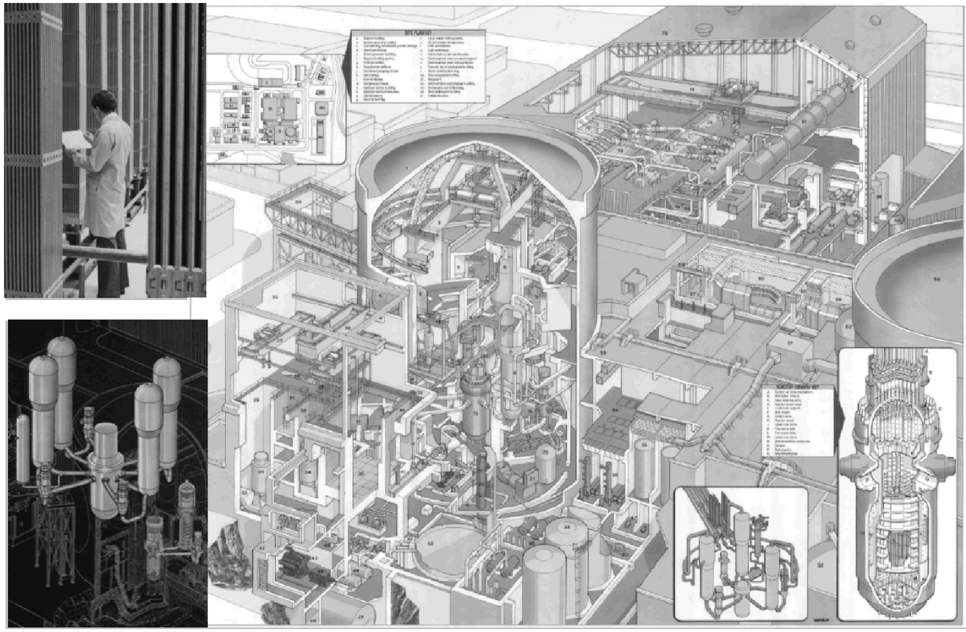
SAND2013-3280C

ENG 505
ENERGY SURETY AND SYSTEMS

Exceptional service in the national interest



Nuclear Energy Technology

Gary E. Rochau
Advanced Nuclear Concepts
Org. 6221, Sandia National Laboratories,
New Mexico (USA)

SANDIA REVIEW & APPROVAL NUMBER

Outline of Presentation

- Brief Biographical Note
- Nuclear Fission Energy Source
- Nuclear Fuel Cycle – Front End
- Nuclear Power Reactors – PWR Example
  - Design
  - Operation
  - Safety
- Nuclear Fuel Cycle – Back End
- Question & Answer Session

ENG 505 - ENERGY SURETY & SYSTEMS

Nuclear Energy Technology

Gary E. Rochau

- Educational Background
  - BA – Physics, Mathematics, Carthage College, Kenosha Wisconsin
  - MA – Physics, Western Michigan University, Kalamazoo, Michigan
- Professional Experience
  - Research Associate in Physics – University of Florida
- Sandia Experience/Career Highlights Summary
  - Design of Physical Protection Systems for Nuclear Fuel Reprocessing
  - Neutron Generator Engineer for B61
  - Plasma Physicist for Pulsed Power – PBFA II
  - Project Manager for X-1 x-ray source
  - Program Manager of ASME Reactor Vessel Annealing Demonstration
  - Program Manager for Inertial Confinement Fusion Power Plant
  - Manager for MELCOR code development and experimental benchmarking
  - Manager for Advanced Nuclear Concepts
  - DOE Technical Project Lead for Advanced Energy Conversion - Nuclear

Recall: What is a Complex System?

- A **complex system** is a system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
- Common Attributes
    - Multiple interacting phenomena
    - Heterogeneous element
    - Non-linear dynamics and effects
    - Adaptive behavior
    - Elements with memory
    - Large network of elements or nested complexity
- **Nuclear power plants** have – or will have – all of these characteristics

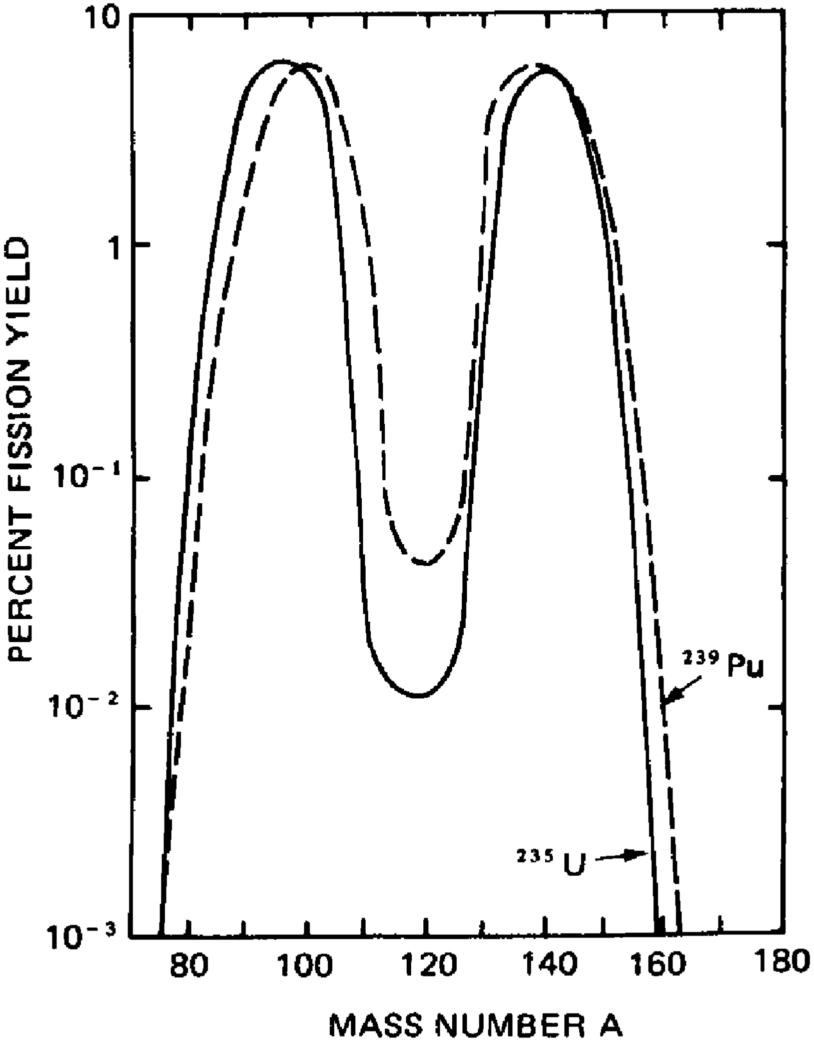
Fission - Introduction

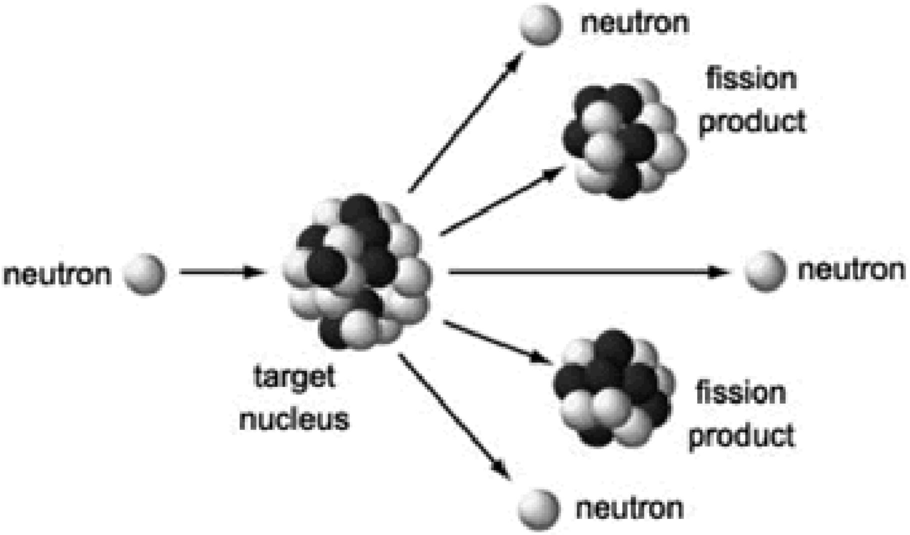
- Creating a fission chain reaction is conceptually simple. Requires right materials in right geometry.
- Good engineering needed to create safe, useful, long-life fission systems.

- 1938 Fission Discovered
- 1939 Einstein letter to Roosevelt
- 1942 Manhattan project initiated
- 1942 First sustained fission chain reaction (CP-1)
- 1943 X-10 Reactor (ORNL), 3500 kWt
- 1944 B-Reactor (Hanford), 250,000 kWt
- 1944-now Thousands of reactors at various power levels

Energy Release and Fission Products

Fission Product Production





<u>Energy Released per Fission</u>

200 MeV / fission

168 MeV = fission fragments

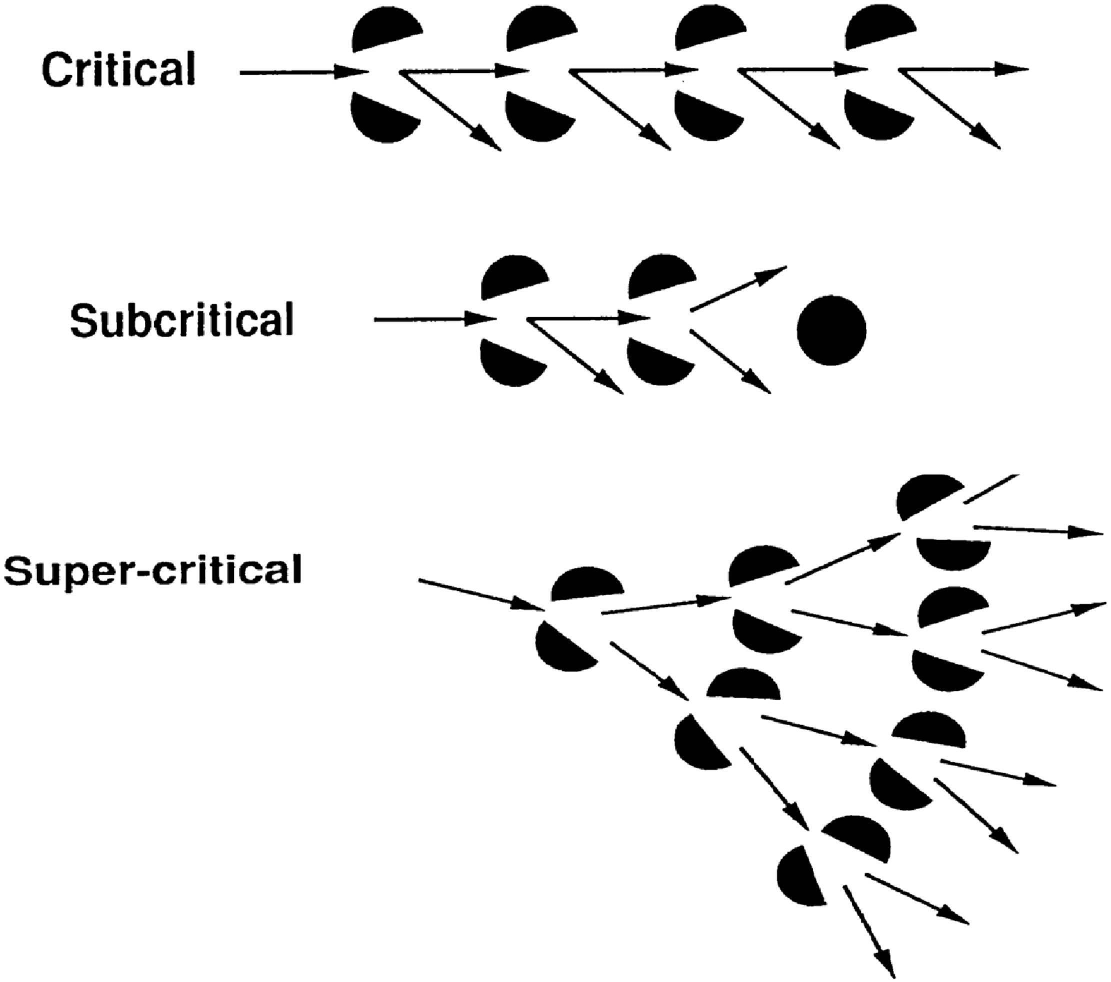
5 MeV = fission neutrons ($\nu = 2.44$ n/fission)

7 MeV = prompt gamma rays

~20 MeV = capture gamma rays
fission product decay

Nuclear Criticality

k
= 1
< 1
> 1

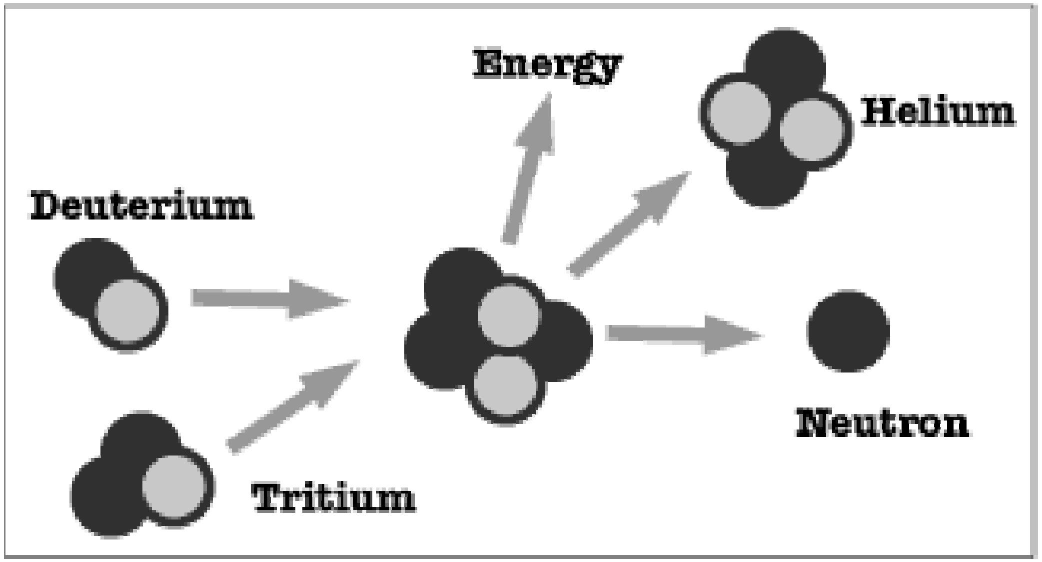


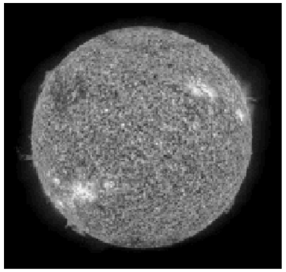
A Word about Fusion

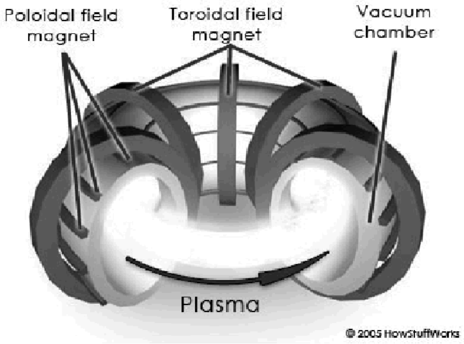
Three to Four times more energy released compared to fission

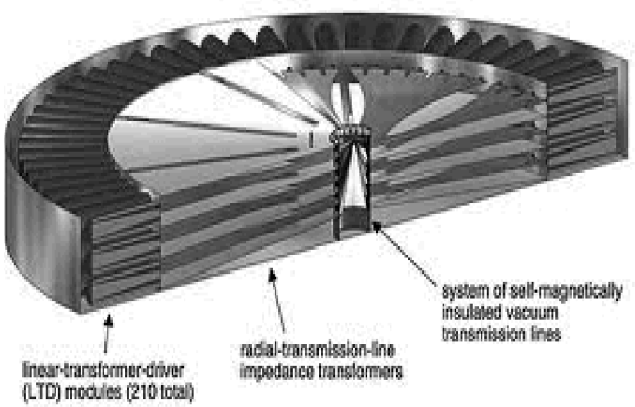
Extreme amounts of energy required for fusion to occur

The byproducts of fusion are x-rays and neutrons. X-rays create heat, neutrons create radioactive materials

