The Nuclear Renaissance in the U.S.

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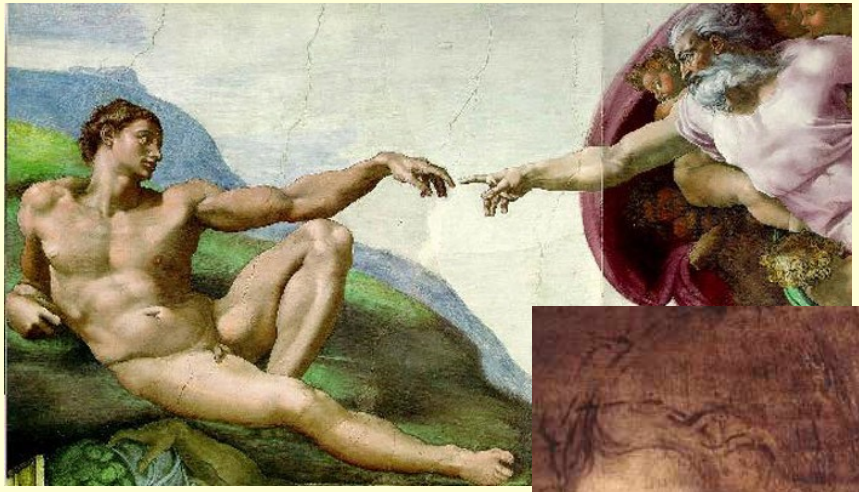
MIT Center for Advanced Nuclear Energy Systems



Renaissance*:
…a renewal of life, vigor, interest... / rebirth, revival…

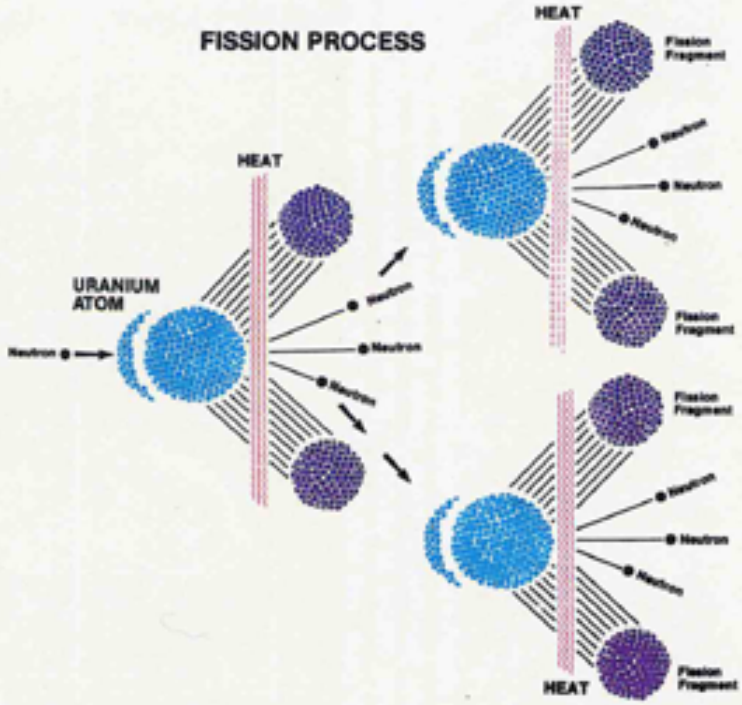
*The Random House College Dictionary

Outline

- Brief nuclear power primer
- Technical features of advanced reactors
- Nuclear power and transportation
- Outstanding challenges to the expansion of nuclear power
- Conclusions

