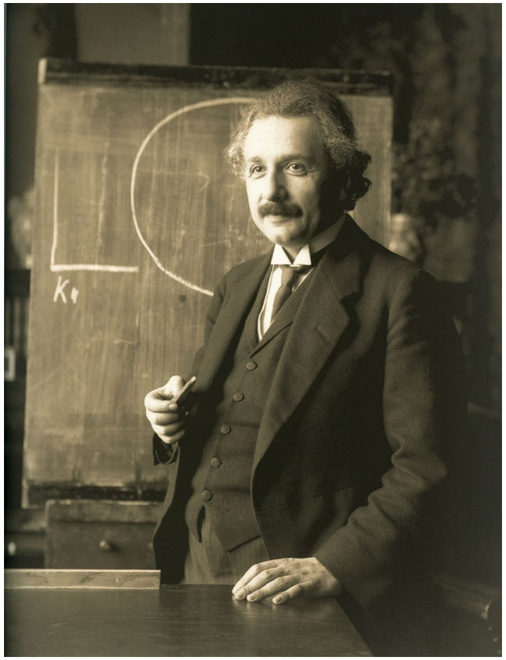




Plum pudding model of the atom



Special Theory of Relativity, $E = mc^2$, 1905



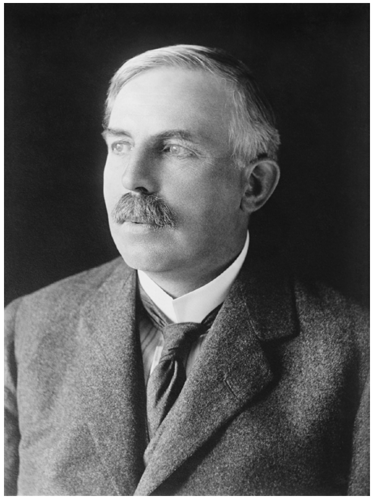
Albert Einstein

Albert Einstein published his Special Theory of Relativity in 1905 and in doing so demonstrated that mass and energy are actually the same thing, with one a tightly compressed manifestation of the other.

The formula defines the energy E of a particle in its rest frame as the product of mass (m) with the speed of light squared (c^2). Because the speed of light is a large number in everyday units (approximately 3×108 meters per second), the formula implies that a small amount of rest mass corresponds to an enormous amount of energy, which is independent of the composition of the matter.

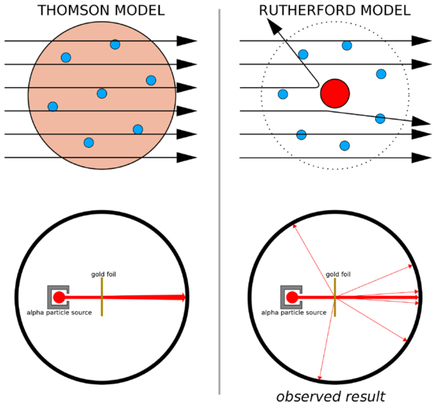
The equivalence principle implies that when energy is lost in nuclear reactions the system will also lose a corresponding amount of mass. The energy, and mass, can be released to the environment as radiant energy, such as light, or as thermal energy. The principle is fundamental to many fields of physics, including nuclear and particle physics.

Discovery the proton and develops a crude model of atom, 1919



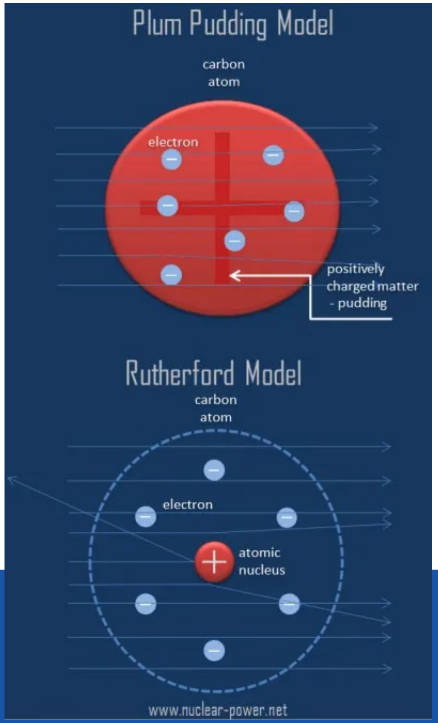
Ernest Rutherford,
father of nuclear physics

The Rutherford model of the atom is a model of the atom devised by Ernest Rutherford. Rutherford’s new model for the atom was based on the experimental results, which were obtained from Geiger-Marsden experiments.