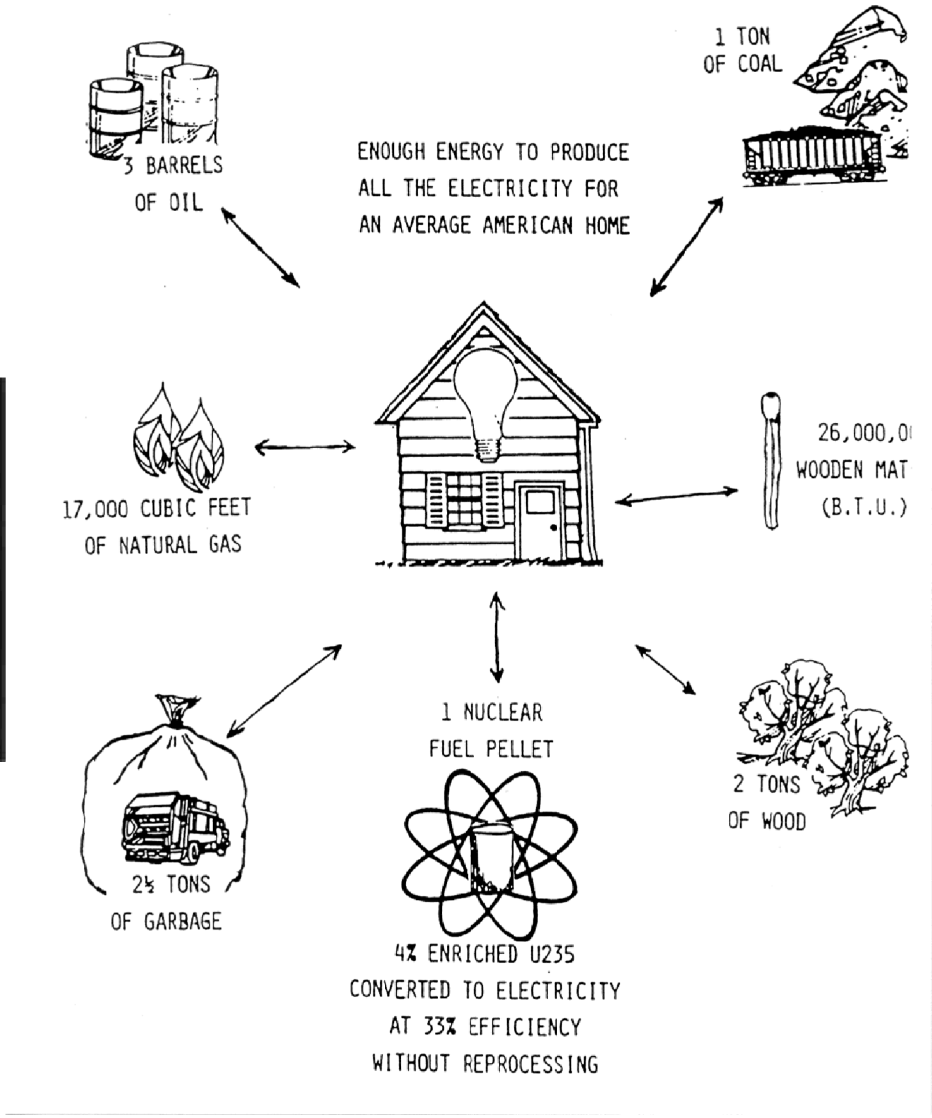






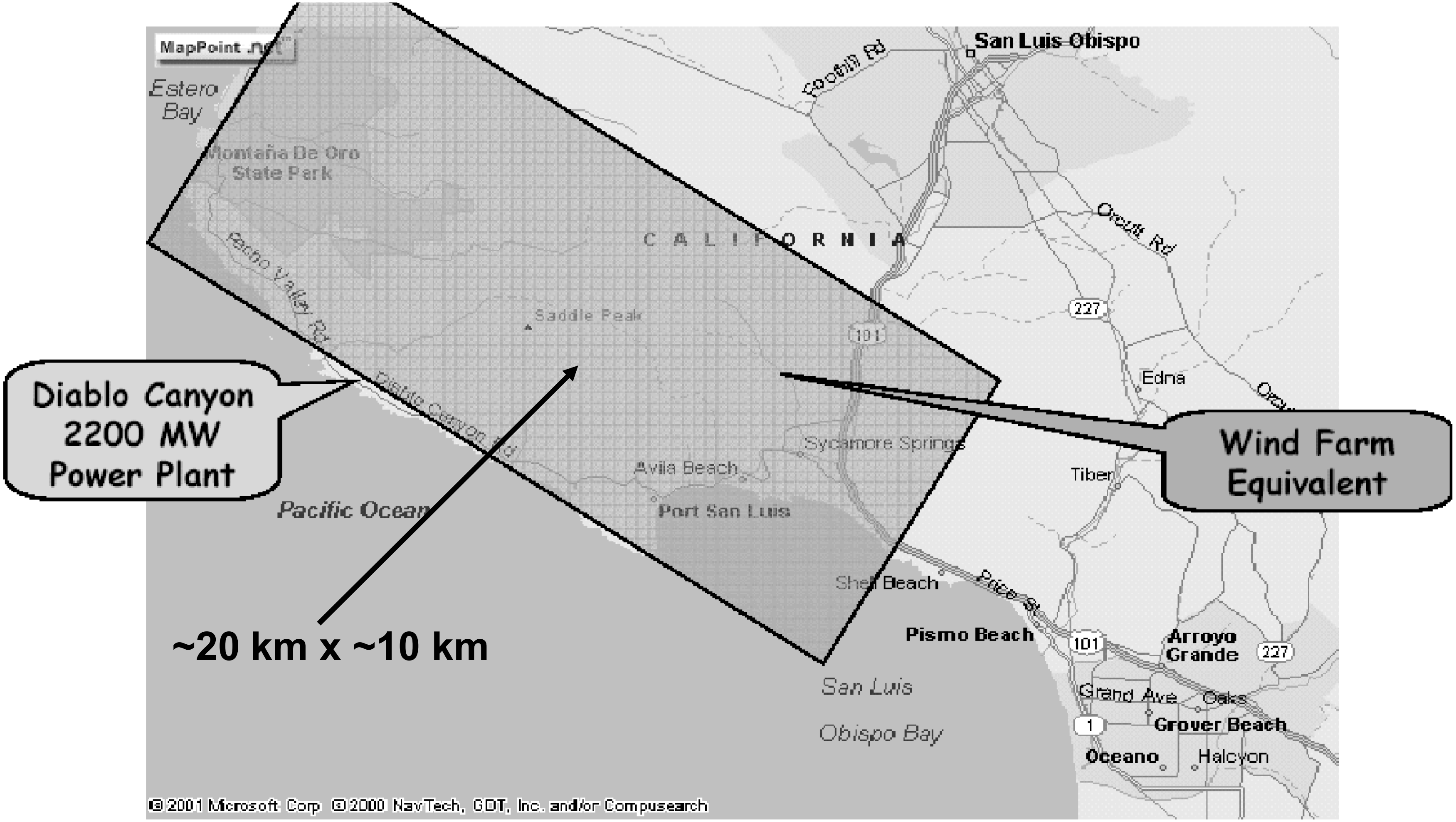


Nuclear Energy Equivalents



2 Unit Diablo Canyon Site (2.2 GW_e Total)

Nuclear Power has a High Energy Density



Diablo Canyon 2200 MW Power Plant

Wind Farm Equivalent

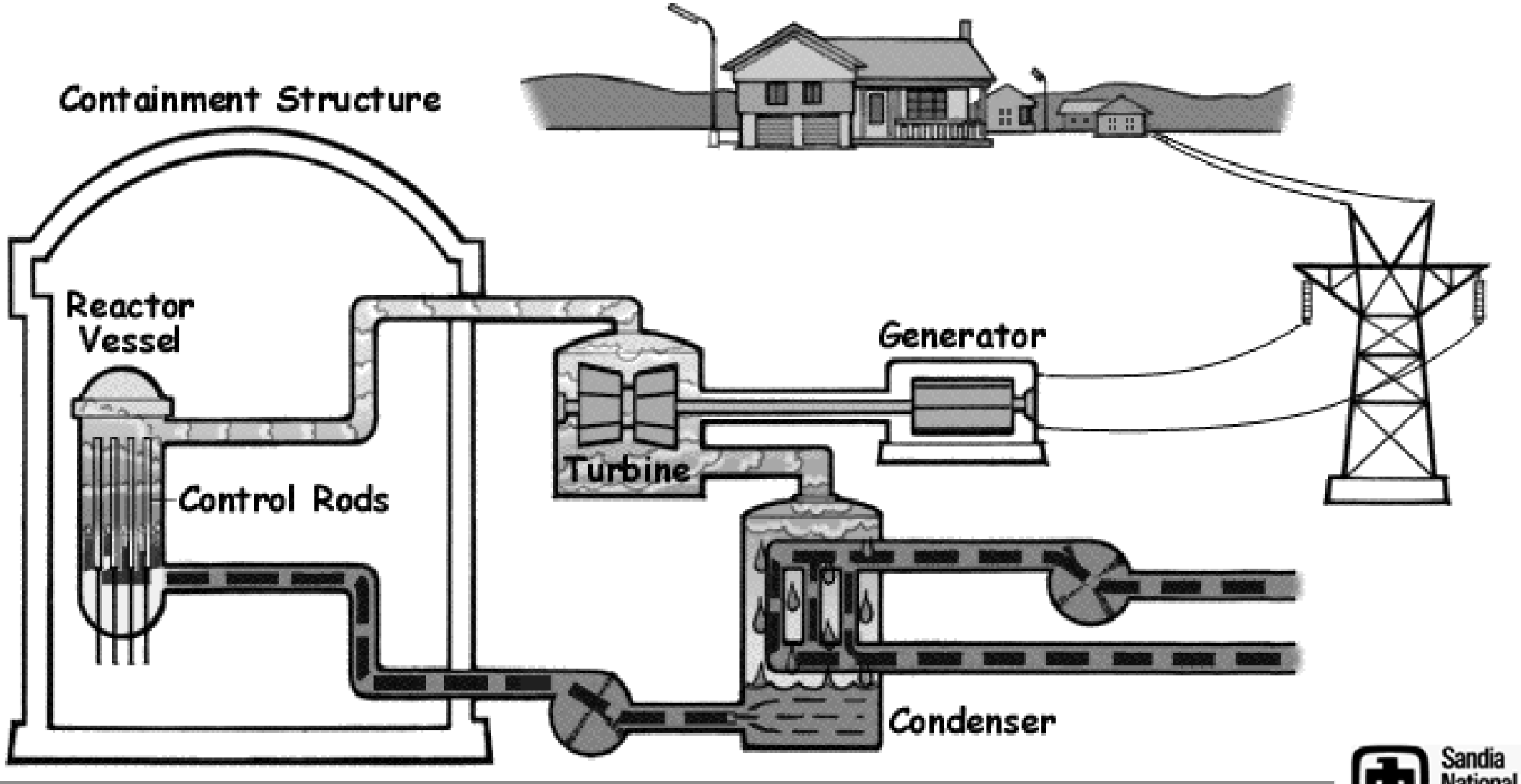
~20 km x ~10 km

BWR Steam Cycle

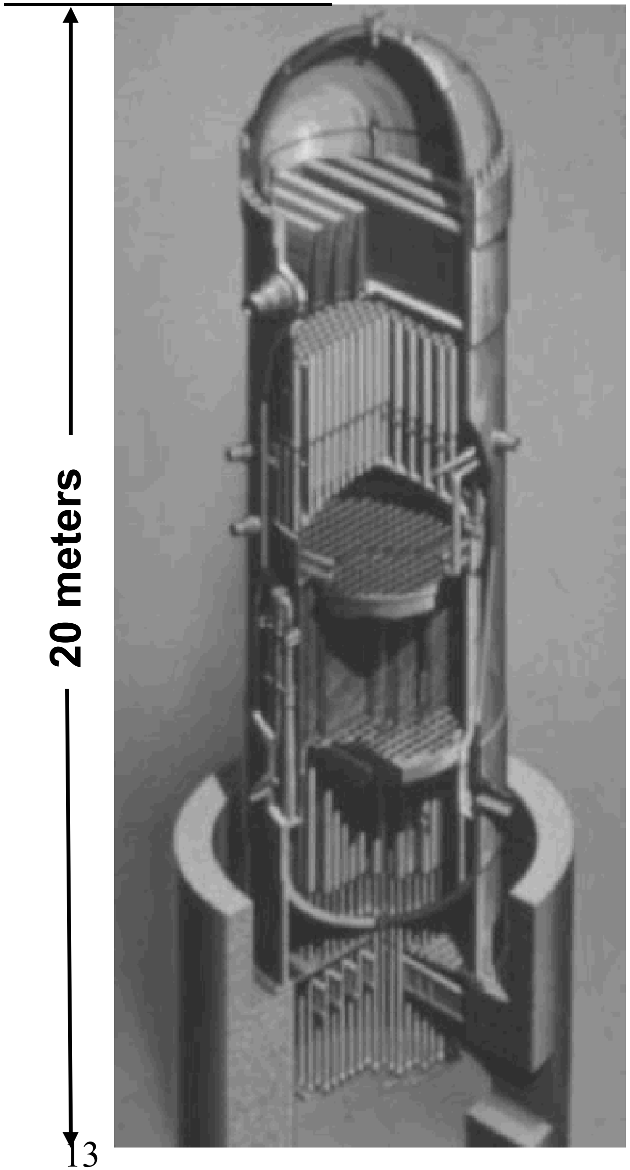
Primary
water-steam-water
70 atmospheres
290^{o} C

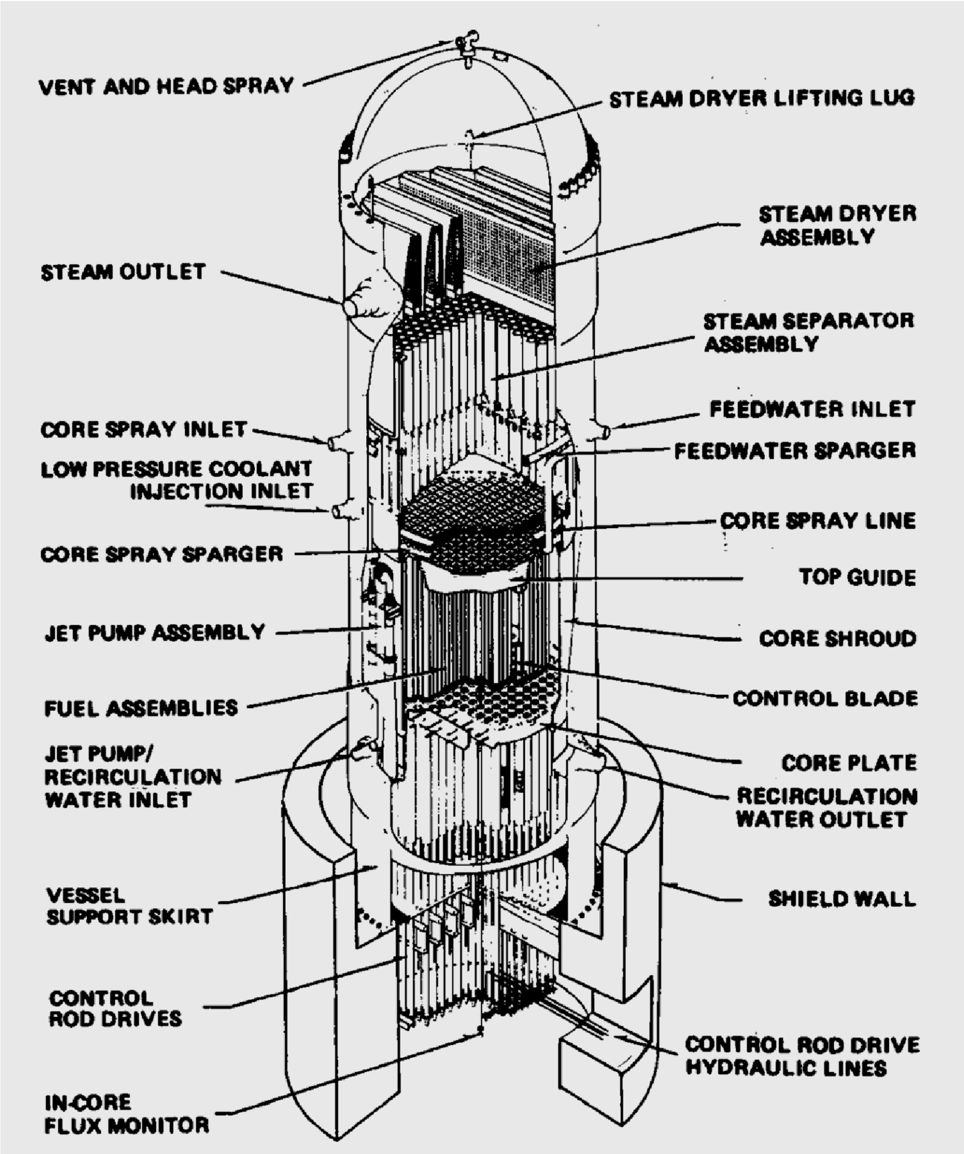
Condenser
water-water vapor
atmospheric pressure
25-35^{o} C

- Water is moderator, coolant, and shield.
- Steam voids reduce moderation and reaction rate.