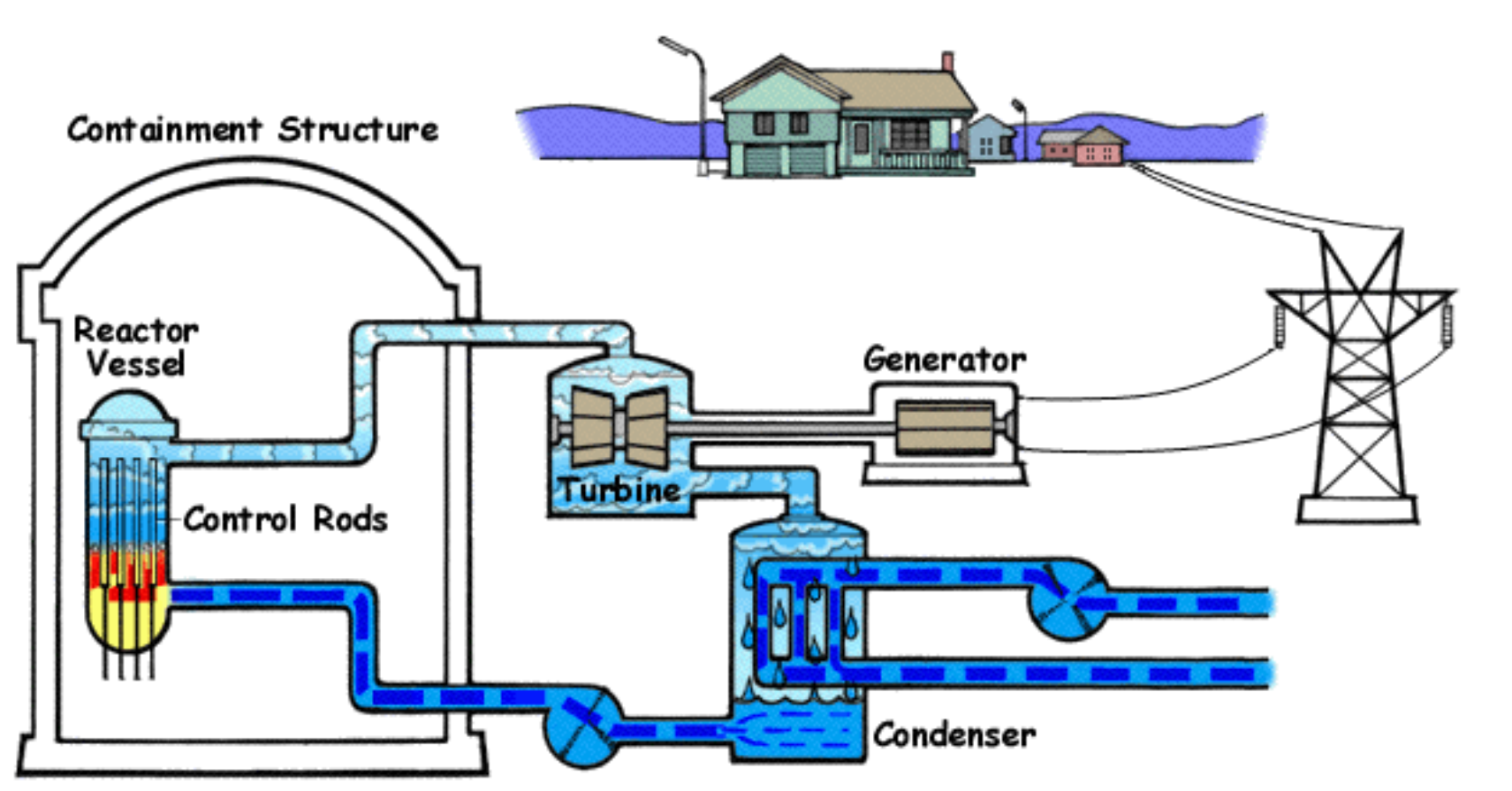
The Nuclear Process

Splitting uranium atoms to produce heat is a process called fission. When a neutron is absorbed by an atom, it will split, producing two smaller atoms, two neutrons and a large amount of energy. The neutrons go on to split other atoms, producing more neutrons and more energy. The energy released heats water to produce steam. This chain reaction takes place entirely within the nuclear fuel.

