**Lyncean Group**

**68th Meeting**

**"Nuclear Reactor Safety and the Accident at Fukushima"**

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# Qualifications and Experience

1. Dipl. Ing. (Mechanical), ETH, Switzerland

### MS, Nuclear Engineering, MIT

### 1972 ScD, Nuclear Engineering, MIT

1967-1972 Shift Supervisor MIT Forschungsreaktor

1972-1979 General Atomic, San Diego, Mgr. GCFR Safety and Reliability

1980-1989 Partner, Pickard, Lowe and Garrick. Level 2 PSA und Severe Accidents.

1990-1994 Independent Consultant for Safety, Reliability and Risk.

1994-Now President, Risk Management Associates, Inc. PSA, Accident Analyses, Severe Accident Management, Severe Accident Simulators



**Nuclear Power History**

12/1957 Shippingport Nuclear Station, Shippingport, PA - First commercial Nuclear Power Plat in Operation.

1957 – 1990 127 Nuclear Electric Plants (> 50 Mwe) built in the US, 104 still in operation producing 102,391 Mwe (35 BWRs, 69 PWRs).

France 60 Nuclear Power Plants in Operation, 63,363 Mwe (59 PWRs, 1 LMFBR). One 1600 MWe under construction at Flamanville (Copy of Okiluto 3 in Finland).

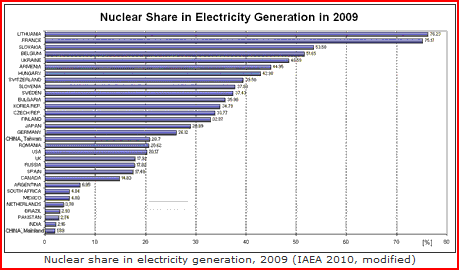
China 11 Nuclear Power Plants in Operation, 8,694 Mwe (9 PWRs, 2 PHWRs). 26 under construction, 26,820 Mwe).

Worldwide 441 Nuclear Power Plants in Operation producing 374,692 Mwe, 60 Mwe under construction representing 58,584 Mwe.

**Number of Nuclear Power Plants in Operation Worldwide Today**

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**Nuclear Power Share of Electricity Today by Country**

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**NUCLEAR POWER PLANT SAFETY**

* **WHY IS SAFETY SUCH A BIG ISSUE IN NUCLEAR POWER PLANTS**
* **WHAT ARE THE SAFETY PRINCIPALS**
* **DEFENSE IN DEPTH**
* **SAFETY BARRIERS**
* **PROBABILISTIC RISK ASSESSMENT**
* **HISTORY**
* **FUKUSHIMA**
* **SIMULATION OF AN ACCIDENT SCENARIO**

**WHY IS SAFETY SUCH A BIG ISSUE IN NUCLEAR POWER PLANTS**

* **HEAT IS PRODUCED BY FISSIONING U-235 ATOMS**
* **ONE FISSION RELEASES 200 MeV OF ENERGY, 97% AS KINETIC ENERGY OF THE RECOILED FISSION PRODUCT FRAGMENTS AND NEUTRONS, 3% IN THE RADIOACTIVE DECAY OF THESE FISSION PRODUCT FRAGMENTS**
* **FISSION PRODUCT FRAGMENTS ARE RADIOACTIVE AND DECAY OVER TIME WITH A CHARACTERISTIC HALF-LIFE RANGING FROM MILLISECONDS TO 100’s OF YEARS**
* **AFTER REACTOR IS SHUT DOWN (FISSION REACTION TERMINATED) RADIOACTIVE DECAY CONTINUES, RELEASING DECAY ENERGY THAT MUST BE REMOVED**
* **NUCLEAR FUEL MUST CONTINUE TO BE COOLED – SUBMERGED IN WASTER - FOR ABOUT 3 YEARS AFTER SHUTDOWN**
* **IF FUEL BECOMES UNCOVERED IT WILL HEAT UP AND MELT, RELEASING THE GASEOUS AND VOLATILE FISSION PRODUCTS ACCUMULATED IN IT.**
* **FISSION PRODUCTS ARE UNSTABLE FORMS OF ELEMENTS WHICH BECOME MORE STABLE BY DECAY. DECAY EMITS RADIOACTIVE PARTICLES OR RAYS:** 
  + **α Particle (He 2+) – Non-penetrating**
  + **β Particle (1- Electron) – can penetrate skin**
  + **γ (Energy Radiation) – deep tissue penetration**
* **FISSION PRODUCTS RELEASED TO THE ENVIRONMENT CAN CAUSE HEALTH EFFECTS IN PEOPLE THROUGH CLOUD EXPOSURE TO RADIATION AND TO INGESTION OF CONTAMINATED PRODUCTS:**
  + **400+ REM causes death within weeks**
  + **50 – 400 REM causes recoverable sickness**
  + **Radiation above a threshhold can cause cancer after many years**
  + **Level of Threshhold is not well defined and still subject to debate**
  + **Many natural and human caused sources of radiation: Background 0.3 to 15 REM/yr, X-ray 10 mREM, CT Scans 2 REM**
  + **Allowable annual radiation at a nuclear power plant:**
    - **Workers 5 REM/yr**
    - **Public – 0.1 REM/yr**