BWR Vessel


20 meters

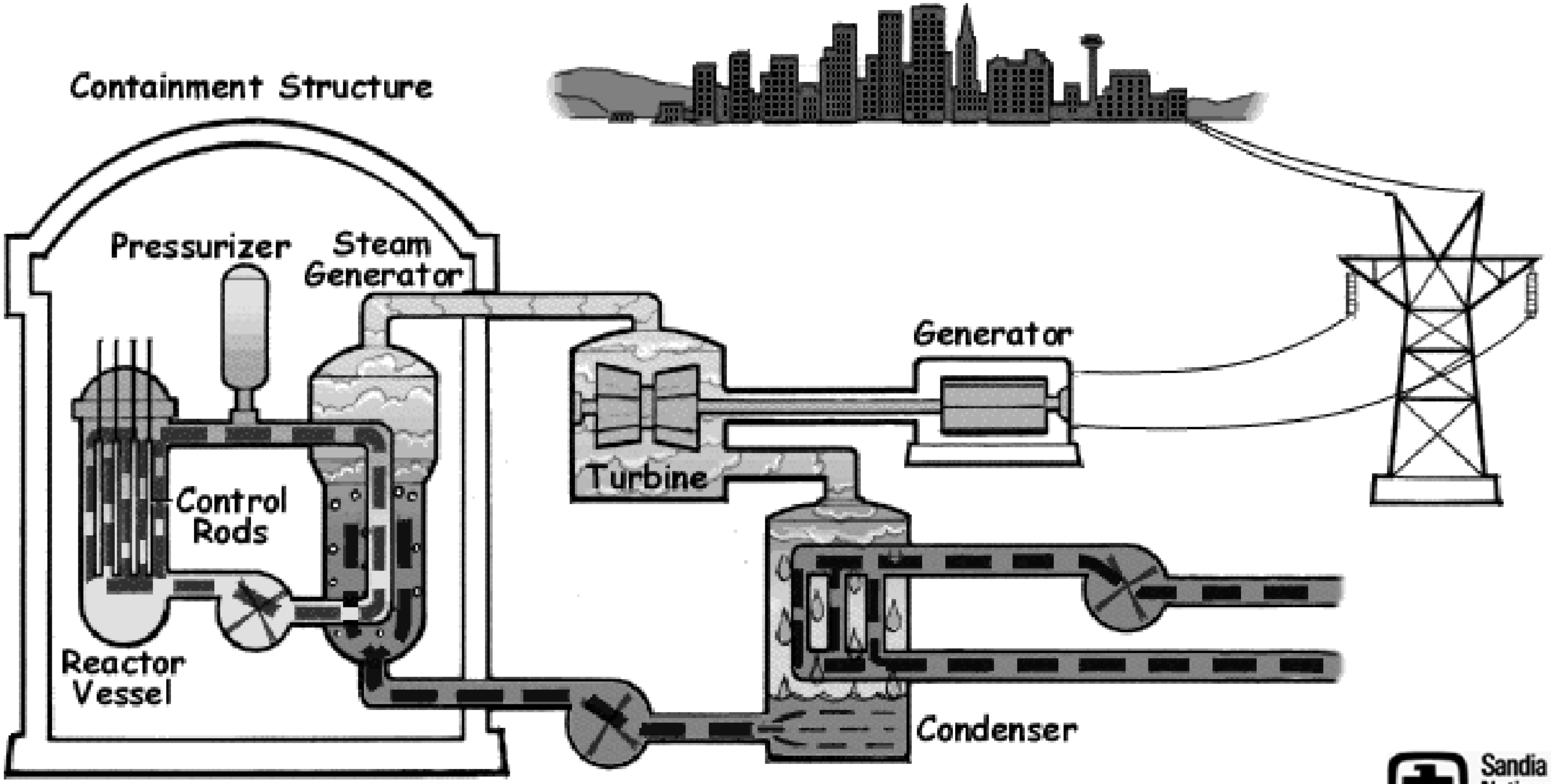

VENT AND HEAD SPRAY
STEAM DRYER LIFTING LUG
STEAM DRYER ASSEMBLY
STEAM OUTLET
STEAM SEPARATOR ASSEMBLY
FEEDWATER INLET
CORE SPRAY INLET
FEEDWATER SPARGER
LOW PRESSURE COOLANT INJECTION INLET
CORE SPRAY LINE
CORE SPRAY SPARGER
TOP GUIDE
JET PUMP ASSEMBLY
CORE SHROUD
FUEL ASSEMBLIES
CONTROL BLADE
JET PUMP/ RECIRCULATION WATER INLET
CORE PLATE
RECIRCULATION WATER OUTLET
VESSEL SUPPORT SKIRT
SHIELD WALL
CONTROL ROD DRIVES
CONTROL ROD DRIVE HYDRAULIC LINES
IN-CORE FLUX MONITOR

PWR Steam Cycle

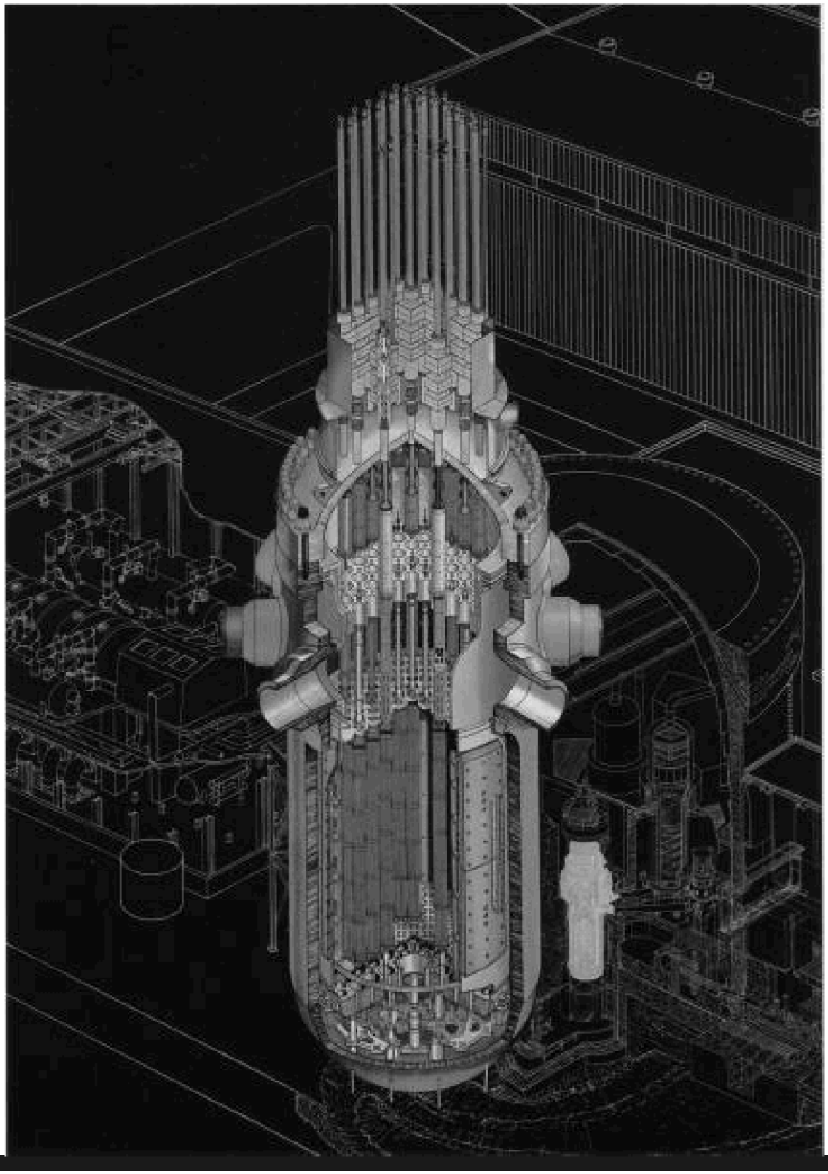
Primary
water only
160 atmospheres
330° C

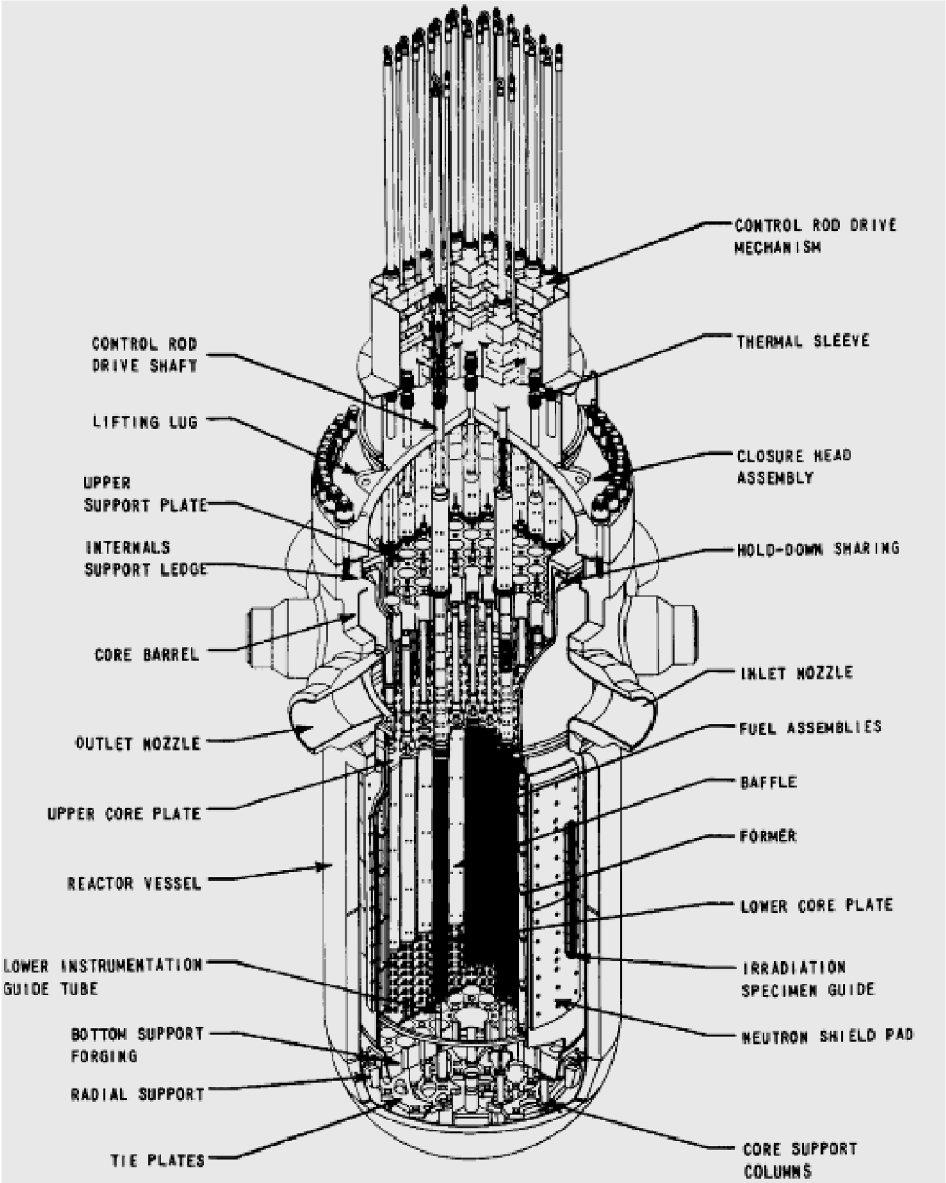
Secondary
water-steam-water
60 atmospheres
280° C

Condenser
water-water vapor
atmospheric pressure
25-35° C



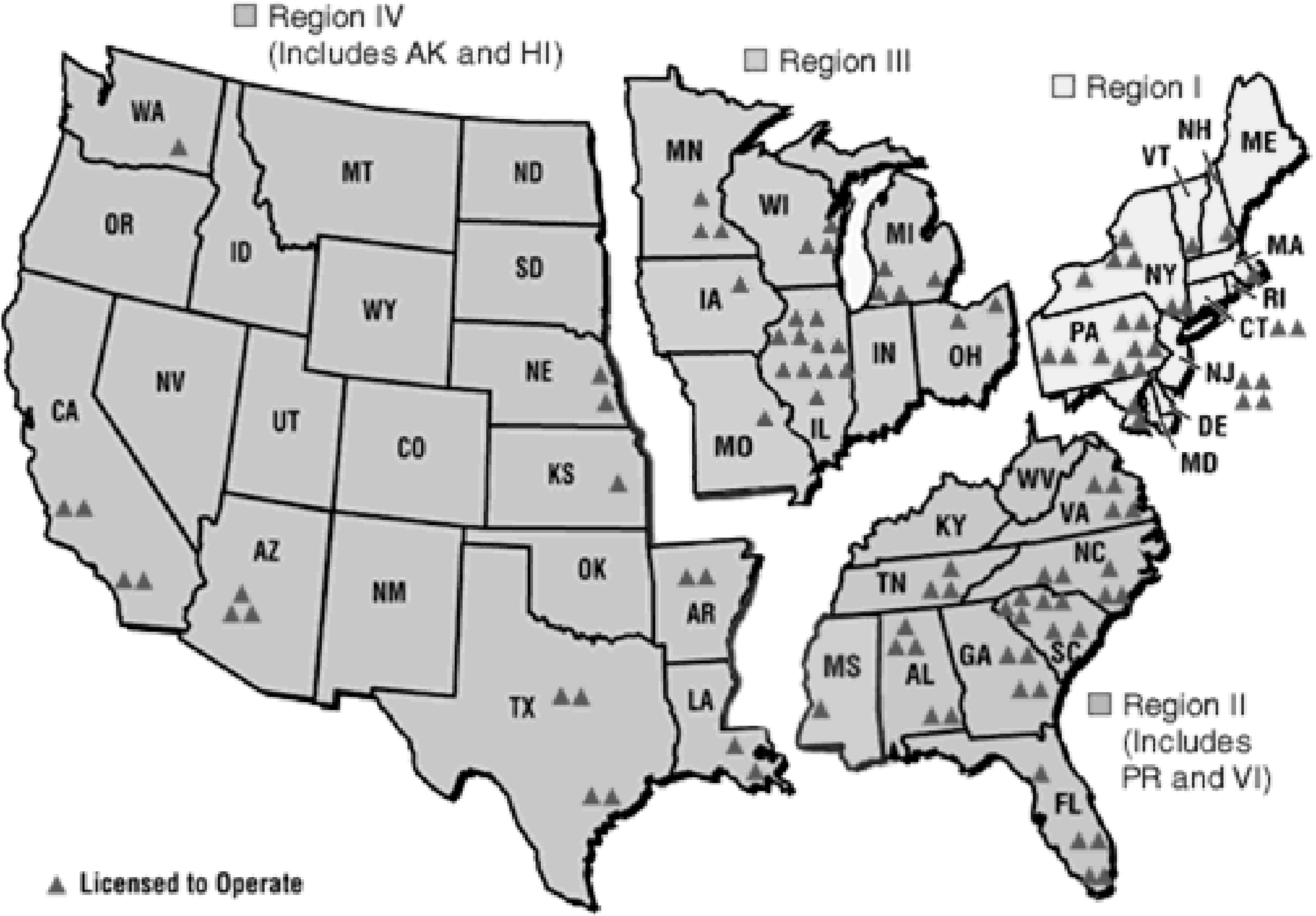
PWR Pressure Vessel





The US has 104 nuclear power reactors

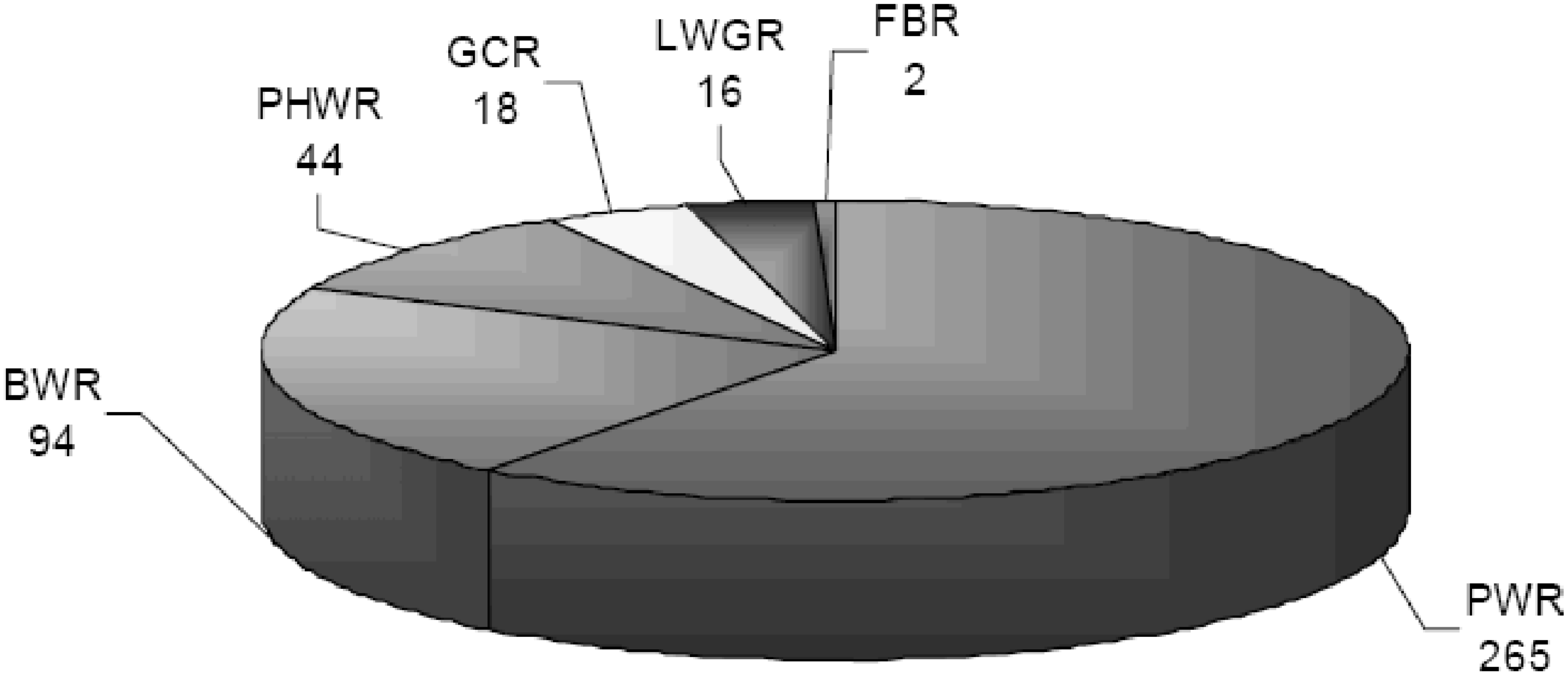
(69 PWR, 35 BWR)



http://www.nrc.gov/reactors/power.html

Worldwide, most nuclear power plants are PWRs

Light Water Graphite-moderated Reactor - LWGR
Pressurized Heavy Water Reactor - PHWR
Fast Breeder Reactor - FBR
Gas Cooled Reactor - GCR
Pressurized Water Reactor - PWR
Boiling Water Reactor - BWR



http://www.regjeringen.no/upload/OED/Rapporter/ThoriumReport2008.pdf

Nuclear Power Plant Safety

Nuclear power plants are designed with two principal safety objectives in mind:

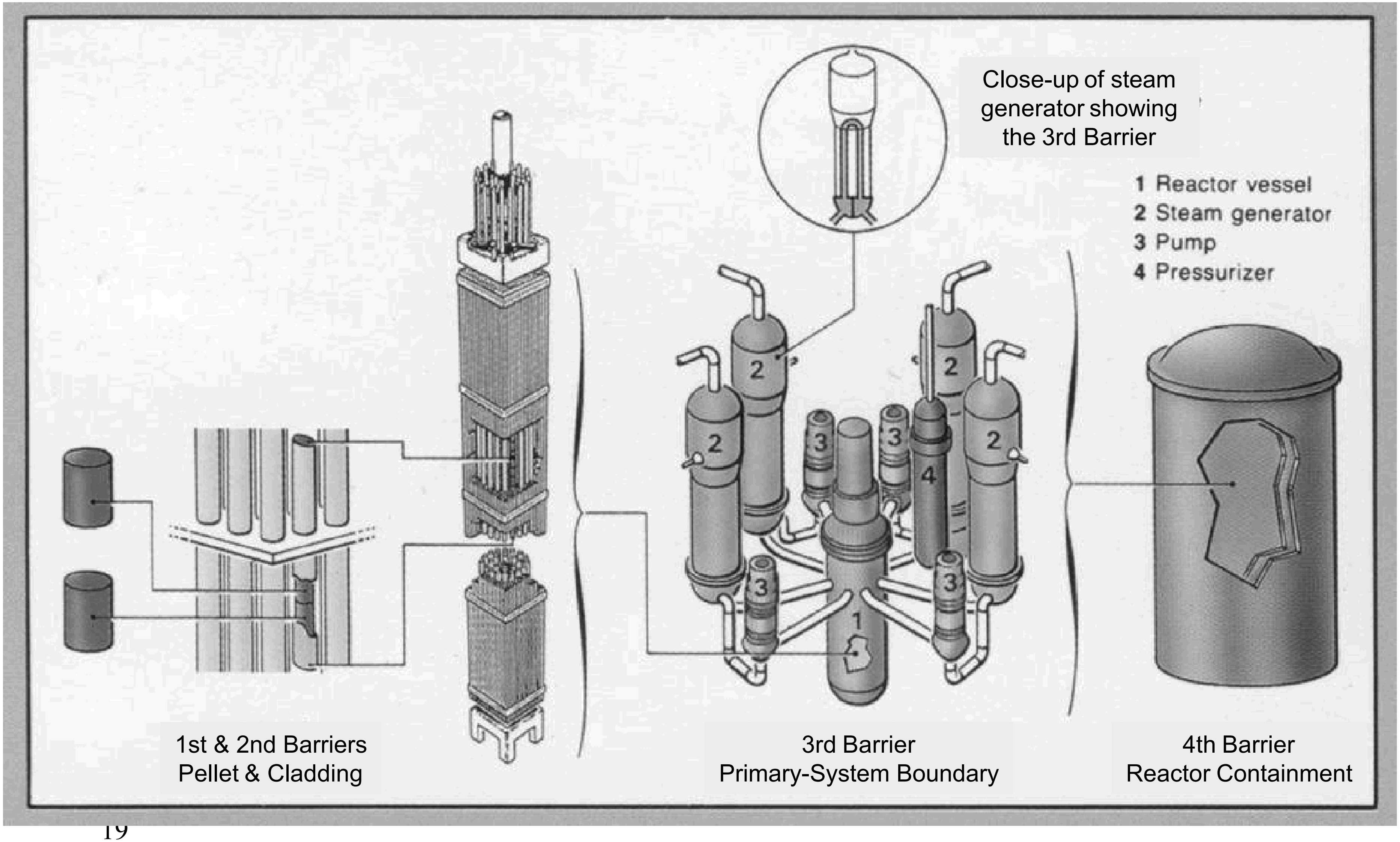
1. To contain fission products to prevent offsite health effects
2. To ensure that heat generated by the reactor, including heat generated by the decay of fission products after reactor shutdown, is removed

Three guiding principles:

- Defense in depth
- Negative feedback
- Passive cooling (mostly next generation)

Engineered Safety

Multiple Barriers to radioactive release

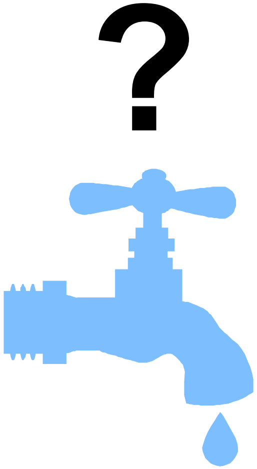


Next generation power reactor designs

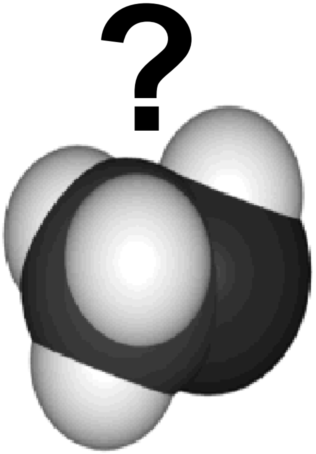
Safety

Waste control

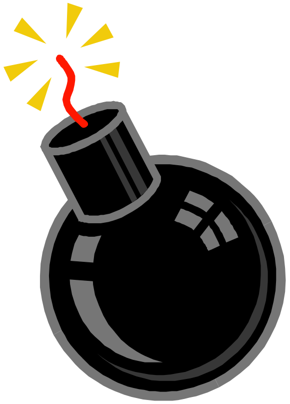
Economy



Fuel supply

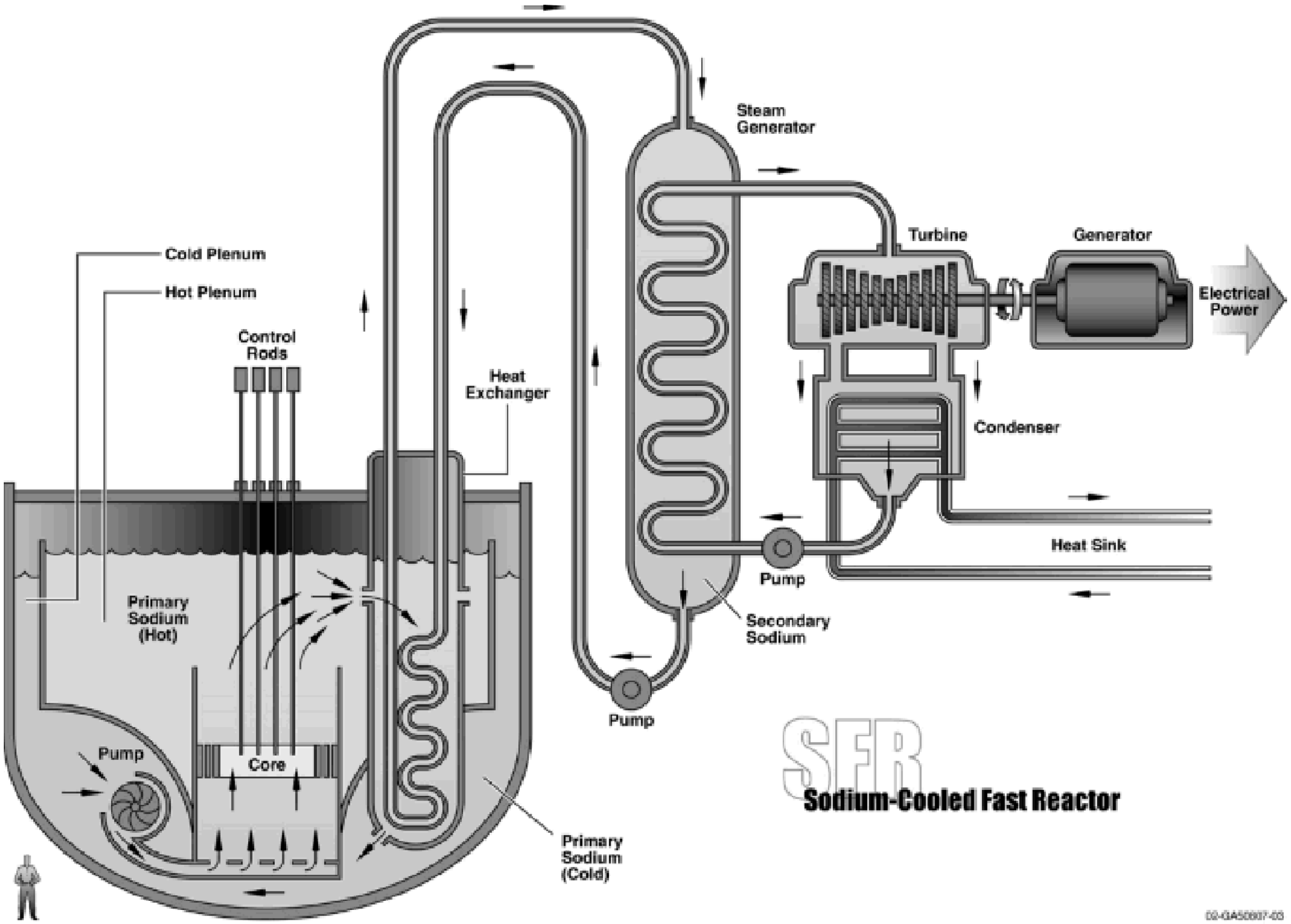


Hydrogen production



Proliferation and terrorism resistance

Sodium cooled fast reactor has low technical risk



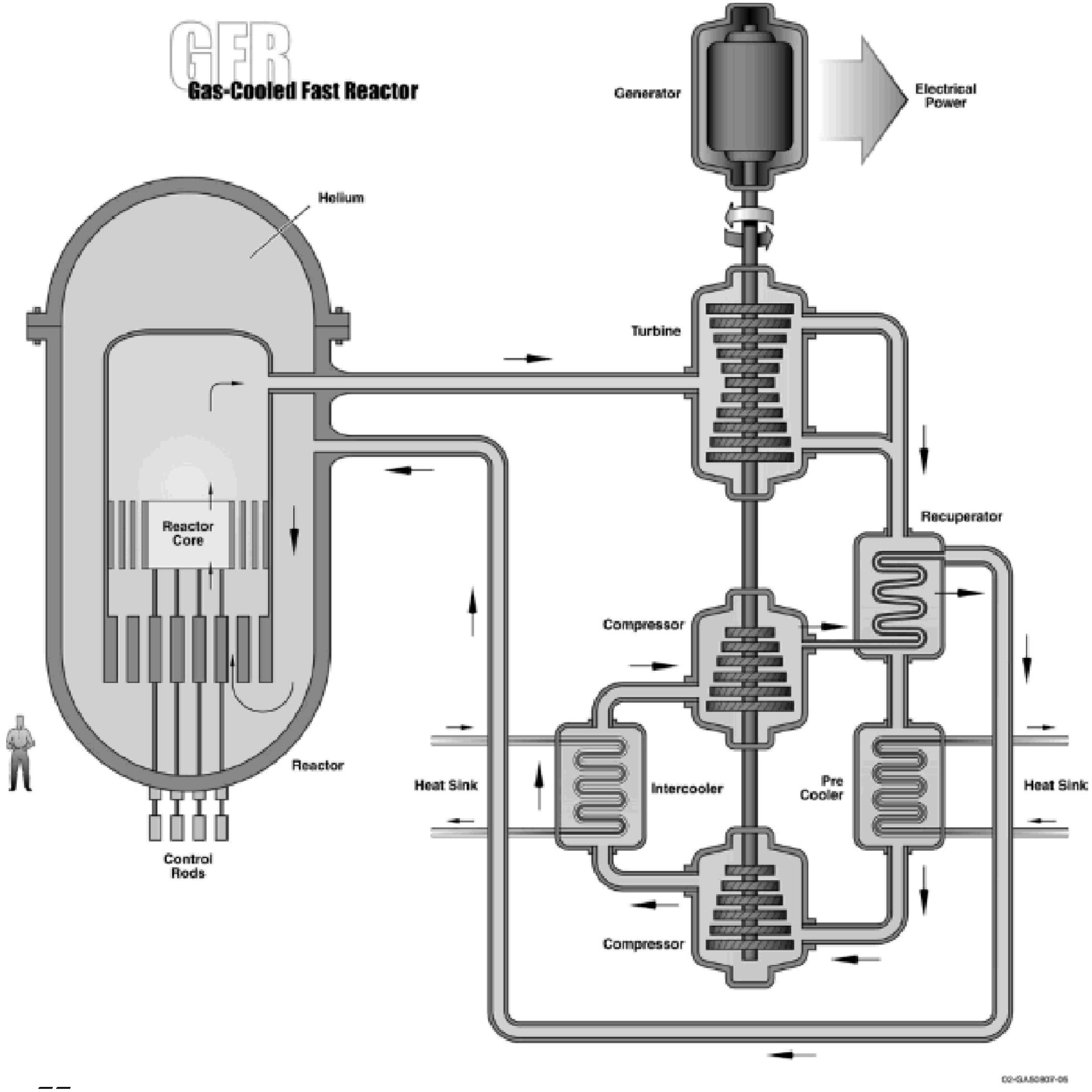
Liquid sodium coolant.
High thermal inertia.
Fast neutrons.
Supercritical CO2 turbine

Natural uranium fuel.
200-1500 MW.
530-550^{o}C.
Low pressure.
Passive safety tested.

Needs reprocessing.
Burns actinides.

Used in UK, Rus, Fra,
Ger, Jap & (prior) US.

Gas Cooled Fast Reactor is Efficient



Helium gas turbine, with Brayton cycle.

Fast neutrons.

48% efficiency.
490^{o}C/850^{o}C in/out.

U_{238}, Th, Pu fuel.

Actinide recycling.

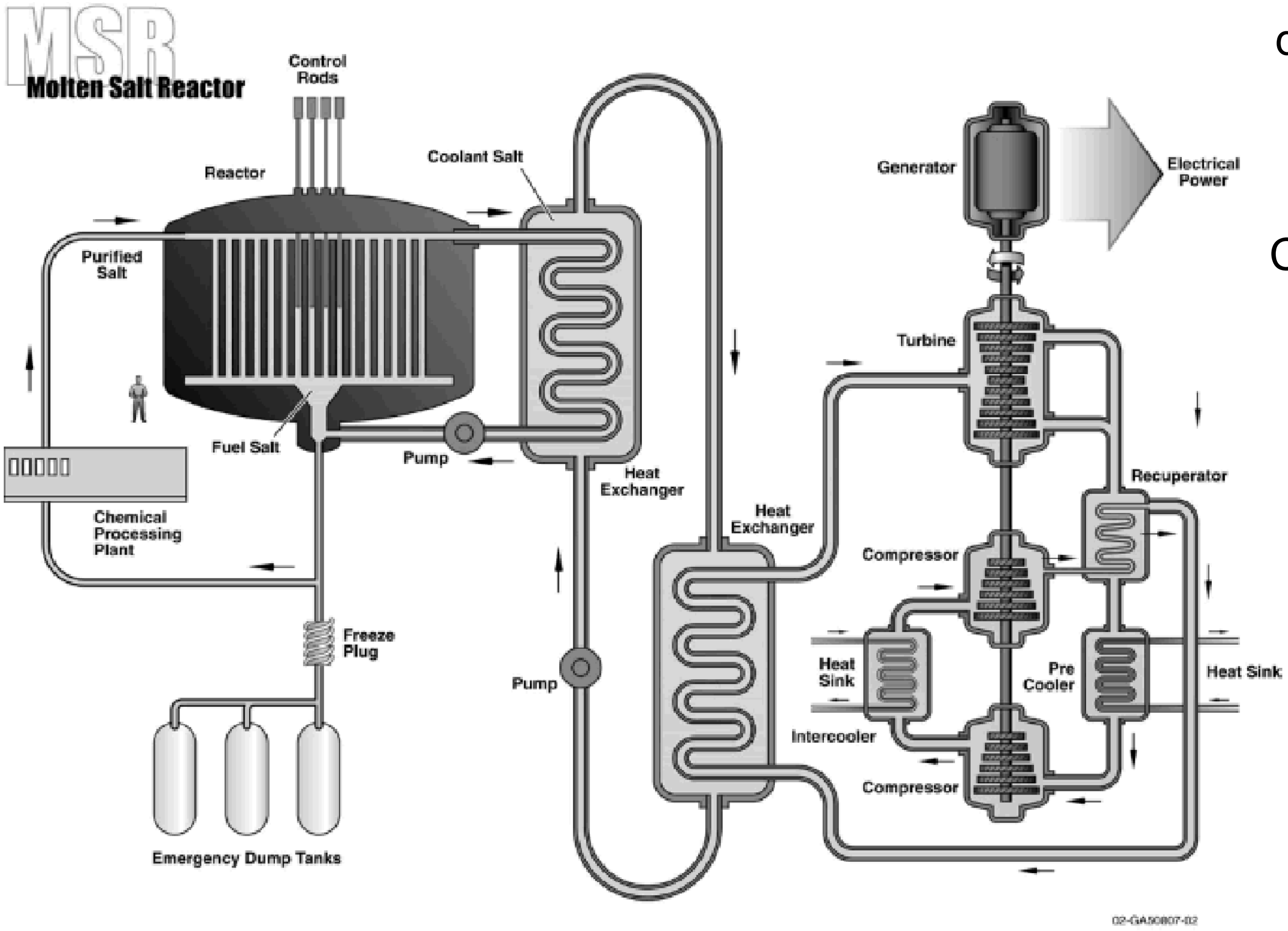
Assumes on-site spent fuel reprocessing plant.