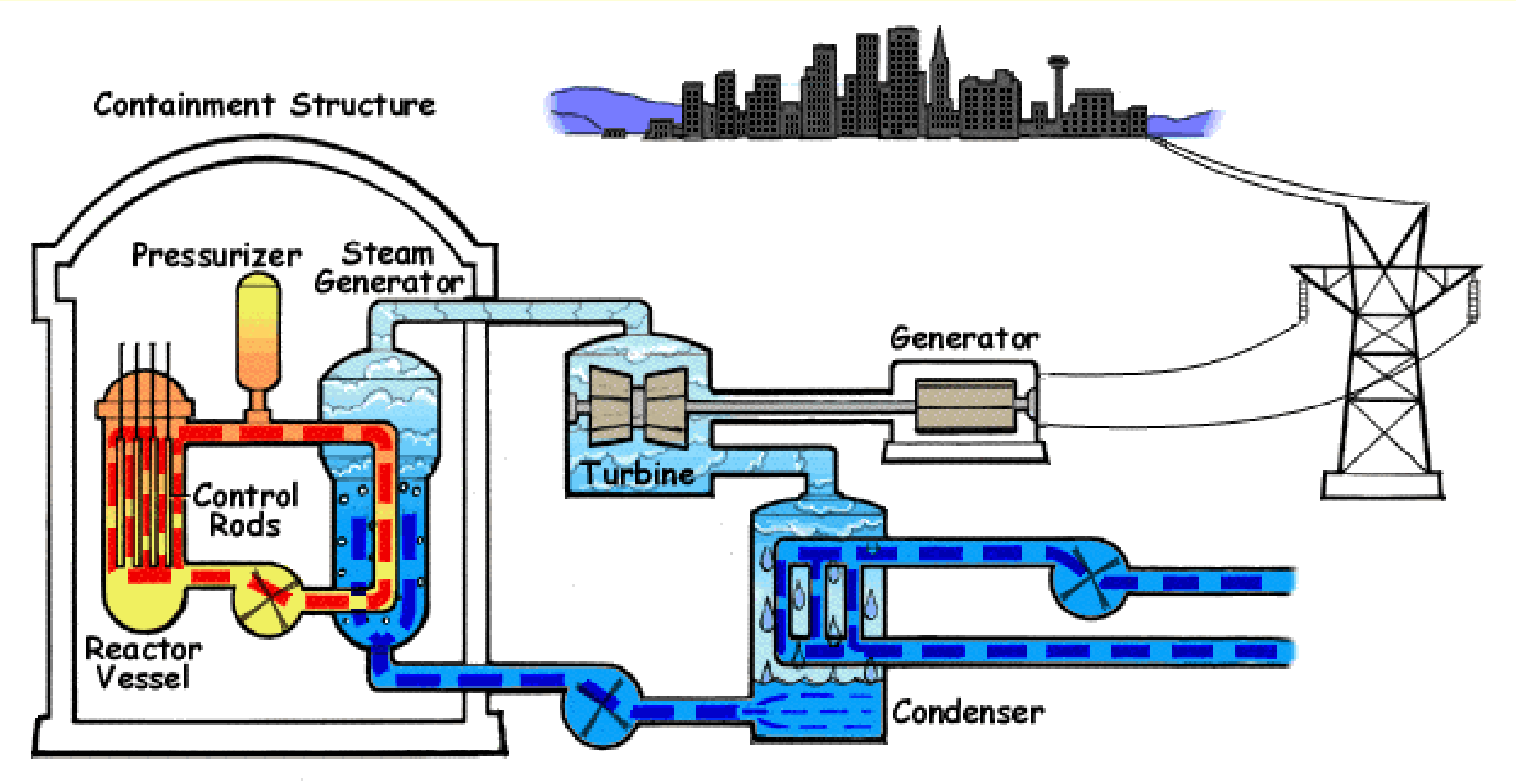


- U-235 has 2.5 million times more energy per pound than coal: 37 tons of fuel (3%-enriched uranium) per 1000 MWe reactor per year
- Nuclear provides a <u>heat source</u> that can be converted into multiple products
  - Electricity (worldwide)
  - Steam for industry (done in Switzerland, Russia, Japan, not in the U.S.)
  - Hydrogen (future with development of technology)

Boiling Water Reactor (BWR)



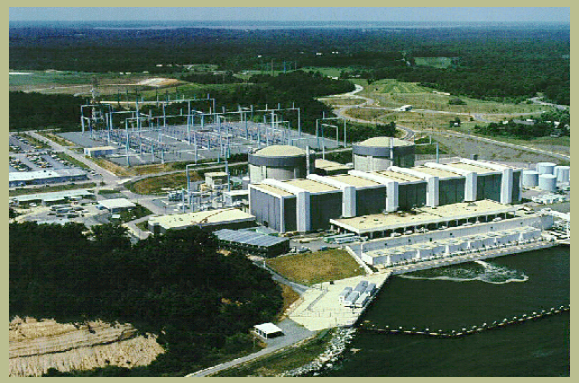
Pressurized Water Reactor (PWR)



Nuclear Energy Today

- **104** US reactors, about **440** World reactors in **30** countries. World-wide, about **34** new reactors are in various stages of construction.
- **99.5** nuclear GWe is **13%** of US installed capacity but provides about **20%** of electricity.
- In 2007 nuclear energy production in the US was **the highest ever**.
- US plants have run at **92% capacity in 2007**, up from **56% in 1980**.
- **3.5** GWe of uprates were permitted in the last decade. **2.0** GWe are expected **by 2013** and more by **2020**.
- **48** reactor **licenses extended, from 40 years to 60** years of operation, **17** more reactors in process.

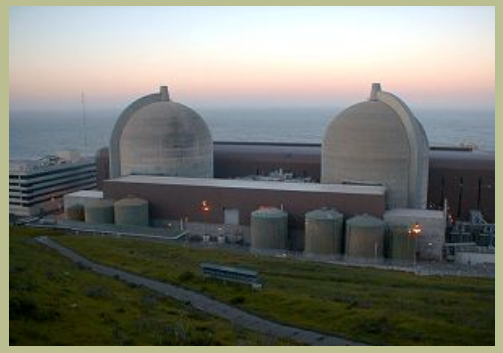
Worldwide distribution of nuclear plants



