CLOSING THE NUCLEAR FUEL CYCLE

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Chemical and Fuel Cycle Technologies

U.S. DEPARTMENT OF ENERGY
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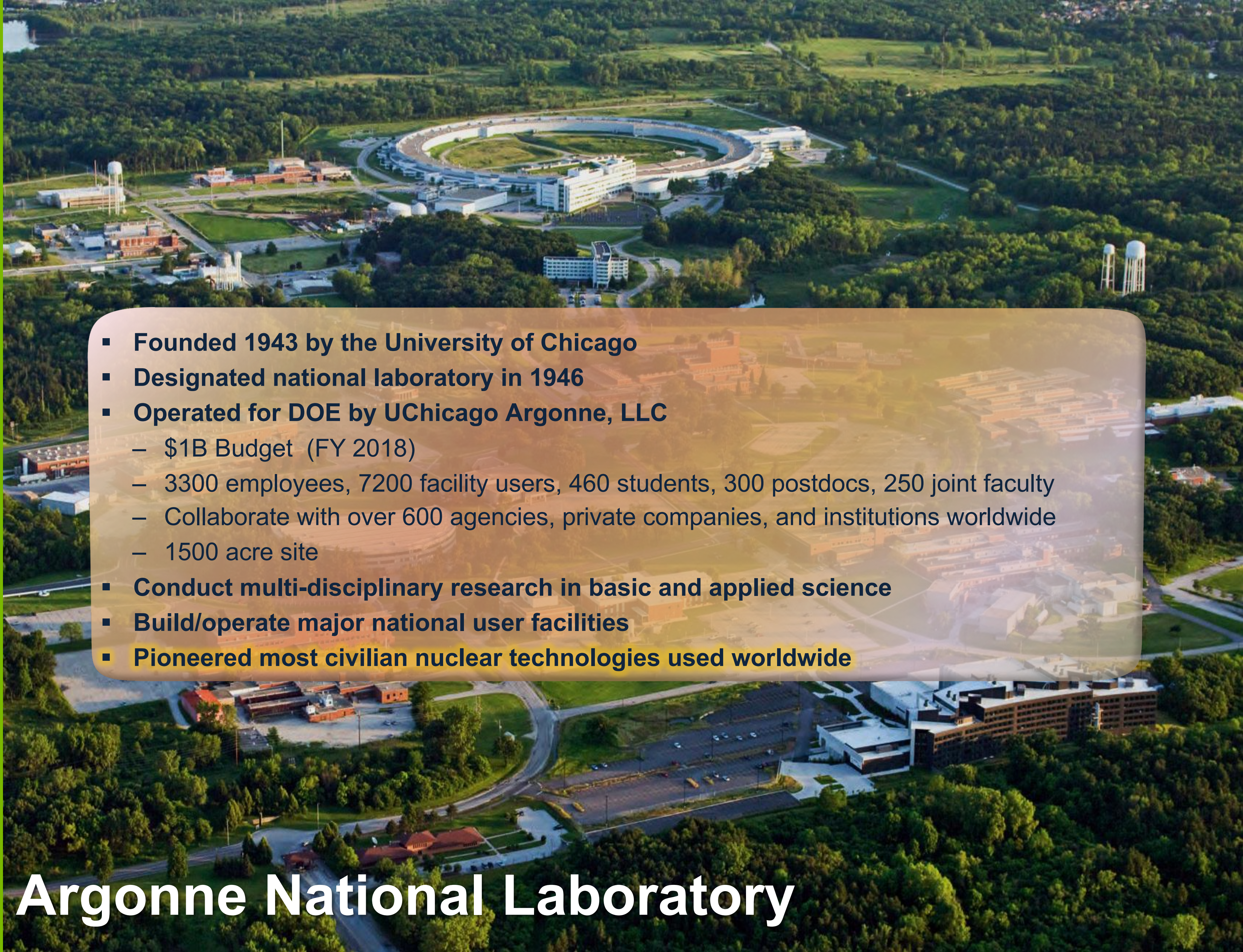
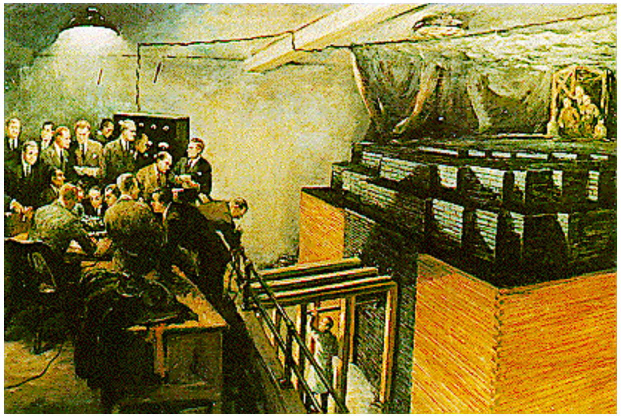
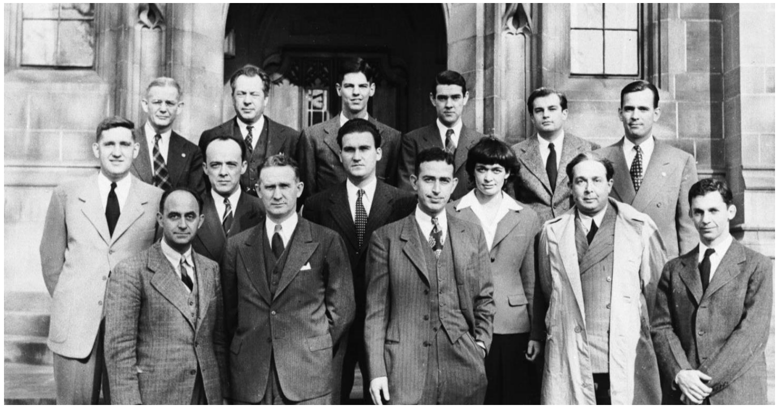