Low radioactive waste.

High volume of waste

http://nuclear.inl.gov/gen4/docs/gen_iv_roadmap.pdf

Molten salt reactor fuel is liquid



U or Pu fluoride, dissolved in molten Na or Zr fluoride.

Actinide burning. Convert U238 or Th232.

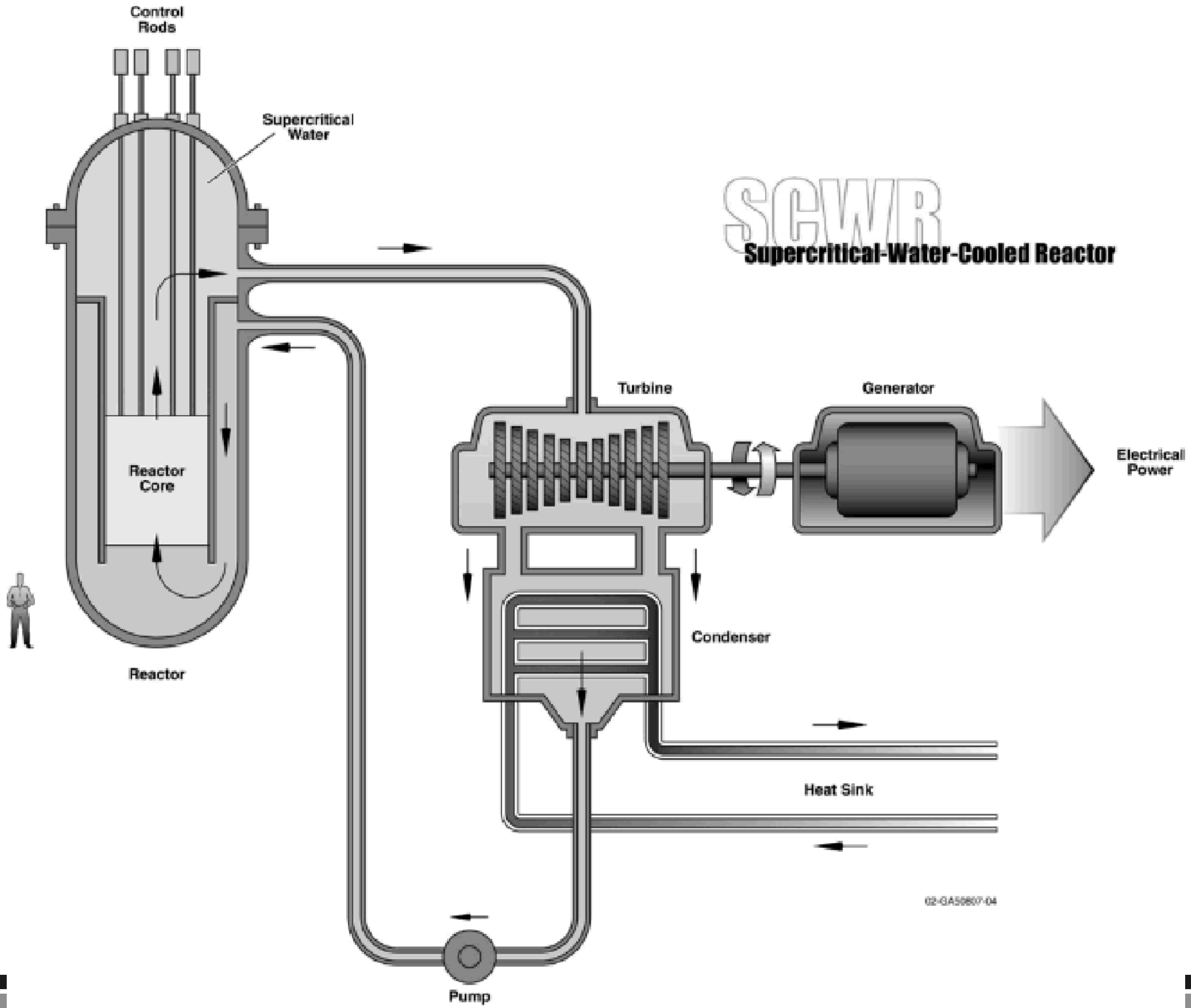
1000 MW.

450-800^{o}C.
Sodium @ ~1 atm.

Graphite moderated.

1954 US ARE aircraft engine experiment.

Supercritical Water Reactor needs no steam generator



SCWR

Supercritical water.
>200 atmospheres.
>374^{o}C.
No phase changes.
44% efficiency.

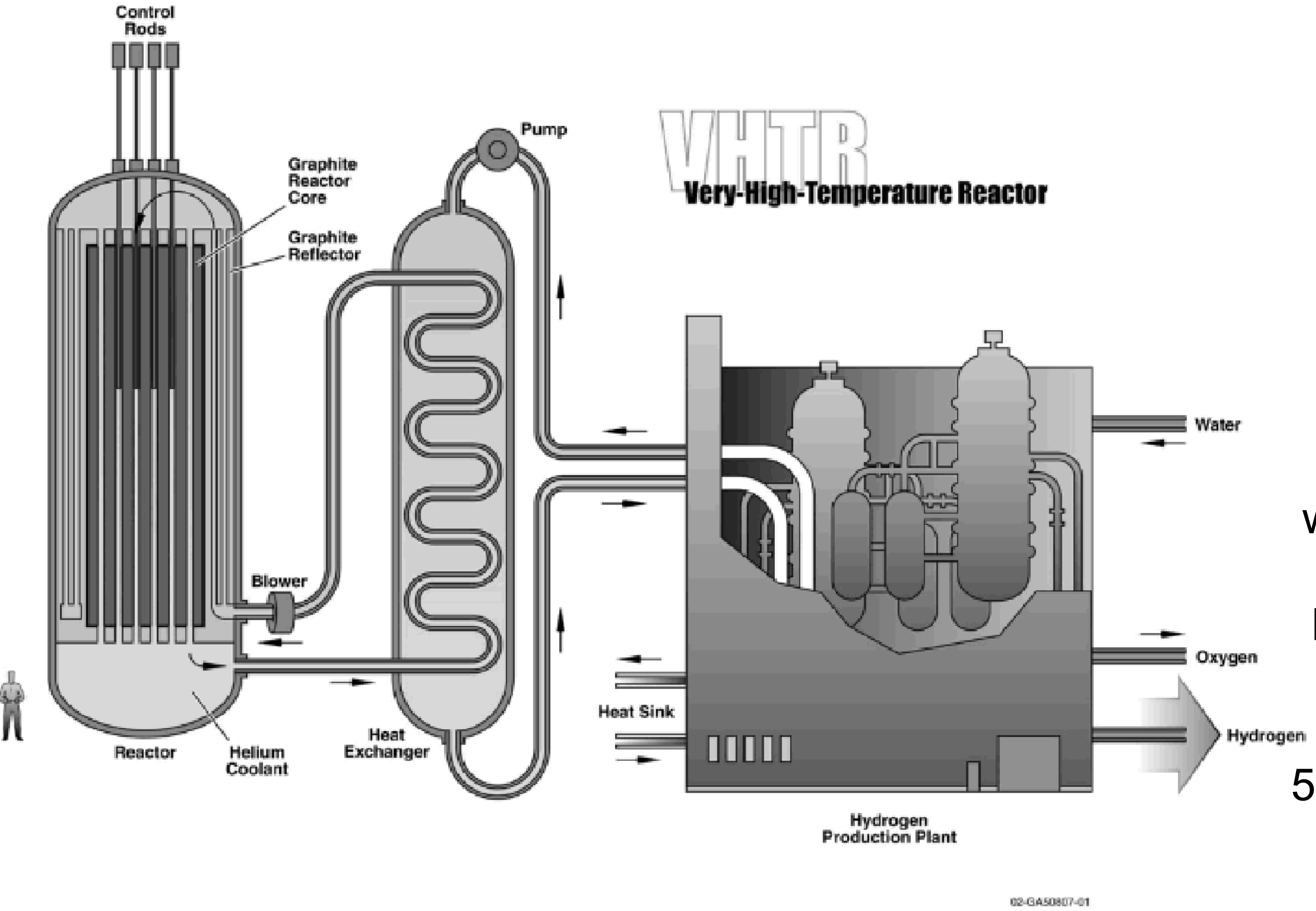
Water moderated.

Fast or thermal neutrons.

1700 MW.
Fewer components.
Low $/W capital cost.

Material Issues

Very High Temperature Reactor



Helium gas cooled.
Graphite moderated.
Thermal neutrons.
Coated fuel particles.
Once-thru LEU fuel.
1000^{o}C.
50% efficiency.

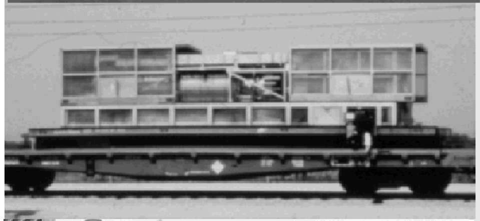
Hydrogen production
with sulfur-iodine cycle.

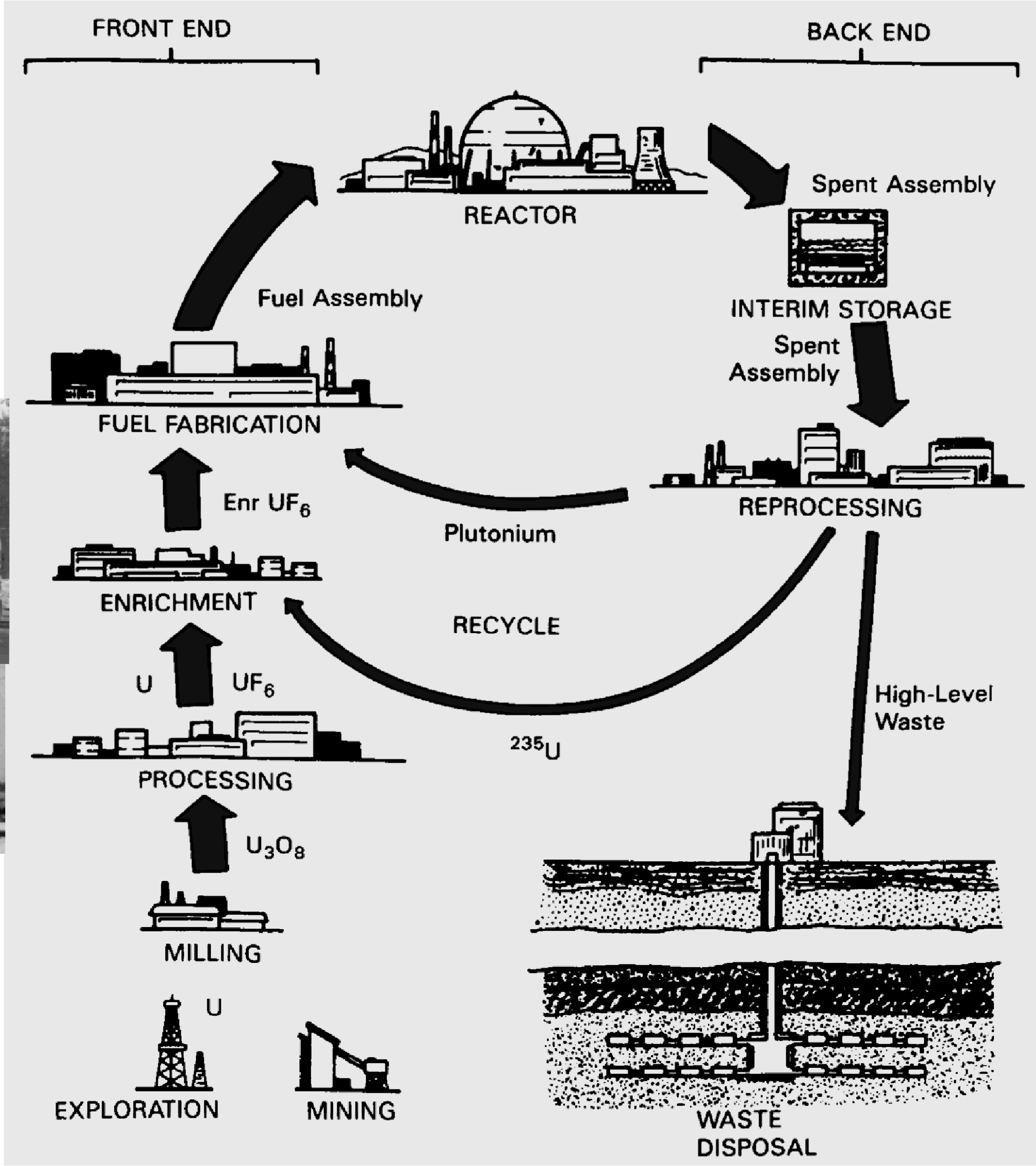
No IHX for direct cycle
electric turbine.

5 prior US HTGR plants.
Like PBR.

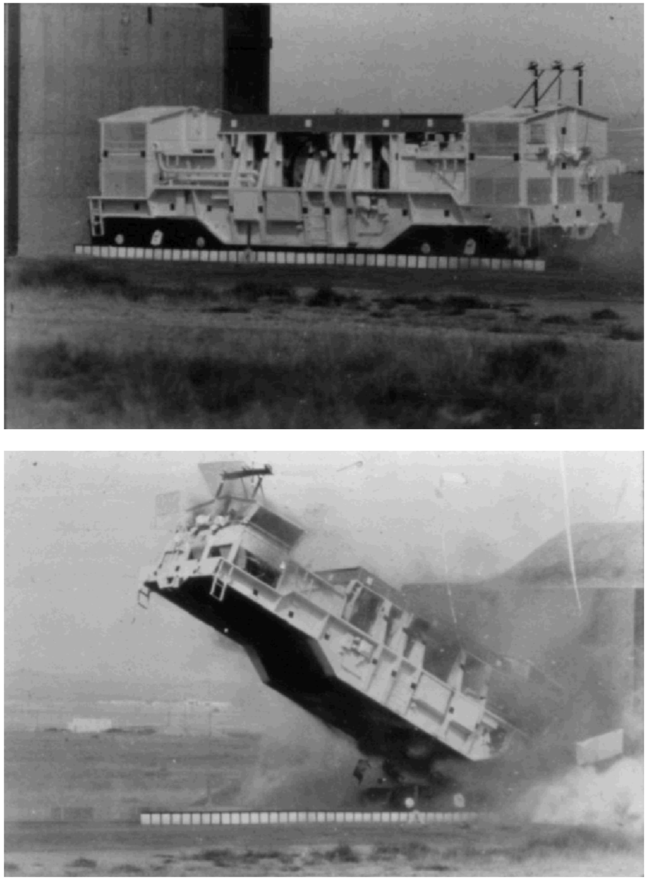
Material Issues

LWR Fuel Cycle



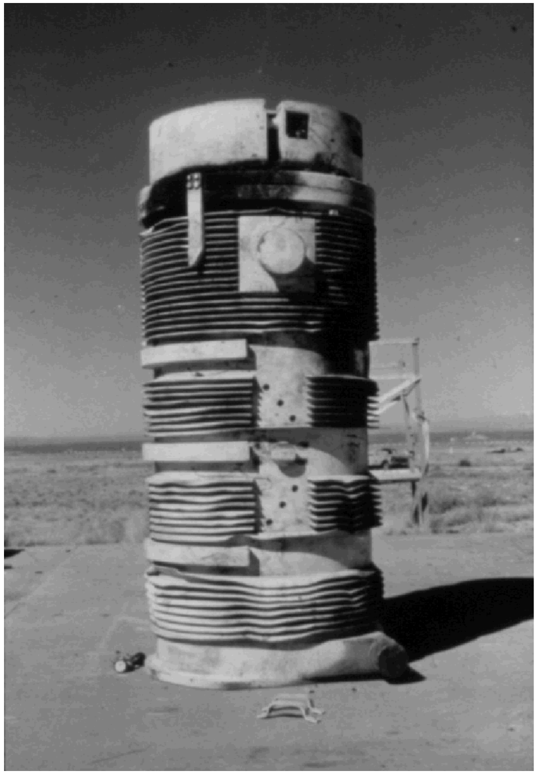


Cask Crash Tests



80 mi/hr Crash

125-min. JP-4 Fuel (980-1150°C) Burn



Minimal Damage
No Leakage

Economic Considerations

- **Fuel Costs**
  - minor part of electricity cost
- **Capital Costs**
  - greater for nuclear compared with coal and gas
- **Operation and Maintenance Costs**
  - labor and overheads
  - expendable materials, taxes, etc.
  - regulatory costs
- **Waste Costs**
  - High uncertainty
- **Decommissioning Costs**