Calvert Cliffs - MD

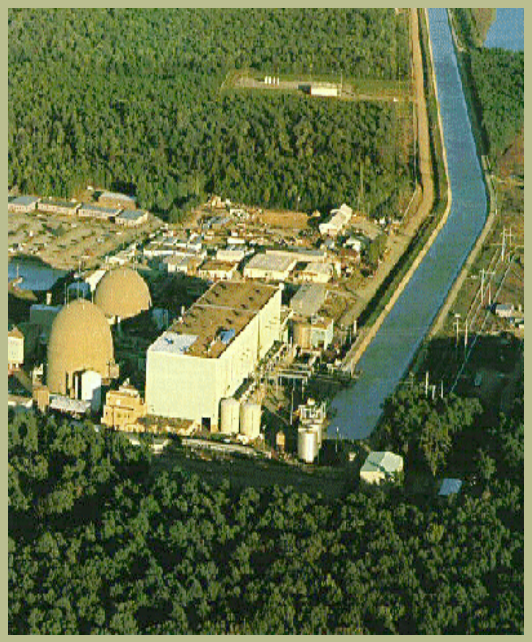
Indian Point - NY

Robinson - SC



Diablo Canyon - CA

Prairie Island site - MN



Surry - VA

Renewed Interest in Nuclear Power in the US

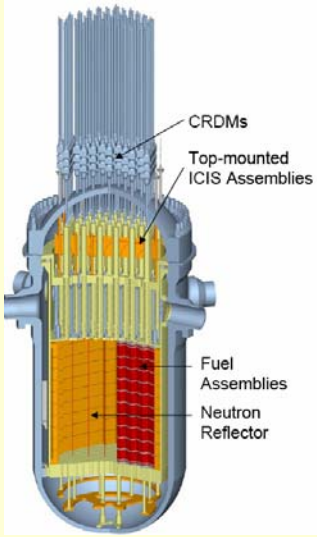
- Improved economics from experience and incremental improvements over 3 decades
  - Plant reliability increased from <60 to >90%
  - Better construction methods to lower capital costs
- Concerns about ***climate change*** and rising ***oil imports***
- 2 orders (4 units total) for new reactor construction signed, 9 license applications (15 units total) filed with NRC, 20+ more units expected

5 Advanced Reactor Designs Considered for New Construction in the US

Gen III+ Plants: Improved Versions of Existing Plant Designs

ABWR (GE-Hitachi)

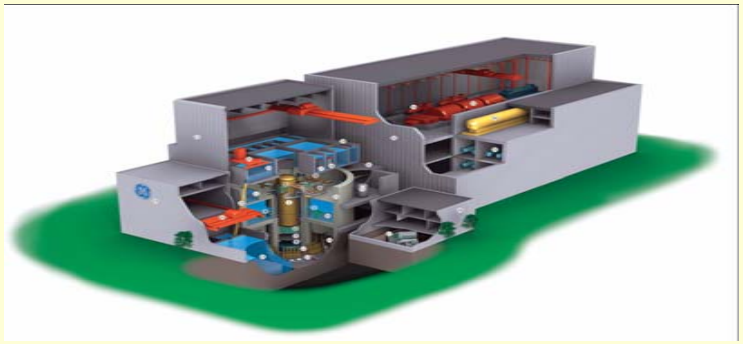
US-APWR (Mitsubishi)