Rutherford’s idea was to direct energetic alpha particles at a thin metal foil and measure how an alpha particle beam is scattered

Based on these results, Ernest Rutherford proposed a new model of the atom. He postulated that the positive charge in an atom is concentrated in a small region, called a nucleus at the center of the atom with electrons existing in orbits around it. Furthermore, the nucleus is responsible for most of the mass of the atom.

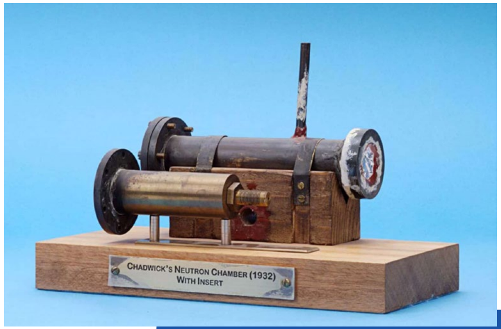


Discovery of neutrons, 1932

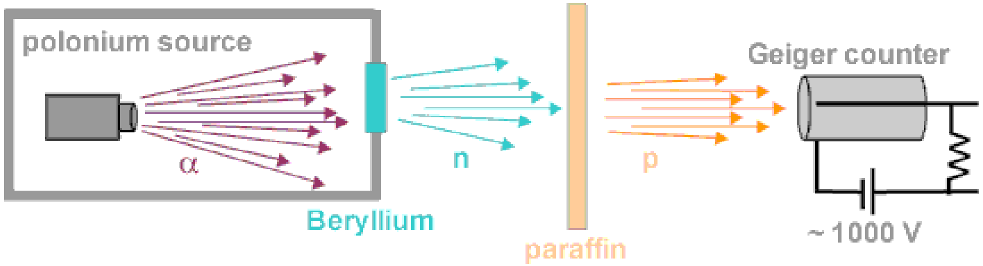
James Chadwick

An experimental in 1932 with the observation by Bothe and Becker found that unusually penetrating radiation was produced if the very energetic alpha particles emitted from polonium fell on certain light elements, specifically beryllium, boron, or lithium.

Chadwick proved that the neutral particle could not be a photon by bombarding targets other than hydrogen, including nitrogen, oxygen, helium, and argon and was able to determine the velocity of the protons. Then through conservation of momentum techniques, he was able to determine that the mass of the neutral radiation was almost the same as that of a proton



Chadwick's neutron chamber contains parallel disks of radioactive polonium and beryllium. Radiation is emitted from an aluminium window at the chamber's end.
Source: imgkid.com



The alpha particles emitted from polonium fell on certain light elements, specifically beryllium, and produced unusually penetrating radiation.
Source: dev.physicslab.org

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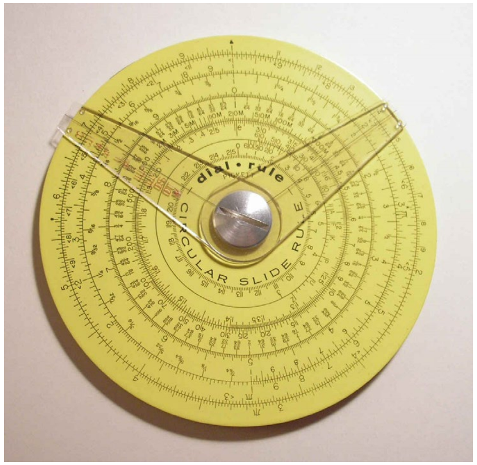
Nuclear Power Timeline