<u>Capital cost example (2008 $/kW)</u>

Nuclear: 4000

Supercritical coal: 2200

Supercritical coal +CCS: 4000

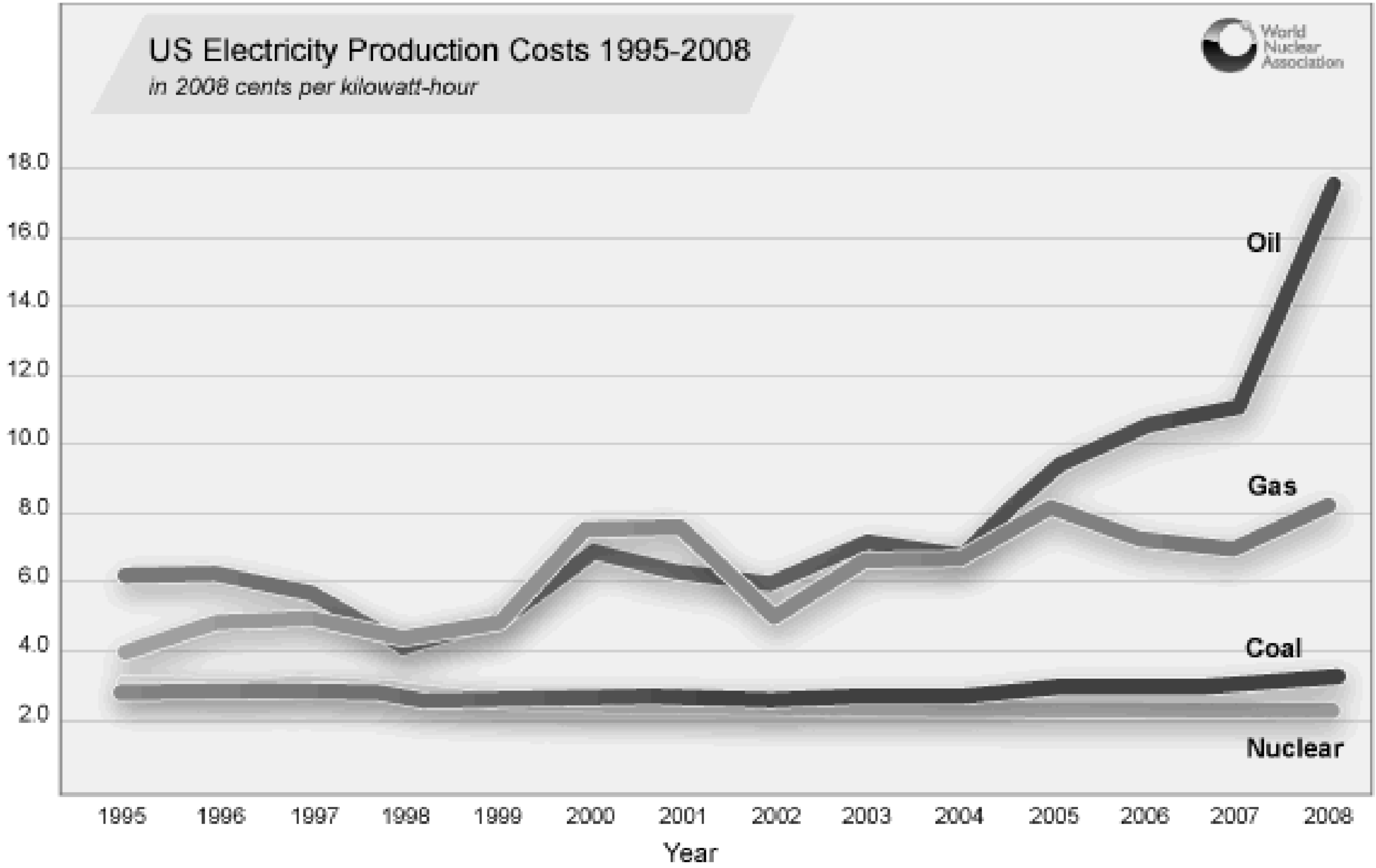
IGCC: 2600

IGCC + CCS: 3400

Gas combined cycle: 870

Gas combined cycle + CCS: 1600

US Production Costs



Production Costs = Operations & Maintenance + Fuel. Production costs do not include indirect costs or capital.

Source: *Ventyx Velocity Suite, via NEI*

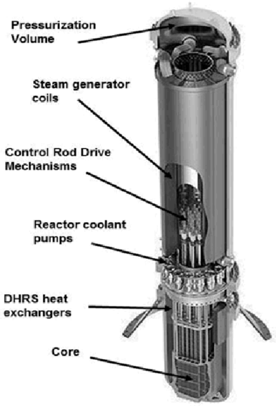
Domestic Small Modular Reactor (SMR) Interest

- Value Proposition
  - Enhanced safety and security
  - Reduced capital cost before generating revenue makes nuclear energy accessible for more utilities/electrical coops/minimum grid
  - Shorter construction schedules due to modular construction
  - Improved quality due to replication in factory-setting
  - Meets electric demand growth incrementally
  - Meets base-load demand electricity demand and other needs (e.g., coal plant replacement, heating/cooling, water desalination)
- Market Drivers
  - Provides a solution to markets that have smaller electrical demand and infrastructure
  - Distributed Power Generation requiring less long distance transmission
  - Responds to markets where electricity demand is projected to increase incrementally
  - Modular construction would overcome skilled workforce issues
  - Require less capital outlay than for larger plants
  - Provide clean, base-load electricity to markets responding to climate and environmental goals

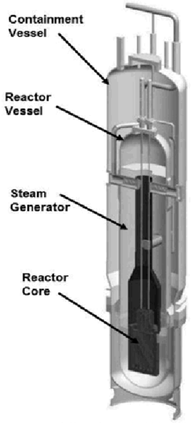
Small Modular Reactor Technology

Near-Term LWR Designs

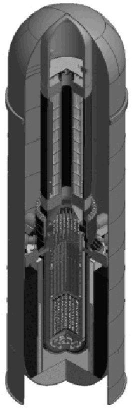
- Well Understood Technology
  - LWR based designs
  - Standard <5% UO2 fuel
  - Regulatory & operating experience
  - Prototype may not be required
  - Deployment by 2020



mPower (Babcock & Wilcox)
125 MWe



NuScale (NuScale)
45 MWe

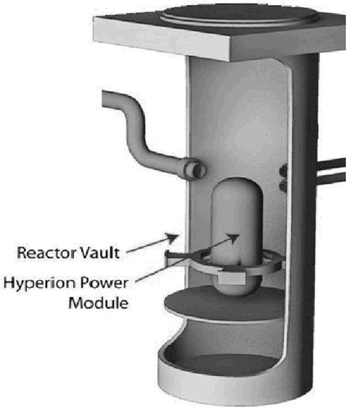


Westinghouse
~200 MWe

Longer-Term SMRs

- New Innovative Technologies
  - Mostly non-LWR based designs
  - Prototypes will be required
  - Deployment 15-20 years
- Broader Applications
  - Process heat applications
  - Transportable/mobile
  - Long-lived cores

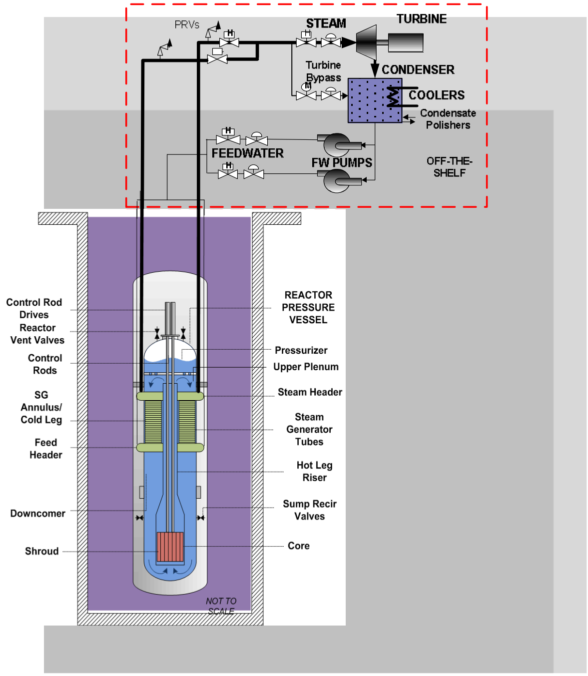
GE PRISM
320 MWe

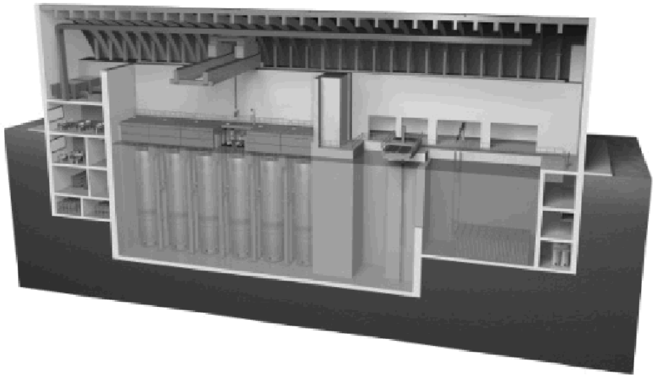


Hyperion
25 MWe

The SMR Safety Case

- Primary system components in a single vessel
- Increased coolant inventory in primary reactor vessel
- Increased pressurizer volume
- Smaller radionuclide inventory
- Cooling of core and vessel by natural convection
- More effective heat removal
- Lower power heat decay
- Below-grade reactor vessel and spent fuel pool
- Enhanced resistance to seismic events





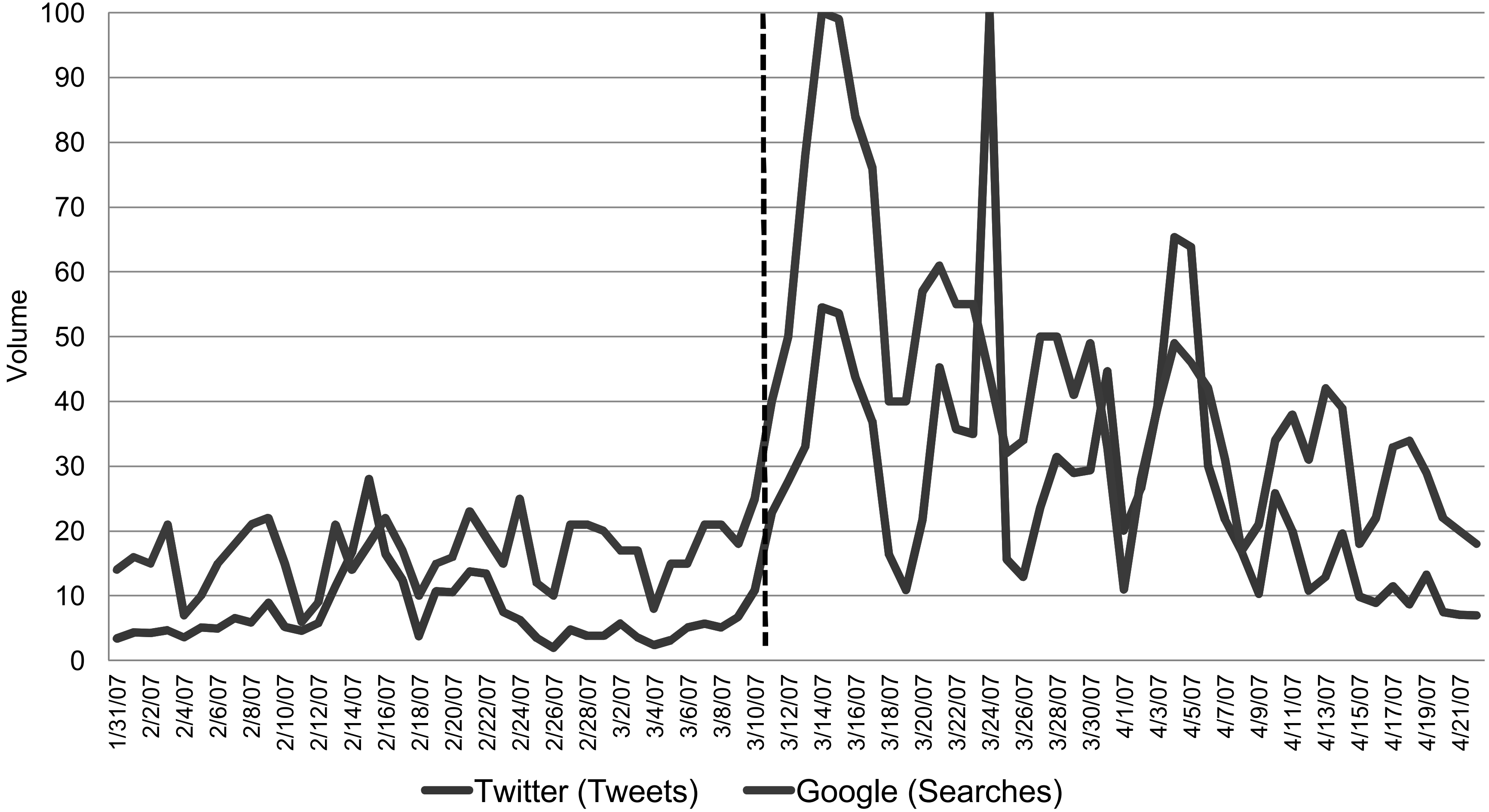
Schematics Courtesy of NuScale Power, Inc.

SMR Plant vs. Fukushima-Type Plant

Fukushima	SMR*
Reactor & Containment	
Emergency Diesel Generators Required	None Required
External Water Supplied Required	Containment submerged in 30-day water supplied
Coolant Supply Pumps Required	None Required
Forced flow of water required for long-term cooling	Long-term (>30 days) cooling by natural convection to air
Spent Fuel Pool	
High density Fuel Racks	Low density fuel racks
Water cooling	Water or air cooling
Elevated spent fuel pool	Below-grade spent fuel pool
Standard Coolant inventory	Large coolant inventory (4 x water/MW power)

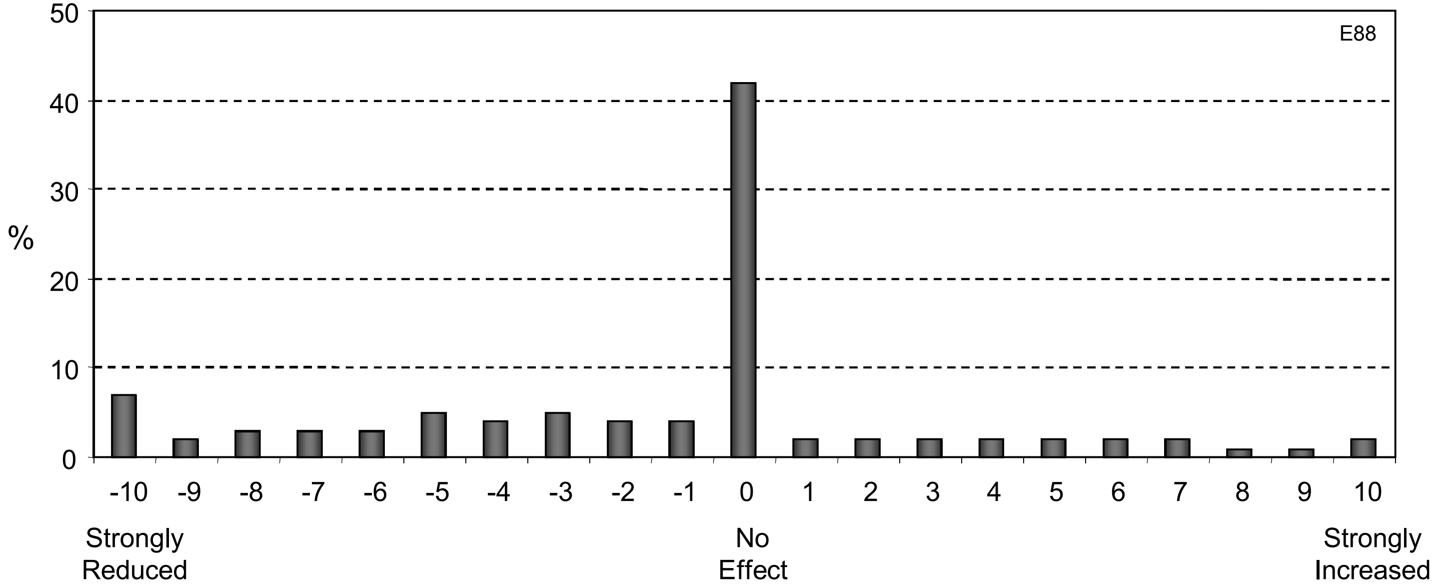
* Information based on NuScale plant courtesy of NuScale Power, Inc.

Nuclear Waste on Google and Twitter: The Fukushima Effect



Survey Measurement: Stated Effects of Fukushima

"How has the recent Japanese experience at Fukushima affected your support for nuclear power production in the United States?"