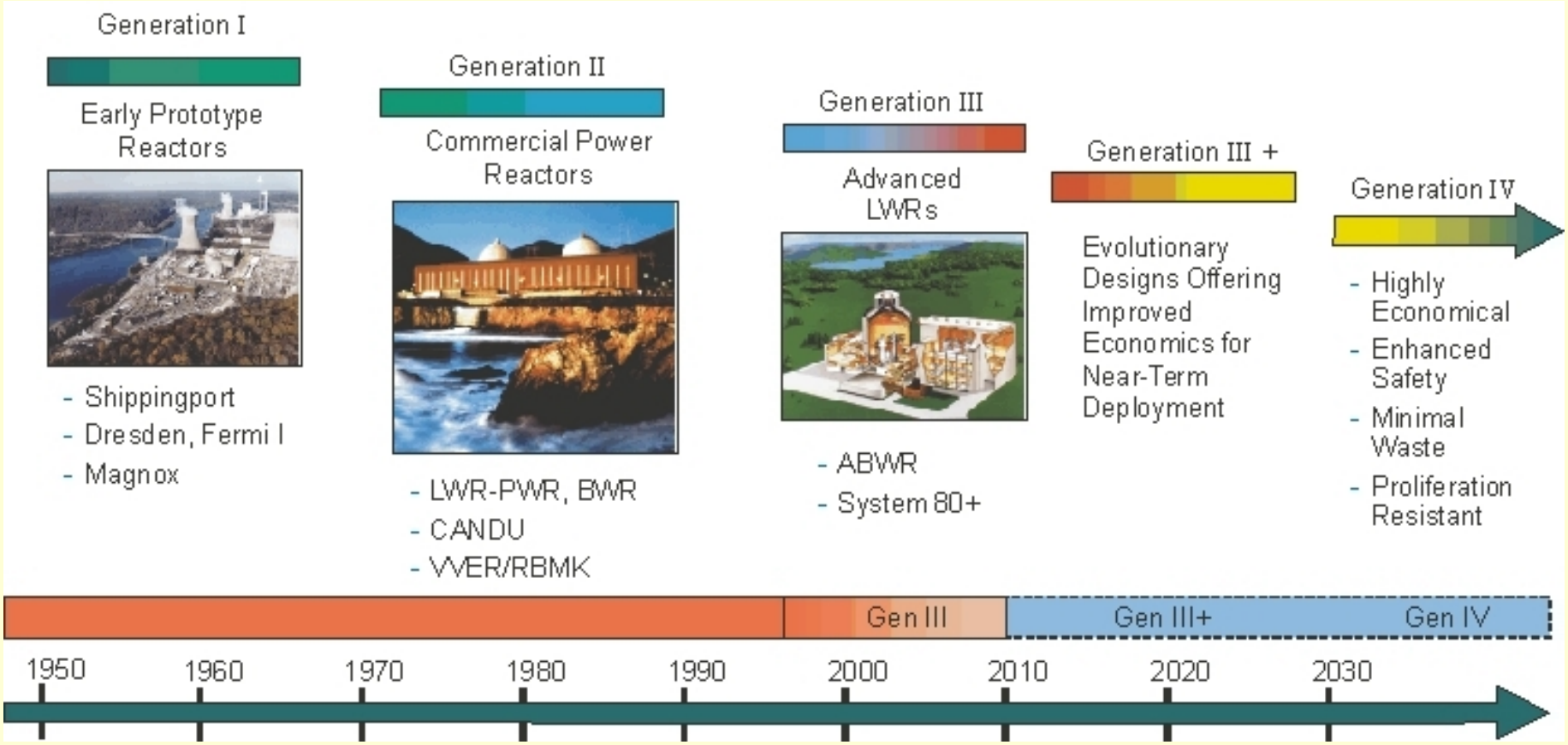
AP1000 (Toshiba: Westinghouse)

US-EPR (AREVA)

ESBWR (GE-Hitachi)



Nuclear Reactor Timeline



Advanced Reactors (Gen III+) that initiated discussions with the NRC

Design	Applicant	Type	Design Certification Status
AP1000	Westinghouse -Toshiba	Advanced Passive PWR 1100 MWe	Certified
ABWR	GE-Hitachi	Advanced BWR 1350 MWe	Certified, Constructed in Japan/Taiwan
ESBWR	GE-Hitachi	Advanced Passive BWR 1550 MWe	Under review
US-EPR	AREVA	Advanced PWR 1600 MWe	Has applied in 2007
US-APWR	Mitsubishi	Advanced PWR 1700 MWe	Has applied in 2007

Performance Targets for Gen III+ Reactors

- Improved economics
  - Increased plant design life (60 years)
  - Shorter construction schedule (36 months)
  - Low overnight capital cost (~$1000/kWe for NOAK plant) *(rather unrealistic target)*
  - Low levelized cost of electricity (~ 3¢/kWh)

- Improved safety and reliability
  - Reduced need for operator action
  - Expected to beat NRC goal of CDF<10^{-4}/yr
  - Reduced large release probability