- 1950 ⇒ WASH-3, sitting radios
- 1951 ⇒ Experimental Breeder Reactor 1 (EBR-1) breeds plutonium and generates the first electricity from nuclear power
- 1953 ⇒ "Atoms for Peace" speech delivered by U.S. President Dwight D. Eisenhower to the UN General Assembly in New York City on December 8
- 1954 ⇒ APS-1 Obninsk (Atomic Power Station 1 Obninsk) connected to the power grid in June 1954
- 1954 ⇒ Atomic Energy Act of 1954 allowing companies to use nuclear materials, build nuclear power plants. and established the Atoms for Peace Program
- 1957 ⇒ The first commercial U.S. nuclear power plant—Shippingport Atomic Power Station, a light-water reactor with a 60-MW capacity—was synchronized to the power grid in Pennsylvania.
- 1957 ⇒ IAEA established with 18 members, today it has 170 member states
- 1957 ⇒ WASH-740,The Brookhaven report (Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants).
- 1960s – 1970s ⇒ The industry grew rapidly. Nuclear construction projects were on drawing boards across the U.S., with 41 new units ordered in 1973 alone.
- 1974 ⇒ WASH-1400, Rasmussen report (The Reactor Safety Study)
- 1991 ⇒ NUREG-1150, Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants

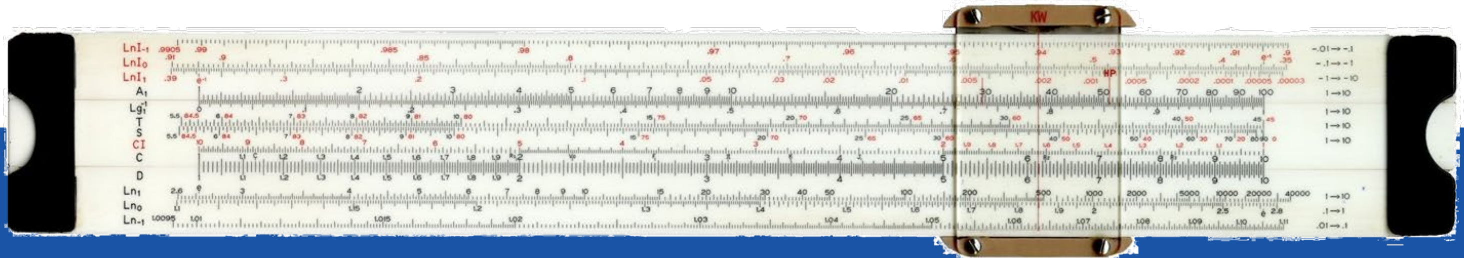
Nuclear Power Timeline

- 1979 $\Rightarrow$ Three Mile Island
- 1986 $\Rightarrow$ Chernobyl
- 2011 $\Rightarrow$ Fukushima

Evolution of Nuclear Safety



- Nuclear technology in US evolved from 1940's wartime environment in national laboratories.
- Computers did not exist.
- Calculations done by hand with "slide rules".
- Confirmatory test data did not exist.
- Accidents did occur – but no fatalities???.
- Fear of "run-away nuclear chain reaction"
- Philosophy of "defense in depth" was born.
  - Use of conservative design parameters and multiple protective barriers.



Evolution of Nuclear Safety

- Concept of design and siting to cope with Maximum Credible Accident or **MCA**.
- In 1950's "run-away chain reaction" and "stability" concerns shifted to new concerns: "Release of radionuclide inventory" from core
- Major unknowns included:
  - Fraction of core radionuclide inventory released
  - Transport and uptake mechanisms
  - Radioactive isotope toxicity effects

Evolution of Nuclear Safety

- Early demonstration reactor projects involved relatively small cores (< 50 MW).
- WASH-3 (1950) "rule of thumb" for Exclusion Zone:

$$R\ (\mathrm{Km}) \sim 0.01 \times (\mathrm{Power\ (KW)})^{0.5} \times 1.609344$$

-implications: 3000 MW $\rightarrow$ 27.9 Km!