- Founded 1943 by the University of Chicago
- Designated national laboratory in 1946
- Operated for DOE by UChicago Argonne, LLC
  - $1B Budget (FY 2018)
  - 3300 employees, 7200 facility users, 460 students, 300 postdocs, 250 joint faculty
  - Collaborate with over 600 agencies, private companies, and institutions worldwide
  - 1500 acre site
- Conduct multi-disciplinary research in basic and applied science
- Build/operate major national user facilities
- Pioneered most civilian nuclear technologies used worldwide

Argonne National Laboratory

ARGONNE'S NUCLEAR PROGRAM BUILDS ON PIONEERING ACHIEVEMENTS





- Seminal work on reactors and fuel cycle technologies
- Our mission today is to advance the safe, secure use of nuclear energy and management of nuclear materials
  - Incorporating S&T advances in the development, design, and operation of nuclear energy systems

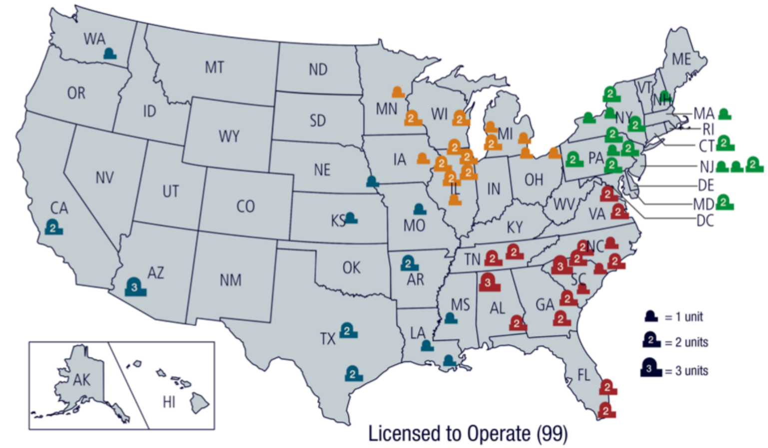
NINETY-NINE OPERATING POWER PLANTS IN U.S.