Nuclear Safety Primer

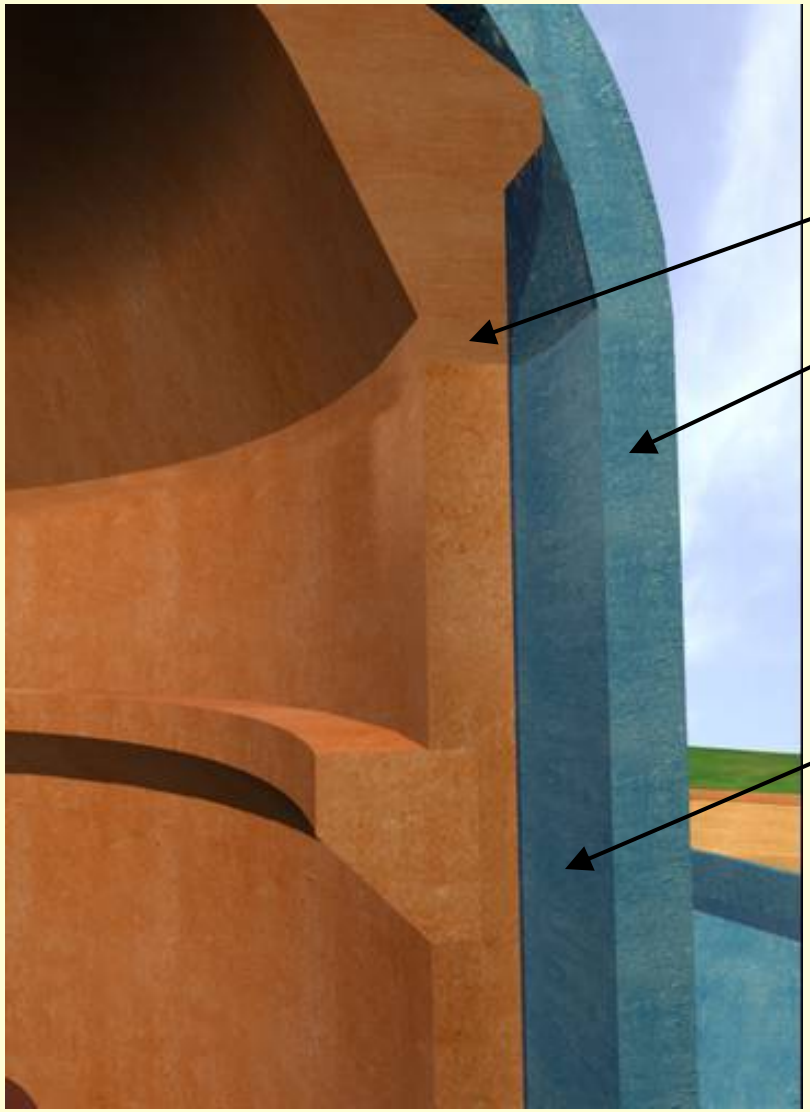
- Hazard: fission products are highly radioactive
- Aggravating factor: nuclear fuel can never be completely shut down (decay heat)
- Objective: prevent release of radioactivity into environment
- Safety Pillars:
  - *Defense-in-depth*: multiple, independent physical barriers (i.e., fuel pin + vessel + containment)
  - *Safety systems*: prevent overheating of the core when normal coolant is lost

Some interesting safety-related features of the Gen III+ reactors…

Higher redundancy (US-EPR ECCS)

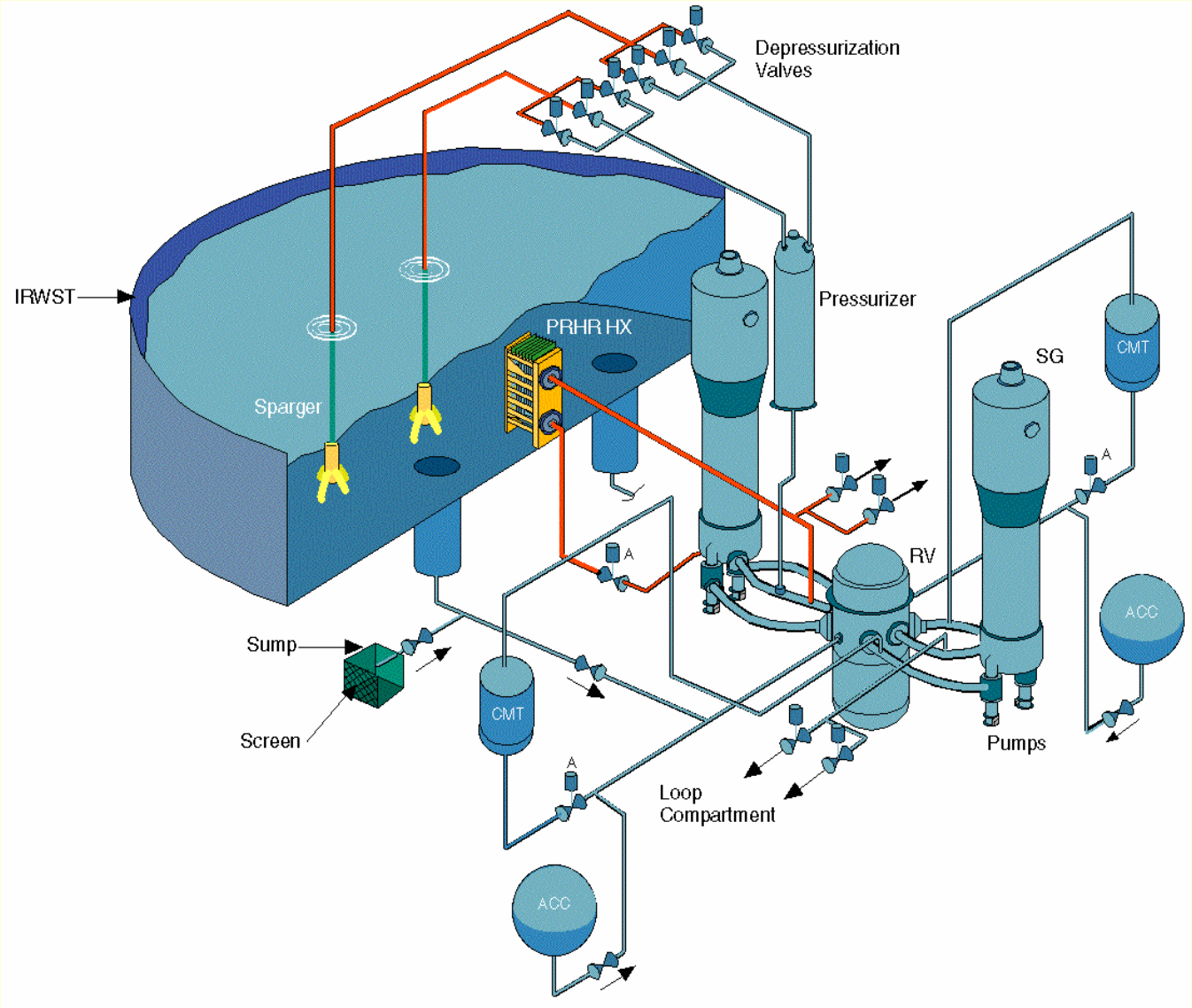
- Four identical diesel-driven trains, each 100%, provide redundancy for maintenance or single-failure criterion (N+2)
- Physical separation against internal hazards (e.g. fire)