- Maximum Credible Accident source terms recognized as very pessimistic !
- In reality, the risk to public were limited by:
  - Relatively small core radionuclide inventory
  - Low population density, remote sites

Evolution of Nuclear Safety

- 1954 Atomic Energy Act encouraged by US government to: "promote the peaceful uses of atomic energy, provided reasonable assurances exist that such uses would not result in excessive risks to the health and safety of the public."
- Authorized private enterprises to build and operate NPPs.
- US. Atomic Energy Commission (AEC) established as government agency to set regulations and issue licenses.
- NOTE: *US. AEC. reorganized as US. NRC. (1976).*

AEC Nuclear Safety Philosophy

- "If worst conceivable accidents are considered no site except one removed from populated areas by hundreds of miles would offer sufficient protection."
- "… if safeguards are included in facility design against all possible accidents having unacceptable consequences, then it could be argued that any site would be acceptable assuming that safeguards would not fail and that some dangerous accidents had not been overlooked."
- It is desired that "In plants finally approved for operation, there are really no credible potential accidents remain against which safeguards have not been provided to the extent that the calculated consequences to the public are unacceptable."

Taken from paper by Dr. Clifford Beck (USAEC) delivered to World Nuclear Congress of 1959 in Rome Italy.

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- ***Worst case scenario= no power plants***
- ***Safegards holding = build power plant everywhere***
- ***Plants to get license must have safegard for everything in place***

AEC Nuclear Safety Philosophy

- "…it is never entirely assured that all accidents have been examined. It should be noted that search for credible accidents often contributes substantially to facility safety."
- "In general, accidents would be considered credible if their occurrence might be caused by one single equipment failure or operational error, though clearly some considerations must be given to the likelihood of this failure or error."
- It has been suggested that this criterion be extended to assignment of decreasing probabilities to accidents occasioned only by 2, 3, or more independent and simultaneous errors or malfunctions, with possibility that accidents requiring more than 3 or 4 such failures be considered incredible….this suggestion has not been found useful."

  - **Not all of the accidents will ever be predicted**
  - **Accidents happen due to a single failure or operational error**

From this Early Statement of Nuclear Safety Philosophy

Need to Consider nuclear safety implications of any credible single failure events:

- Any pipe break or seal leak in any location
- Any electrical fault
- Any mechanical component failure
- Single Operator Error
- Not to consider certain "incredible events"
- Catastrophic failure of the Reactor Pressure Vessel
- Multiple independent failure events

WASH– 740, Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants"

Consequences of Major Accidents in Large Nuclear Power Plants estimated maximum possible damage from a meltdown with NO containment building at a large nuclear reactor. 1957 (revised 1964 to account for the larger reactors).

- 50% of Radioactive Inventory Released.
- Worst possible Meteorology.
- Up to 3400 fatalities.(45000)
- Up to 43000 (100000) injuries.
- property damage of $7 billion ($17 billion).
- adjusted for inflation to 2023= $74,5 billion ($164,06 billion).

Siting criteria established in 1950's

- Exclusion zone
- Low population zone (LPZ)
- Dose limits in exclusion zone
- Dose limits in LPZ.

Evolution of Nuclear Safety

Projection of commercial NPPs indicated need for 1000 - 3000 MW cores, located nearer to major electrical load centers

$\Rightarrow$1950's era simplified site criteria impractical.

Concept of design and site selection for reactor based on Design Bases Accident or DBA Source Terms.

1960 revised Reactor Site Criteria proposed effects of ECCS, Containment, Air Scrubbing, etc., factored in to DBA Source Terms.

Effects of Average Site Meteorology Considered.

Evolution of Nuclear Safety

1960 Siting Rulemaking report effort effectively changed exclusion zone “rule of thumb” from:

$$R\ (\text{km}) \sim 0.01 \times (\text{Power (KW)})^{0.5} \times 1.609344$$

to:

$$R\ (\text{km}) \sim 0.00018 \times (\text{Power (KW)})^{0.61} \times 1.609344$$

Source terms changed from Maximum Credible Accident source terms (MCA) to Design Bases Accident source terms (DBA)

Scenario of DBA limited by functioning of safeguards systems.

Evolution of Nuclear Safety

Worst conceivable accident. (1940's)

Maximum credible accident. (1950's)

Design bases accident. (1960's)

WASH-1400, “The Reactor Safety Study”

USNRC sponsored a broad study on risk of Nuclear Power: WASH-1400.