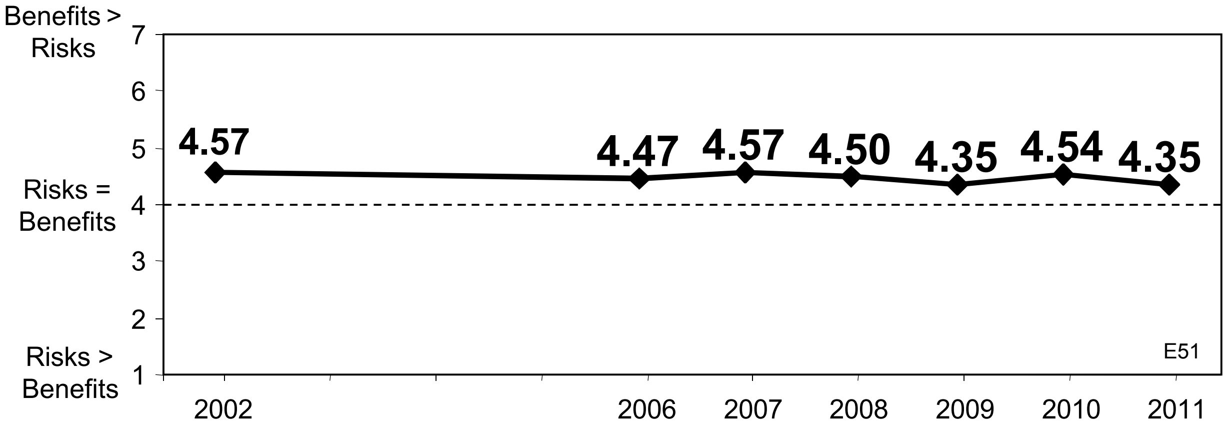
Mean: 2011

–1.41

Reduced Support : 40%   No Effect: 42%   Increased Support: 18%

Nuclear Energy Risks & Benefits

Mean Balance of Nuclear Energy Risks and Benefits



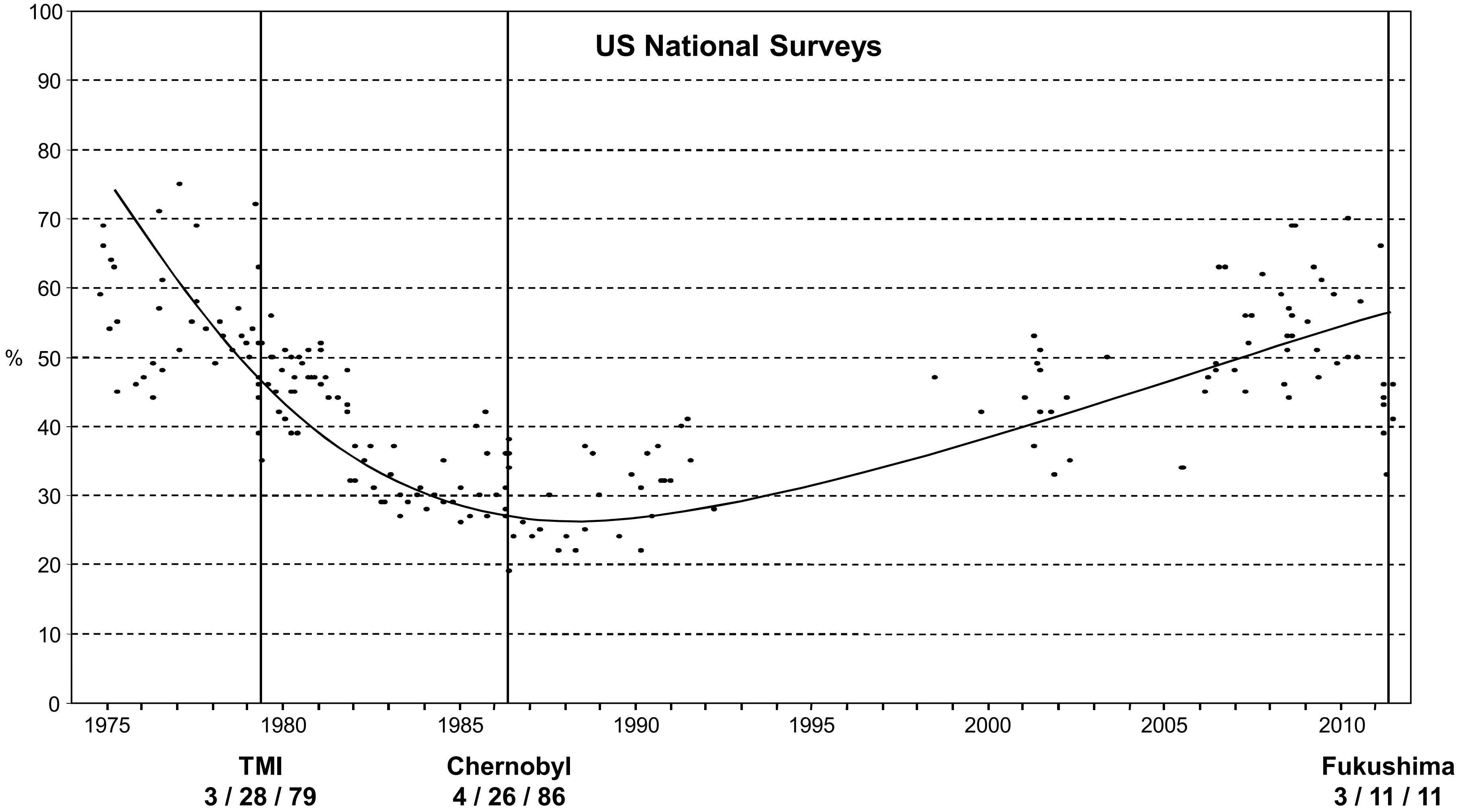
2010 vs. 2011
–0.19
$p < .0001$

Risk & Benefit Components: 2010–2011

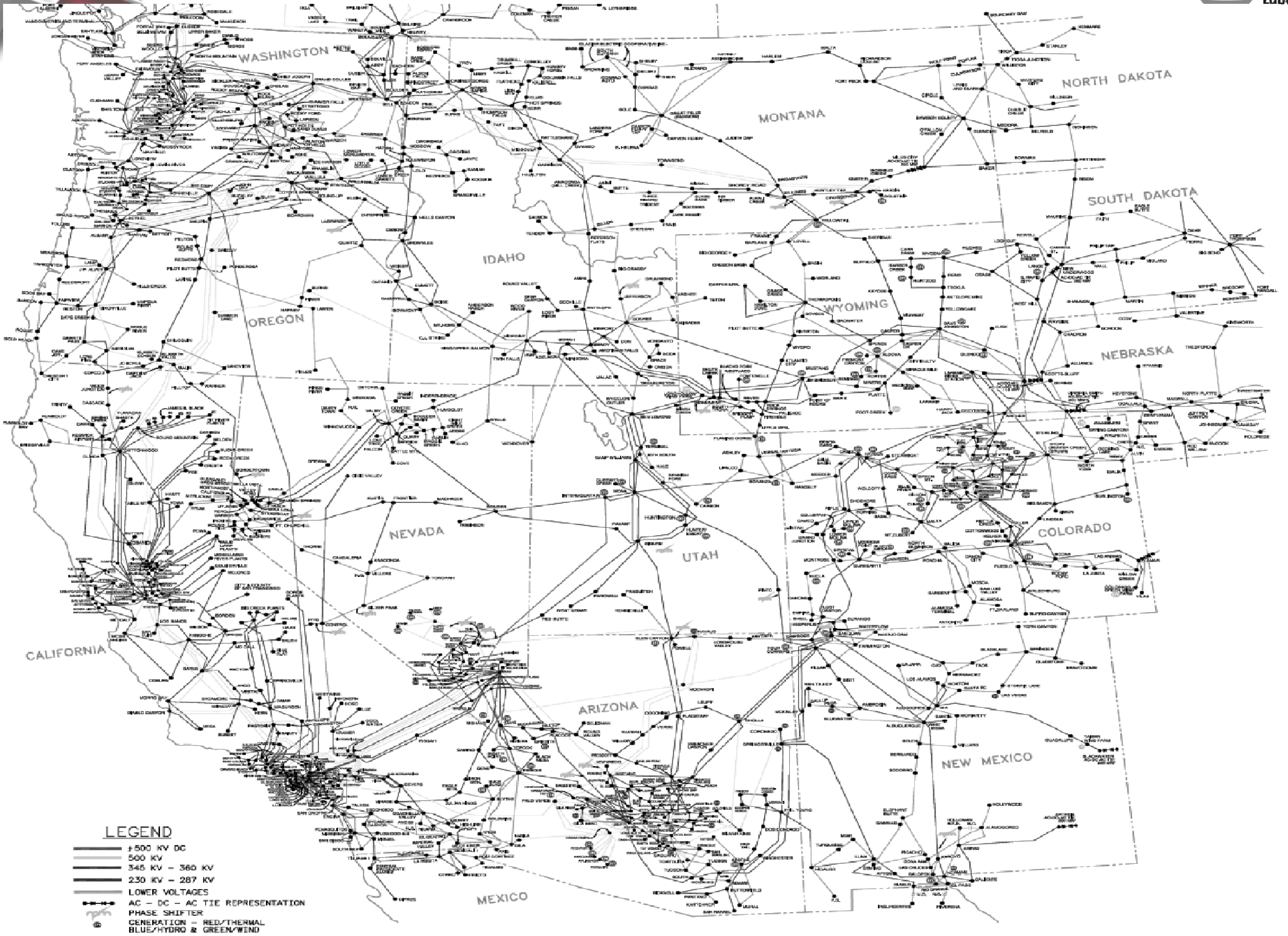
0 = No Risk— 10 = Extreme Risk	2010	**2011**
Terrorist attack	6.72	**6.70**
Operational accident	6.19	**6.37**
Transportation accident	6.23	**6.16**
Diversion to weapons	5.63	**5.60**

0 = Not At All Beneficial— 10 = Extremely Beneficial	2010	**2011**
Energy independence	7.41	**7.13**
Reliable power	7.25	**6.94**
Less mining / extraction	7.10	**6.84**
No GG emissions	7.06	**6.76**

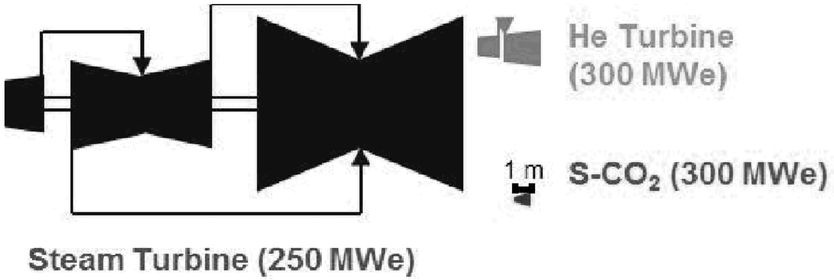
Support for More Nuclear Generation

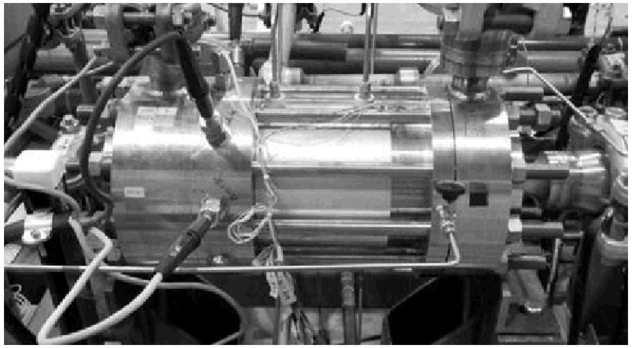


The Problems with Transmission

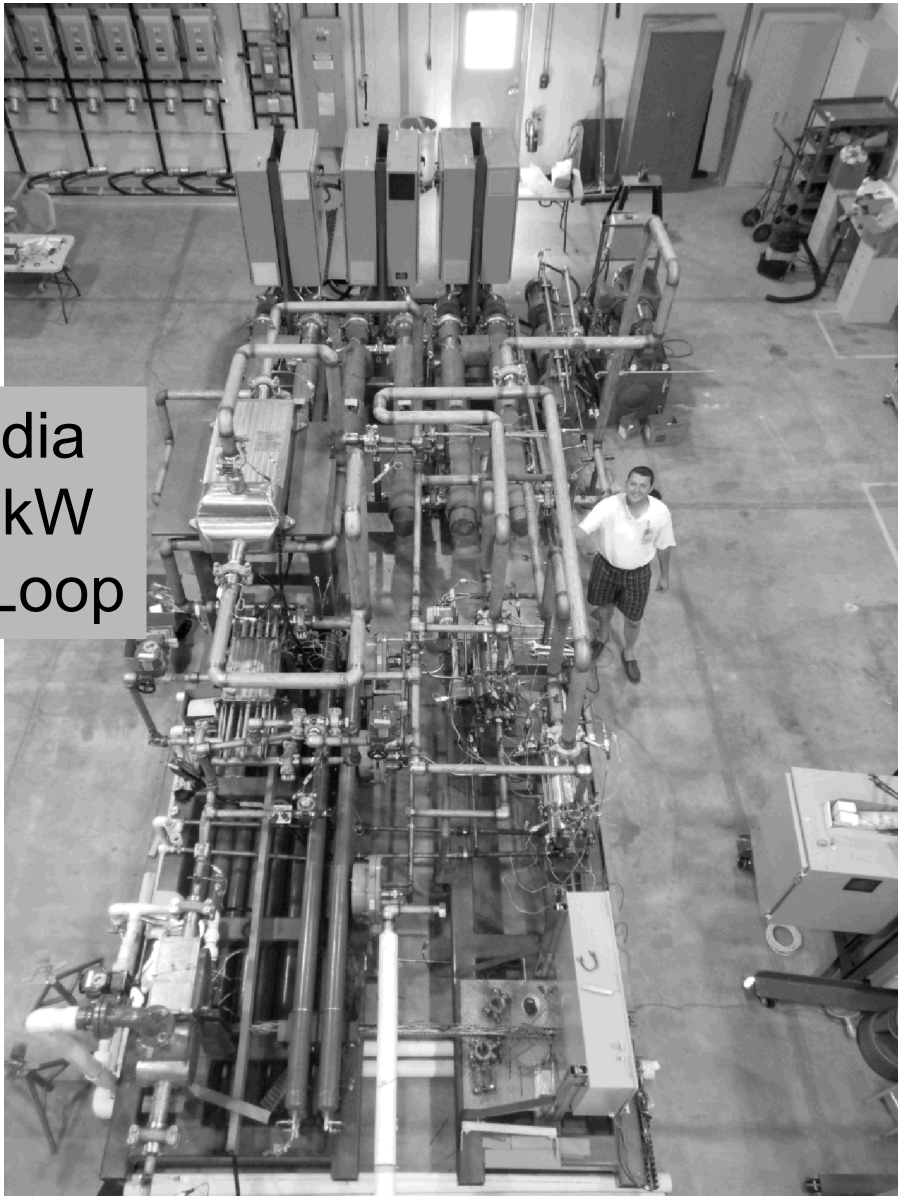


Supercritical CO_2 Brayton Cycle



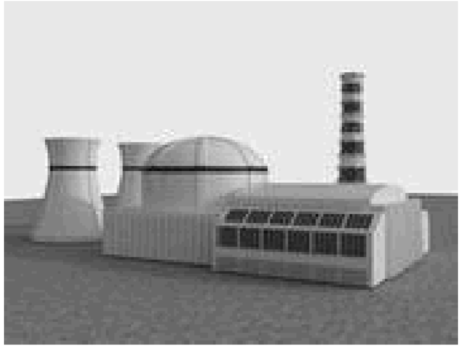


Sandia
250 kW
Test Loop

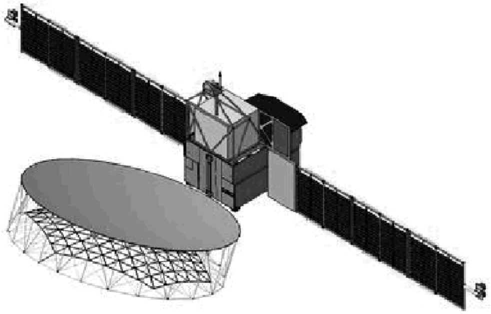


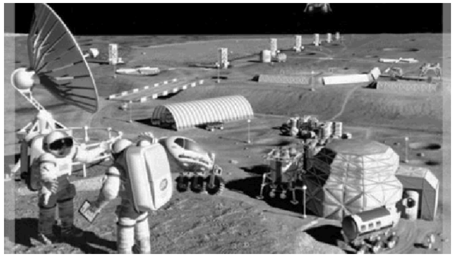
50% Higher Efficiency,
1/100th of the volume,
1/10th the cost
Of Conventional Steam
Cycles

Field of Use Explored

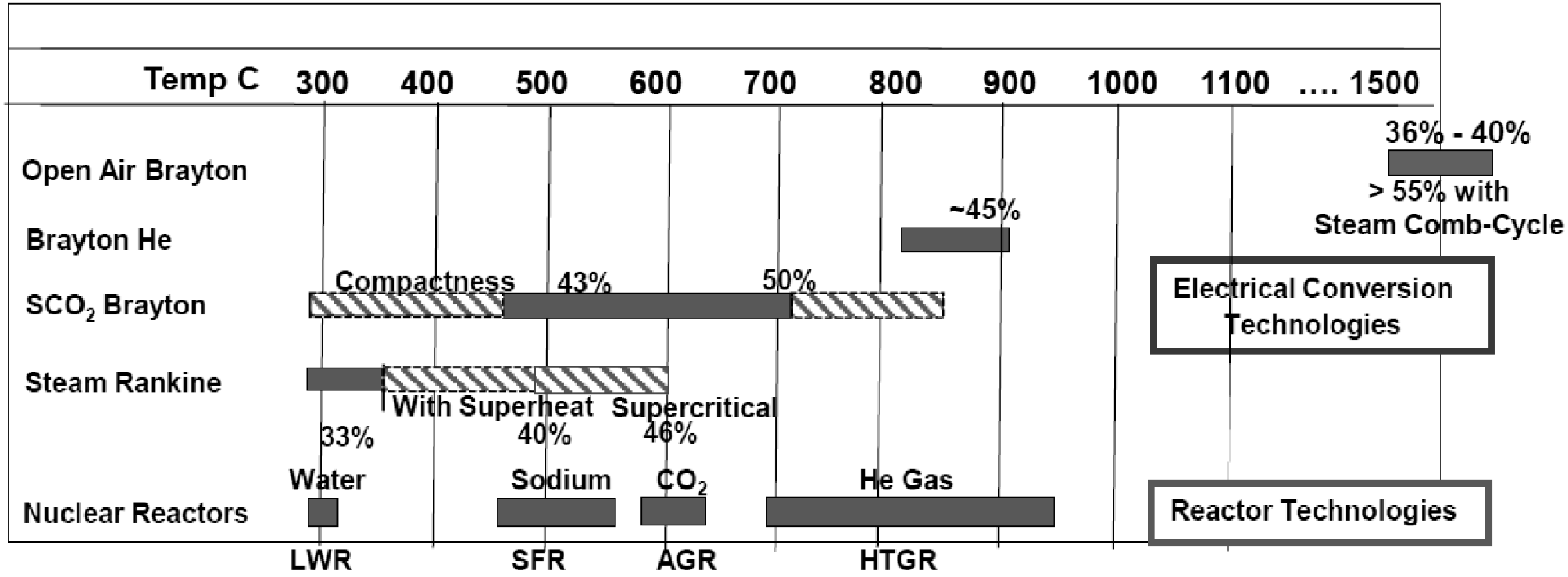


- Light Water Reactors (1000 MWe)
- Sodium Fast Reactors (500 MWe)
- High Temperature Gas Reactor (750 MWe)
- Molten Salt Reactor (1000 MWe)
- Small Modular Reactors (50 MWe)
- Maritime Propulsion (100-250 MWe)
- Concentrated Solar Power (10-150 MWe)
- Geothermal (50-150 MWe)
- Fossil Energy (500-1000 MWe)
- Advance Coal Combustion/Carbon Sequestration (500 MWe)
- Space Nuclear Propulsion
- Solar Electric Propulsion (250 KWe)