U.S. nuclear plants generate ~2,000 tonnes of used fuel per year

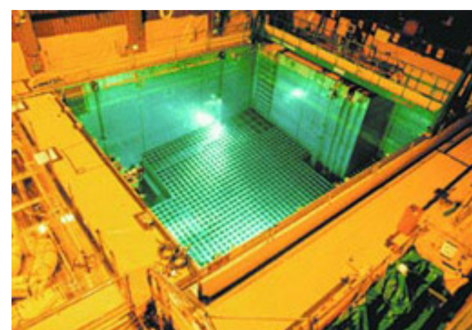
- Each plant provides water basin storage capacity for about 40 years worth of used fuel generation
  - Most utilities have added dry cask storage capacity because there is no pathway at present to ultimate disposal of the used fuel
  - Approximately 80,000 tonnes accumulated to date in U.S.

- Used nuclear fuel contains sufficient energy to provide electricity for centuries
  - Up to 96% of the metals in used nuclear fuel can be recovered and recycled for energy production
  - Approximately 4% of material in used fuel is waste that can be disposed in a geologic repository

U.S. Operating Commercial Nuclear Power Reactors



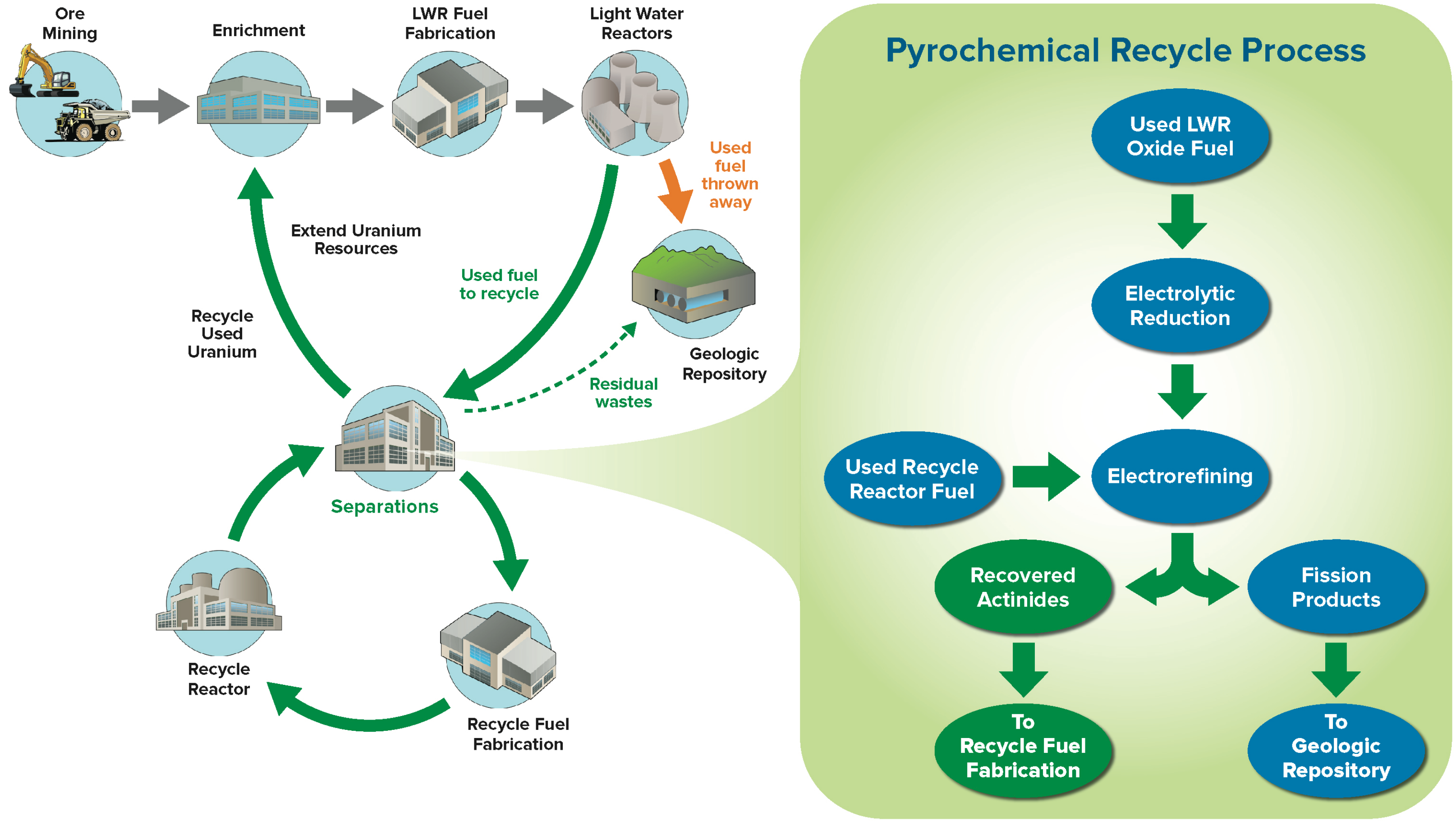
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment
As of July 2018