- Obtained a prob. Vs. consequence curve.
- Did not find much difference between a PWR and a BWR.
- Found that greater risk results from accidents other than design-base events; e.g., station black-out, containment bypass; small break LOCA.
- Found large LOCA of low risk.
- Found containment as the best safety device.
- Performed comprehensive, detailed fault and event tree analysis and consequence analysis; considered 1 specific PWR and 1 BWR.

TABLE 6-3 INDIVIDUAL RISK OF EARLY FATALITY BY VARIOUS CAUSES

(U.S. Population Average 1969)

Accident Type	Total Number for 1969	Approximate Individual Risk Early Fatality Probability/yr [a]
Motor Vehicle	55,791	3×10^{-4}
Falls	17,827	9×10^{-5}
Fires and Hot Substance	7,451	4×10^{-5}
Drowning	6,181	3×10^{-5}
Poison	4,516	2×10^{-5}
Firearms	2,309	1×10^{-5}
Machinery (1968)	2,054	1×10^{-5}
Water Transport	1,743	9×10^{-6}
Air Travel	1,778	9×10^{-6}
Falling Objects	1,271	6×10^{-6}
Electrocution	1,148	6×10^{-6}
Railway	884	4×10^{-6}
Lightning	160	5×10^{-7}
Tornadoes	118 [b]	4×10^{-7}
Hurricanes	90 [c]	4×10^{-7}
All Others	8,695	4×10^{-5}
All Accidents (from Table 6-1)	115,000	6×10^{-4}
Nuclear Accidents (100 reactors)	—	2×10^{-10} [d]

(a) Based on total U.S. population, except as noted.
(b) (1953-1971 avg.)
(c) (1901-1972 avg.)
(d) Based on a population at risk of 15×10^{6}.

NUREG-1150, Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants", 1991

- **Average probability of an individual early fatality per reactor per year:**
  - NRC Safety Goal: 5×10^{-7}
    - Typical Pressurized Water Reactor(PWR): 2×10^{-8}
    - Typical Boiling Water Reactor(BWR): 5×10^{-11}
- **Average probability of an individual latent cancer death per reactor per year:**
  - NRC Safety Goal: 2×10^{-6}
    - Typical PWR: 2×10^{-9}
    - Typical BWR: 4×10^{-10}
- **Probability of containment failure**
    - Typical PWR: 8%
    - Typical BWR: 84%
- **Probability of core damage is about 30% over 20 years**
- **Chance of a major release of radiation from the 104 current-design (2005) U.S. plants is under 8% every 20 years**

Pre-Fukushima Swedish Safety Requirements and Modernization

Safety Requirements update

- The Swedish Safety Design Requirements were updated in 2004 in alignment with IAEA safety standards and international best praxis.
  - Defence in depht independence between level 1/2 and 3 and between 3 and 4
  - Independence between subdivisions for DBA (Internal Hazards, LOCA, Transients)
  - Diversification for Fundamental Safety Functions (Reactivity control, Core, f Reactor Coolant Pressure Boundary protection and Containment isolation),
  - Internal and External Hazards protection for DBA (>=1E-5 /yr),
  - Design Extension Conditions protection for specific areas-CCF
  - Severe Accident (DEC) protection including Practical Elimination

Basic Design

- BWR: ABWR type with 4 safety divisions supported with 4 diesels
- PWR: Westinghouse 1970s design with reinforced emergency power supply
  - 4 safety divisions supported with 4 diesels
- All sites have Gas Turbines for station blackout events (US RG1.155)

Pre-Fukushima Swedish Safety Requirements and Modernization

Safety Modernization

- In the early 1980s safety modernization based on TMI accident lessons learned
- In the late 1980s all NPP was upgraded with severe accident mitigation capabilities, including filtered venting systems
  - Wet core melt cooling
  - Filtered vent and Independent Containment Spray
  - Igniters and New Recombiners
- The ongoing modernization program up to 2016 includes,:
  - Safety modernization to meet NNB requirement for long term operation safety approval with main focus on:
  - DBA (Design Bases Accidents) Internal Hazard protection,
  - DEC (Design Extension Conditions) CCF (Common cause failure) prevention/ protection
  - DBA LOCA local effect prevention/ protection.