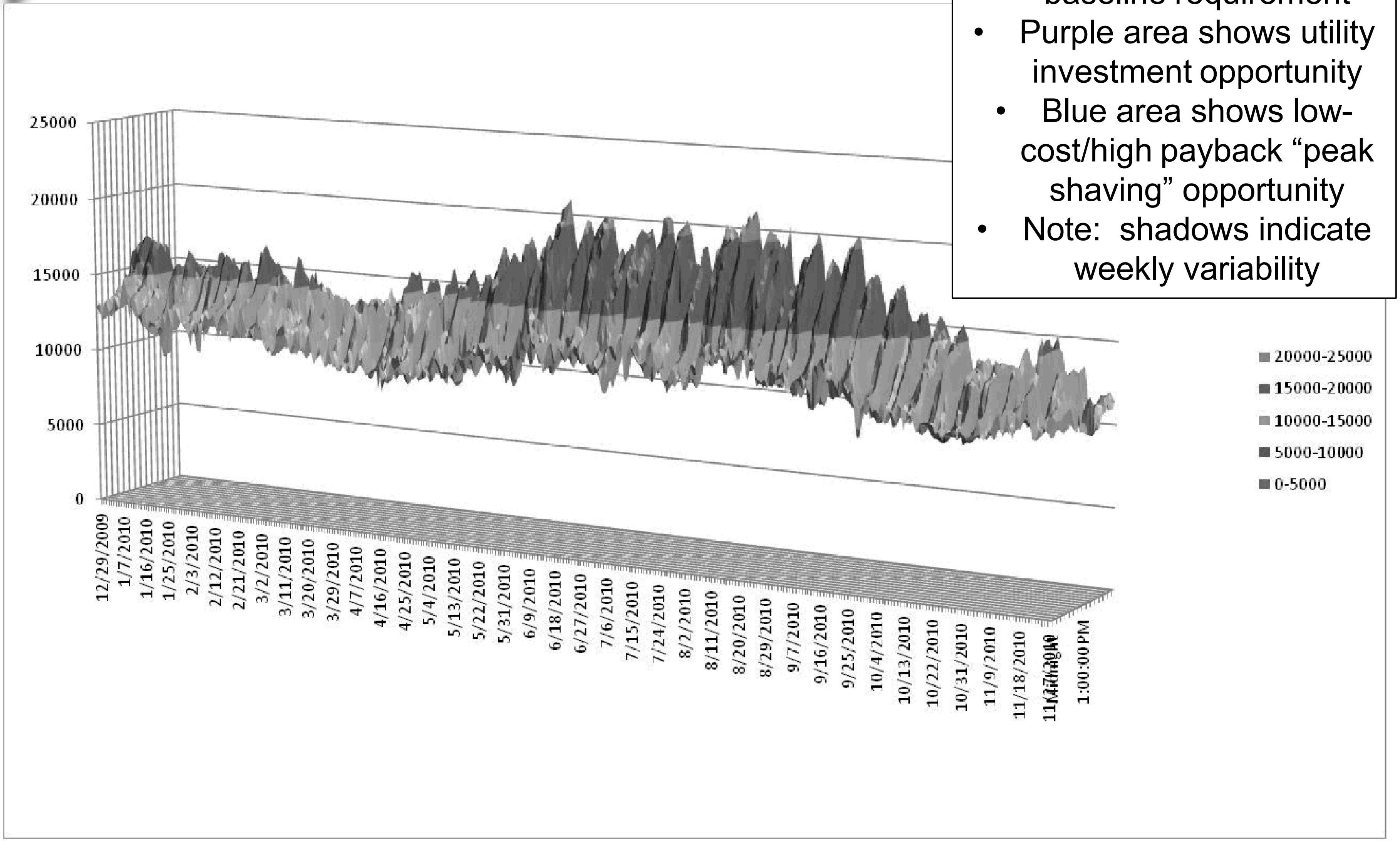


Power Conversion and Nuclear Reactor Outlet Temperature Ranges



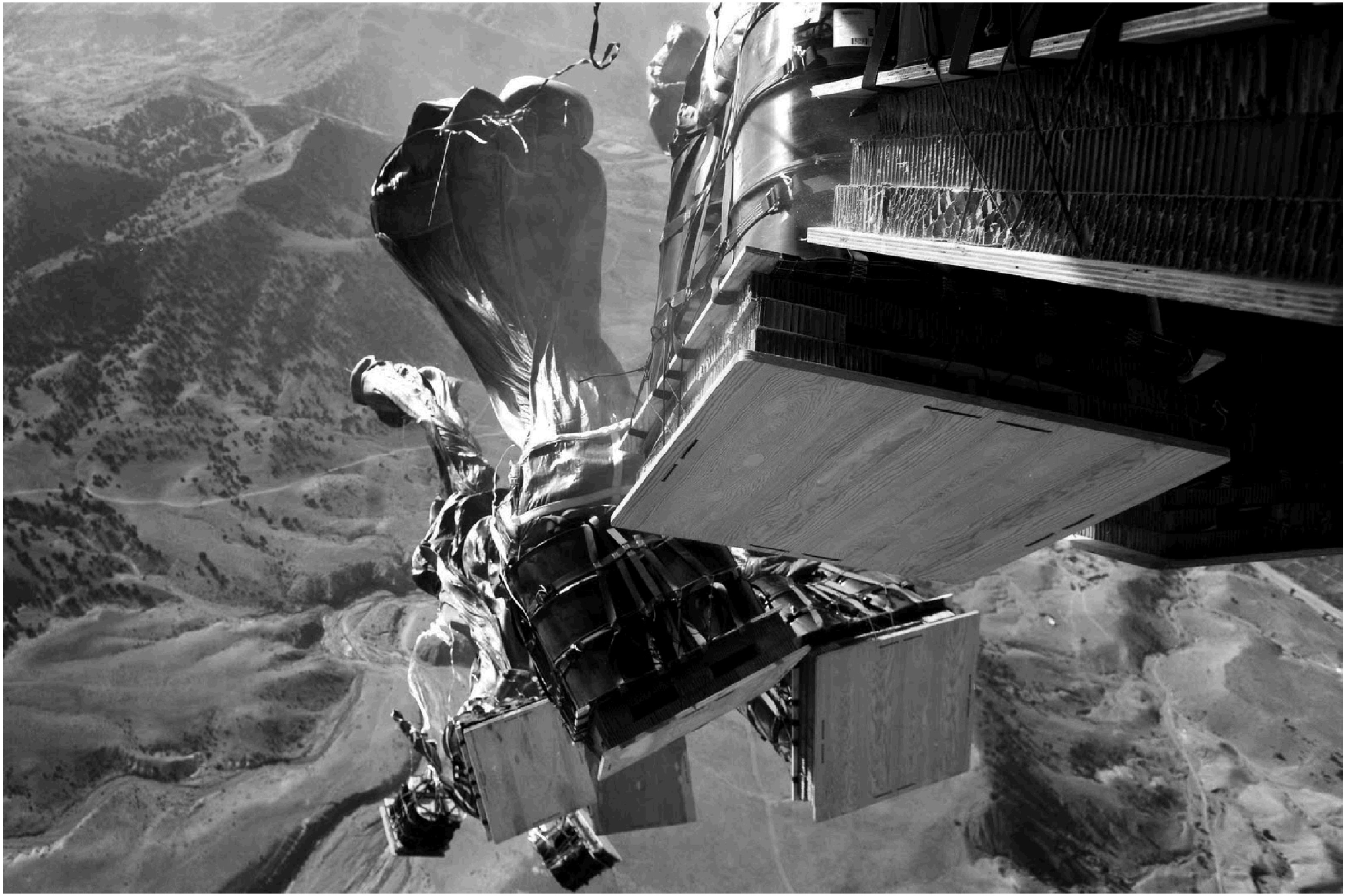
S-CO_2 Power Conversion Operating Temperatures Matches all Advanced Reactor Concepts
LWR – compactness, condensing cycle appear promising
LWR- highly efficient with S-CO2 Condensing Power Cycles

Behind the Meter Opportunities



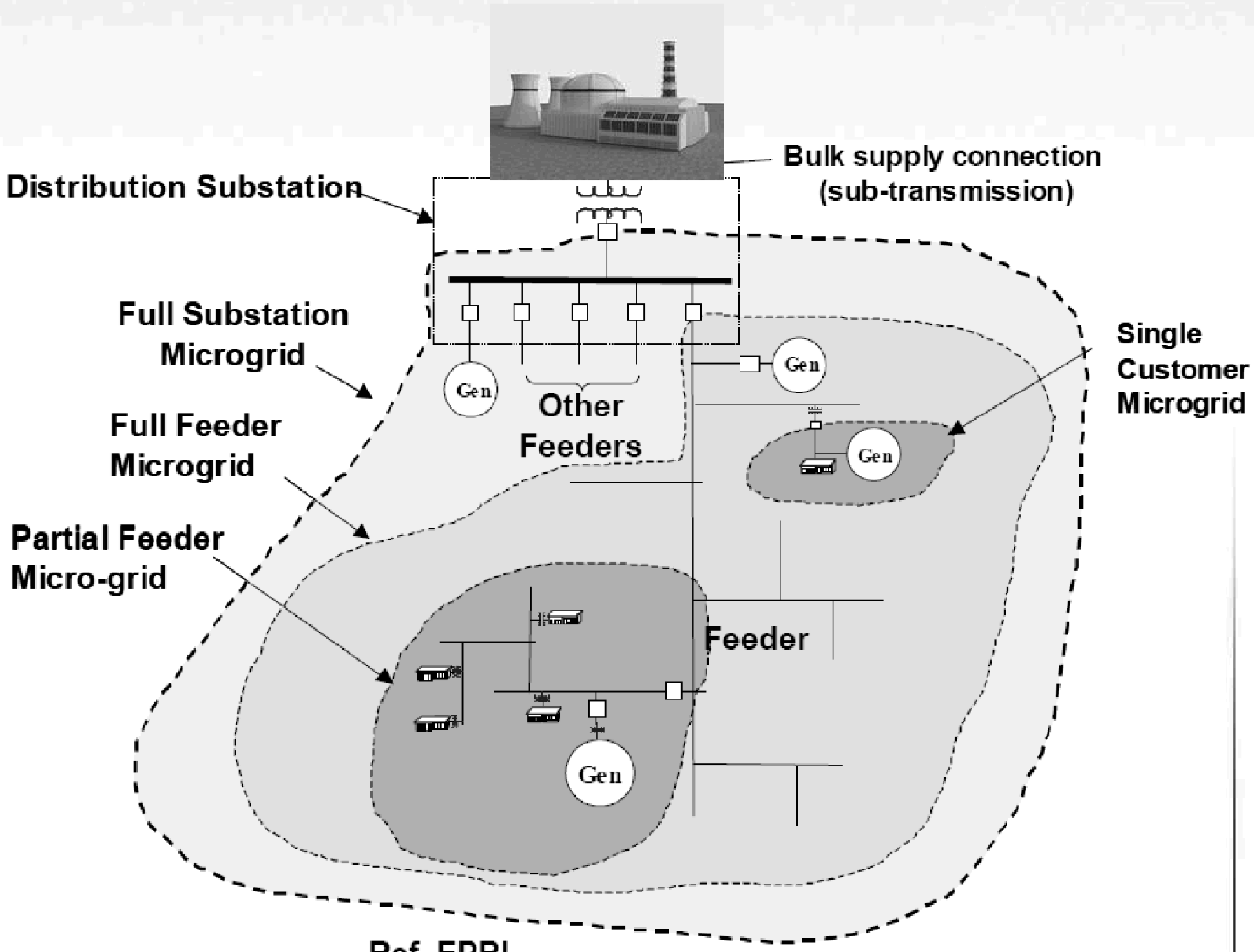
- Green area shows baseline requirement
- Purple area shows utility investment opportunity
- Blue area shows low-cost/high payback “peak shaving” opportunity
- Note: shadows indicate weekly variability

Advance Designs for CONUS and FOB



Use Renewable and Distributed Generation to Support DoD Microgrids and the Smart Grid

- Small combustion and μ-turbines
- Fuel cells
- IC engines
- Small hydro and wind
- Solar electric and solar thermal
- Energy storage (batteries, flywheels,…)
- Plug in hybrid vehicles
- Small nuclear power



Distribution Substation

Bulk supply connection (sub-transmission)

Full Substation Microgrid

Full Feeder Microgrid

Partial Feeder Micro-grid

Single Customer Microgrid

Other Feeders

Feeder

Ref. EPRI

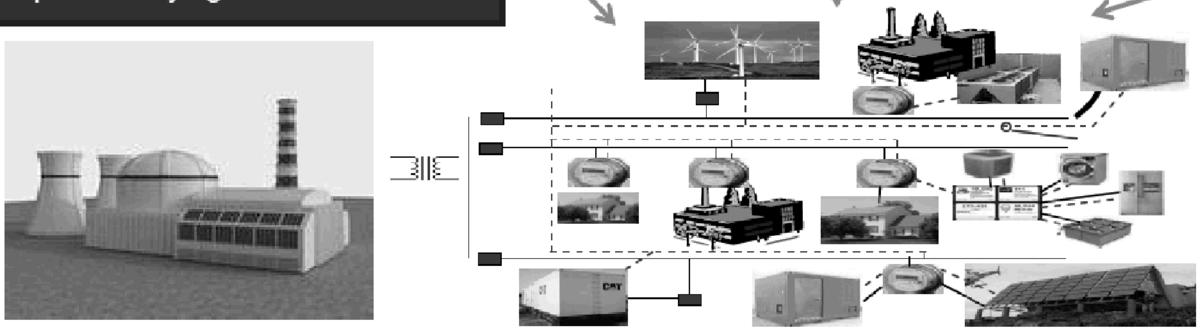
Residential	Less than 10-kW, single-phase
Small Commercial	From 10-kW to 50-kW, typically three phase
Commercial	Greater than 50-kW up to 10MW

JCTD Elements and Example Technologies

Cyber-Security
- Virtual Secure Enclave
- Live Action Network
- Secure Distributed Monitors
- Situational Awareness

Smart Grid
- Advanced Metering Infrastructure
- Substation & Distribution Automation
- Two-Way Communications & Control
- Adaptive Relaying

Islanded Micro-grid
- Load Control Systems
- Islanding Control System
- Energy Management System
- Seamless Grid Synchronization



Independent power source

Energy Secure Installation

Demand Side Management
- Energy Efficiency Technologies
- Dynamic Voltage Regulators
- Smart Sockets
- Automated Load Shedding

Backup Power
- Vehicle-to-Grid
- Fuel Cells
- Batteries

Renewable Integration
- Photovoltaic
- Wind
- Biofuel

Key SMR Safety Assurance Research Needs

- Emergency Planning Zone
  - Technical basis needed for EPZ requirements for smaller cores
  - Preliminary source term and PRA being developed at SNL as the technical basis for this type of analysis
- Operations & Staffing
  - Current NRC regulations based on 1-2 large cores; modular designs with smaller cores need to be examined
  - INL evaluating multi-module facilities operations and staffing issues
- Physical Security
  - Below-grade and smaller cores may reduce physical security and staffing costs
  - SNL applying Integrated Safety, Operations Security and Safeguards (ISOSS) principles to address adequate staffing issues

Conclusions

- Nuclear Technology Benefits:
  - Support energy security, climate change mitigation, & economic growth goals
    - Nuclear power remains a key element of the U.S. energy strategy and portfolio; benefits higher than risks
  - Regain technical leadership and innovation
  - Improve U.S. manufacturing capability and supply chain infrastructure
  - Create high-quality manufacturing, construction, and engineering jobs
  - Become global leader in SMR technology based on mature nuclear infrastructure and NRC certified designs
- Challenges:
  - Define the business case for < 300 MWe baseload plants
  - Demonstrate/validate enhanced safety features
  - Prove economy of mass production
  - Identify Owners/Operators willing to support DoD and commercial requirements