Figures from NRC.gov

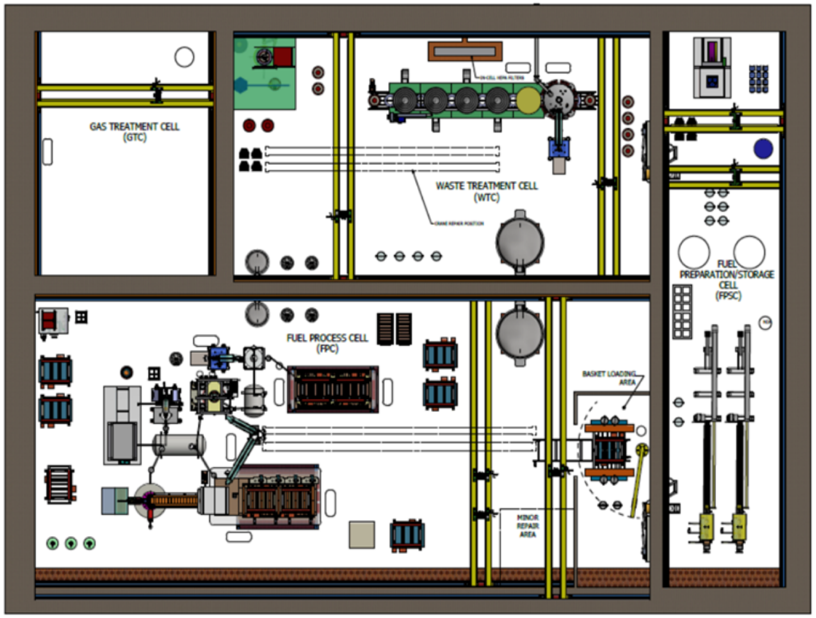
CLOSED NUCLEAR FUEL CYCLE

Sustainable nuclear energy production with fast reactors and actinide recycling



PYROPROCESSING FACILITY DESIGN

- Industrially practicable and economical facility
  - High capacity factor, remote operation requiring limited intervention
  - Modular systems to facilitate repair, low maintenance
  - Minimal impact on overall cost of electricity
  - System meets U.S. non-proliferation objectives



- Conceptual design of 100 MT/yr pilot plant for LWR fuel treatment completed
  - Integrated process flowsheet model and operational model developed
  - Process equipment design developed
  - Worked with A&E firm to complete facility design and balance of plant
- Design provides launching point for detailed plant design