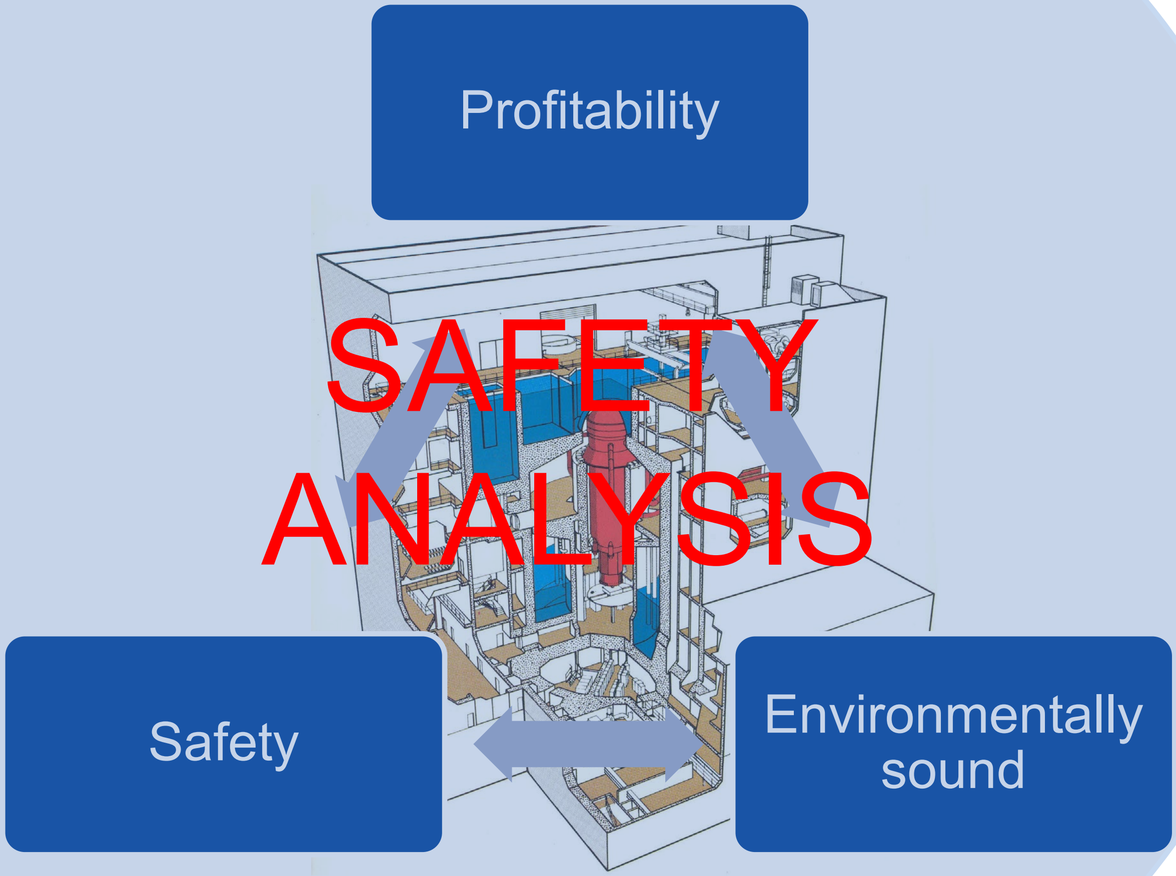
Post-Fukushima Safety Demonstration and Actions

Safety demonstration

- ELAP (Extended Loss of AC Power) and LUHS (Loss of Ultimate Heat Sink) protection
- Extreme External Event protection

Operating Plant Actions

- Independent Core cooling protected for DEC External Events
- Mobile Emergency Power Units
- SPC by Feed and Bleed
- PWR. For PWR Independent Core Cooling will be complemented by:
  - High Integrity RCP seals
  - Mobile RC make up system