Higher redundancy (US-EPR Containment)

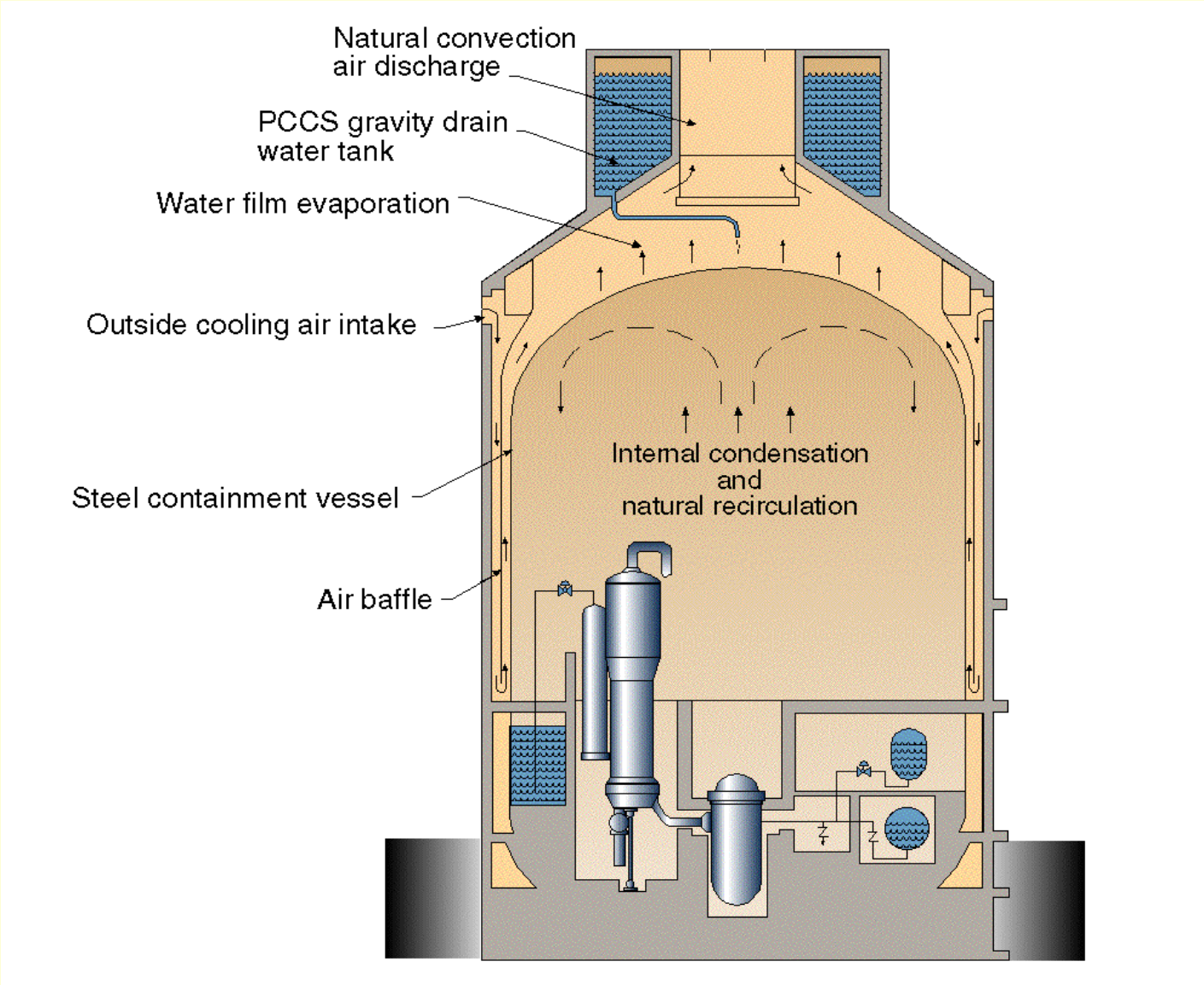


- Inner wall pre-stressed concrete with steel liner
- Outer wall reinforced concrete
- Protection against airplane crash