REACTOR CHARACTERISTICS LEAD TO DIFFERENT FUEL CYCLE STRATEGIES

- **Thermal reactors** (Gen III and III+) typically configured for once-through (open) fuel cycle
  - Operate on low enriched uranium
  - Require an external fissile feed to maintain operation
  - Higher actinides (i.e., transuranic elements) must be managed to allow recycle
    - Separation of higher elements – still a disposal issue
    - Extended cooling time for curium decay

- **Fast reactors** (Gen IV) are typically intended for closed fuel cycle with uranium conversion and resource extension
  - Higher actinide generation is suppressed
  - Neutron balance is favorable for fission of recycled higher actinides
    - No external fissile material is required (e.g., no enrichment)
    - Can enhance or limit U-238 conversion depending on design
  - Destruction of the higher actinide elements is targeted to eliminate long-term heat, radiotoxicity, and dose in used fuel

EXPERIMENTAL BREEDER REACTOR II

- EBR II design features
  - Metal alloy fuel with inherent safety features
  - Pool-type design with heat transfer system components in cold pool, serving as a massive heat sink
  - Key safety tests conducted and demonstrated safety
    - Inherent safety - reactor shuts itself down safely under transients
    - Passive safety - heat removal with natural circulation systems; no electricity required

- EBR II 30 years of successful and safe operation
  - High capacity factors approaching 80% even with an aggressive testing program
  - Maintenance techniques were proven
    - Very low exposure to personnel
    - Excellent safety record
    - Liquid sodium management demonstrated
  - Over 150,000 metal fuel pins irradiated up to 20% burn-up without failure
  - Fuel reprocessing demonstrated with 35,000 metal fuel pins reprocessed

SUMMARY

Pyrochemical processing coupled with a GEN IV fast reactor enables nuclear fuel cycle closure

- Sustainability
  - Maximize resource utilization
  - Major role in waste management

- Competitive economics
  - Industrially practicable
  - High capacity factor
  - Modular systems to meet throughput needs and facilitate maintenance and repair

- Safety and safeguards assurance
  - Inherently and passively safe operations
  - Designed to meet U.S. non-proliferation standards

- Waste minimization
  - Encapsulate fission products in engineered waste forms that can be disposed in a geologic repository

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PYROCHEMICAL PROCESSES IDEALLY SUITED FOR FAST REACTOR FUEL RECYCLE

GEN IV FAST REACTORS HAVE UNIQUE FEATURES IMPACTING CHOICE OF REPROCESSING TECHNOLOGY

- High concentration of transuranic elements in fuel (e.g., 20 wt%)
- Short cooling time to allow for in-vessel storage of used fuel prior to reprocessing
  - No extensive out-of-reactor used fuel storage system required
  - Eliminates large out-of-reactor inventory of transuranic elements
- Sodium used for bonding metal fuel with cladding material for improved heat transfer
  - Reacts to form sodium chloride that is soluble in molten salt

ADVANTAGES OF PYROCHEMICAL PROCESSES

- High solubility for actinides yield compact process operations
- Resistant to high radiation fields thus allowing treatment of short-cooled fuel
- High actinide concentrations in the salt are critically safe
- Wide electrochemical potential (i.e., voltage) window allows for recovery of actinides as metals
- Low melting point salt permits use of low-cost containment vessels

SODIUM COOLED FAST REACTORS - SAFETY

- Superior heat transfer properties of liquid metals allow:
  - Low pressure operation – no “pressure vessels” needed
  - Designed to prevent loss of coolant
  - Enhanced natural circulation for heat removal

- Inherent safety design
  - Designed to provide feedbacks to prevent fuel damage during transients
    - Loss of heat removal
    - Loss of flow (circulation pumps)
  - Transient response is such that as temperature increases, power is reduced and reactor reaches safe condition
  - Demonstrations performed (EBR-II and FFTF)

- Passive Safety Features
  - Multiple paths for passive decay heat removal envisioned
    - Natural circulation systems
    - Response time