**WHAT ARE THE SAFETY PRINCIPALS**

* **Design to contain consequences of a nuclear reactor meltdown?**
* **1970s Congressional rulemaking on Emergency Core Cooling Systems**
  + **With 1970 State of knowledge it was not considered practical to design to contain a nuclear reactor meltdown**
  + **Defined required redundancy in safety systems to insure low risk od a meltdown – redundant systems and single failure criterion for safety systems**
  + **Defined defense in depth barriers: fuel, cladding, reactor coolant system boundary, containment**
* **More Recently:**
* **ALARA – Exposure “As Low As Reasonably Achievable”**
* **Probabilistic Risk Assessment**
* **Risk vs Benefit Measures**

**PROBABILISTIC RISK ASSESSMENT**

* **WASH-1400 1975 – Rasmussen study**
* **What can go wrong?**
* **How likely is it?**
* **What are the consequences**
* **Distinguish:**
  + **Operation at power**
  + **Operation during shutdown**
  + **Internally caused events – anything causing a scram**
  + **Area events (fires, floods on-site)**
  + **Externally caused events (earthquakes, floods, storms, etc.)**
* **Level 1 PRA – What is the frequency of core damage**
* **Level 2 PRA - What is the frequency and magnitude of an accidental relaese**
* **Level 3 PRA - What is the frequency and magnitude of harm to the public**
* **Automation vs Operators**
* **Individual plant studies and NUREG-1150 (1991)**

**HISTORY**

* **Three Mile Island (TMI) - 1979:** 
  + **Hardware malfunction and operator errors**
  + **Accident contained by Containment**
  + **No release to envirnment**
  + **Led to introduction of Severe Accident Management Guidelines (SAMGs)**
* **Chernobyl - 1986:**
  + **Dual purpose reactor design**
    - **Produce fuel for weapons**
    - **Produce electric power**
    - **No Containment**
  + **Operator Error in an unsafe design**
    - **Test after shutdown**
    - **Procedure required 6 hour wait time to build in Xenon poisoning**
    - **Conducted test without delay and caused a reactivity excursion**
  + **Consequences**
    - **Design abandoned by Russia**
    - **30 plant workers and fire fighters died within weeks**
    - **Long term evacuation (still today) and cancer risks**
    - **Detectable increase in cancers above occurrence from other causes in exposed population is still debated**

**FUKUSHIMA**

* **What happened:**
  + **Site with 4 reactors, one was shutdown and defueled**
  + **Larger than design basis Earthquake failed all Electrical Power, RCIC functioned**
  + **1 hour later a larger than design basis Tsunami failed battery power and RCIC**
  + **All core cooling lost, water boils off, core uncovers, hydrogen generation, containment pressure increase**
  + **Waited too long to vent containment, may have caused local containment failure**
  + **Waited too long to inject sea water into vessel to recover core**
  + **Major core melting in-vessel at 3 reactors. Some debris may have been released through reactor vessel bottom head failure into containment.**
  + **Containment venting released hydrogen into reactor building and caused dramatic explosions in reactor building**
  + **Major release of activity to environment, mostly out to sea**
  + **For 9 months core/debris was kept covered with water boiloff but without cooling resulting in continued low level release of activity**
  + **Now is core/debris actively cooled again without boiloff**
  + **No plant worker over-exposed (2 workers had feet over-exposed, not whole body)**
  + **No member of public over-exposed as far as we know**
  + **In long run (20 to 50 years) some additional cancer fatalities are expected**
  + **Probbably not detectable againnst normal variation of cancer caused deaths from all other causes**

**FUKUSHIMA (continued)**

* **Contributing Causes**
  + **Earthquake/Tsunami killed 25,000 people instantly**
  + **Inadequate response to 1996 larger than design basis earthquake at Kashiwasaki**
  + **No full scope risk assessments for external events**
  + **No or inadequate Severe Accident Management Guidelines for external events**
  + **No or inadequate preparation for loss of all systems**
  + **Inability of making unplanned decisions in an emergency**
  + **Decision of corrective/mitigating actions had to be made by the President of Japan**
  + **Larger consequences were avoided by plant manager’s unauthorized decision to turn on sea water injection and by wind predominantly out to sea**

**SIMULATION A SEVERE ACCIDENT**

Accident Sequence Definition

* **Loss of all AC power at time 0.0, recovered when water level reaches bottom of active fuel**
* **Loss of diesel power at time 0.0, recovered when water level reaches bottom of active fuel**
* **Battery power is available for 2 hours**
* **RCIC and HPCI fail when battery power is lost**

**Accident Sequence Evolution**

**0.0 h Loss of power, reactor scrams, feedwater tripped**

**12 m RCIC starts automatically on low level,**

**16 m RCIC stops on high level**

**2.0 h Batteries run out and RCIC fails at 2 hours.**

**5.5 h Core begins to uncover**

**6.0 h Fission products begin to be released from fuel**

**6.5 h Fuel melting and relocation in core begins**

**7.5 h Water level at bottom of active fuel, core slumped onto grid palte, RCIC recovered**

**14.7 h RCIC supply tank runs empty, suction switched to suppression pool, temperature too high and RCIC fails due to cavitation. Core debris starts to reheat**

**20.5 h Core debris melts through grid plate into lower plenum**

**21.0 h Vessel lower head fails at control rod guide tube penetration, debris relocates to drywell (containment) where it is quenched by water**

**21.0 h Containment pressure increases to 10.7 bar, hardened vent is opened to environment (rupture disk), gaseous and some volatile fission products and all hydrogen are vented to environment**

**22.8 h Water is boiled off, debris uncovers, reheats and begins to erode into concrete. Vent remains open and activity release to environment continues at much lower level.**