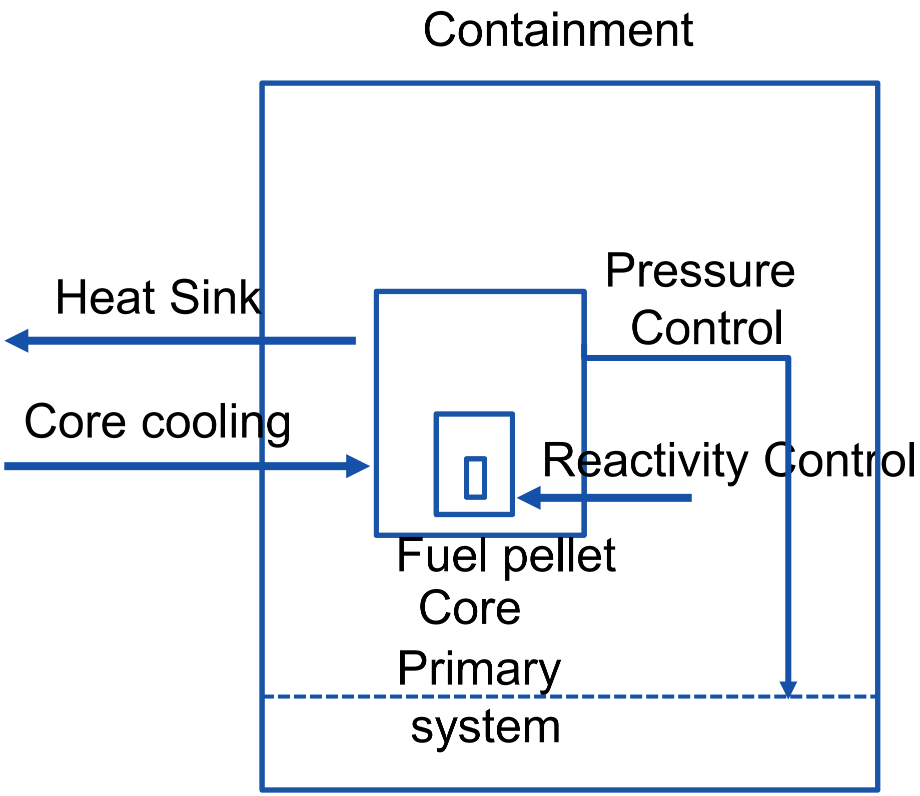

Profitability
SAFETY
ANALYSIS
Safety
Environmentally sound

How do we look at safet today?

Basic safety requirements and objectives

- Protecting people, society and the environment from harm by maintaining an effective defense against radiological accidents.
- Limiting the harmful effects of ionizing radiation within the power plant, as a result of emissions of radioactivity from the power plant and from formed waste, as far as possible during normal operation (ALARA-principle).
- To take all reasonable practical steps to prevent radiological accidents and mitigate the consequences of radiation damage in the case of accidents.

Think Barriers!



Requirement structures

Basic Requirements:	• Basic Safety Principles • Basic requirements • Core damage frequency • MTO	• IAEA, INSAG 12 • US. NRC. GDC 1-5 • < 1e-5/year • INSAG 4, GDC 19
Barriers:	• Fuel pellet • RCPB • Containment • Reactor building	• GDC 11-13 • GDC 14-15,30-32 • GDC 16,50-55 • GDC 60-64
Barrier Protection:	• Reactivity control • Isolation • RCPB protection • Core cooling • Heat sink	• GDC 60-64 • GDC 56-57 • ASME III 89 • GDC 33, 35-37 • GDC 34, 38-39,44,46
Protection and Reactivity Control Systems:	• Reactor Protection system	• GDC 20-24,29
Power systems:	• Electric Power Systems • Inspection and Testing of Electric Power Systems	• GDC 17 • GDC 18

GDC: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appa.html
INSAG: Publications Advanced Search | IAEA

Requirement structures

Environmental requirements

Acceptance criteria

Dimensioning & specifications criteria

General requirements

NEED TO BE VERIFIED BY ANALIZES

THEORETICAL PART, NUCLEAR SAFETY CONCEPTS

- Safety Objectives
- Operational and accident conditions
- Defense in depth
- Safety assessments
- Safety analysis
- Deterministic safety analysis
    - Conservative analysis
    - Best Estimate analysis
- Probabilistic Safety analysis
- Acceptance criteria
- Computer codes
- Verification and validation of computer codes