- Protection against external explosions
- Annulus sub-atmospheric and filtered to reduce radioisotope release

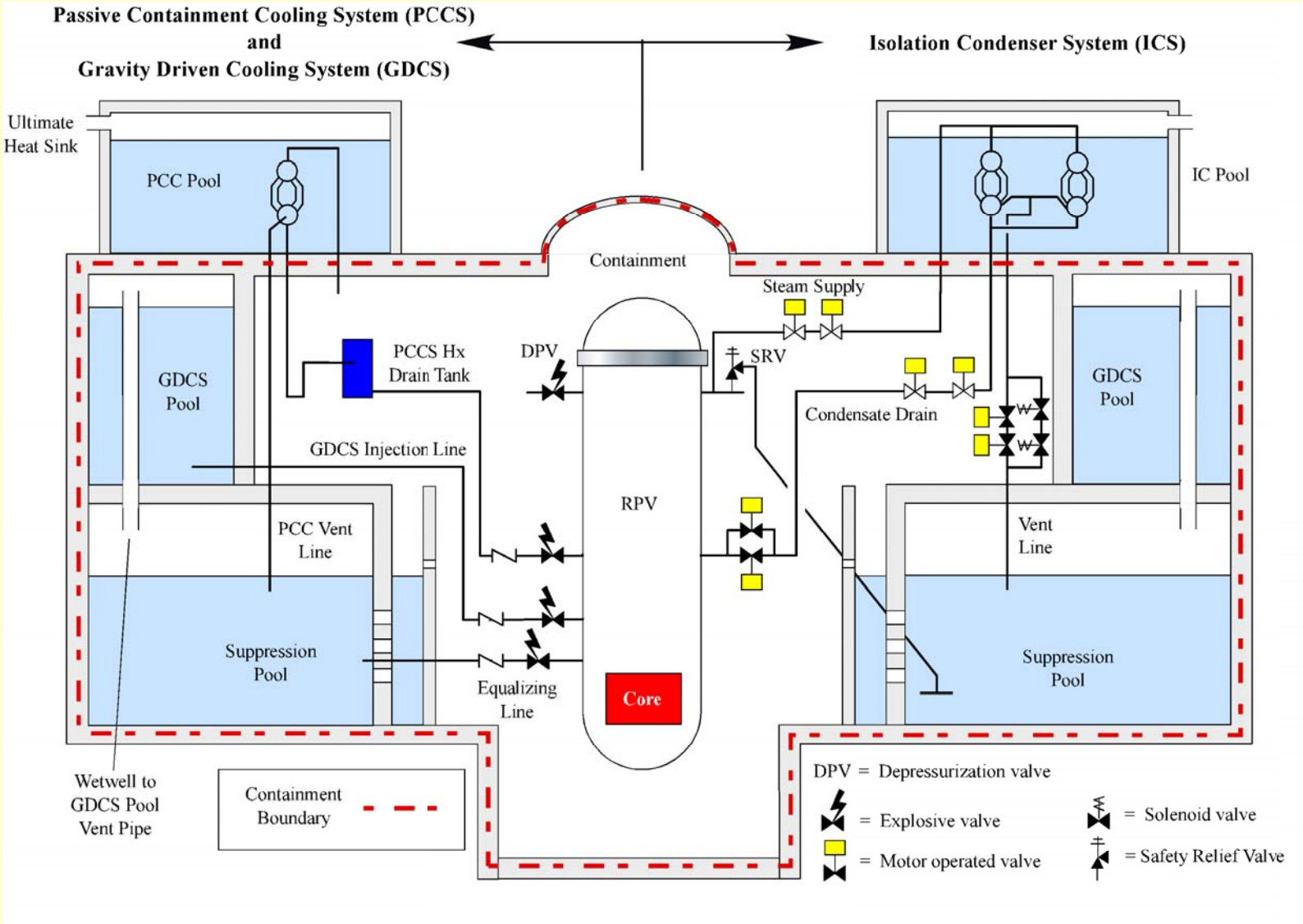
Passive safety systems (AP1000 ECCS)



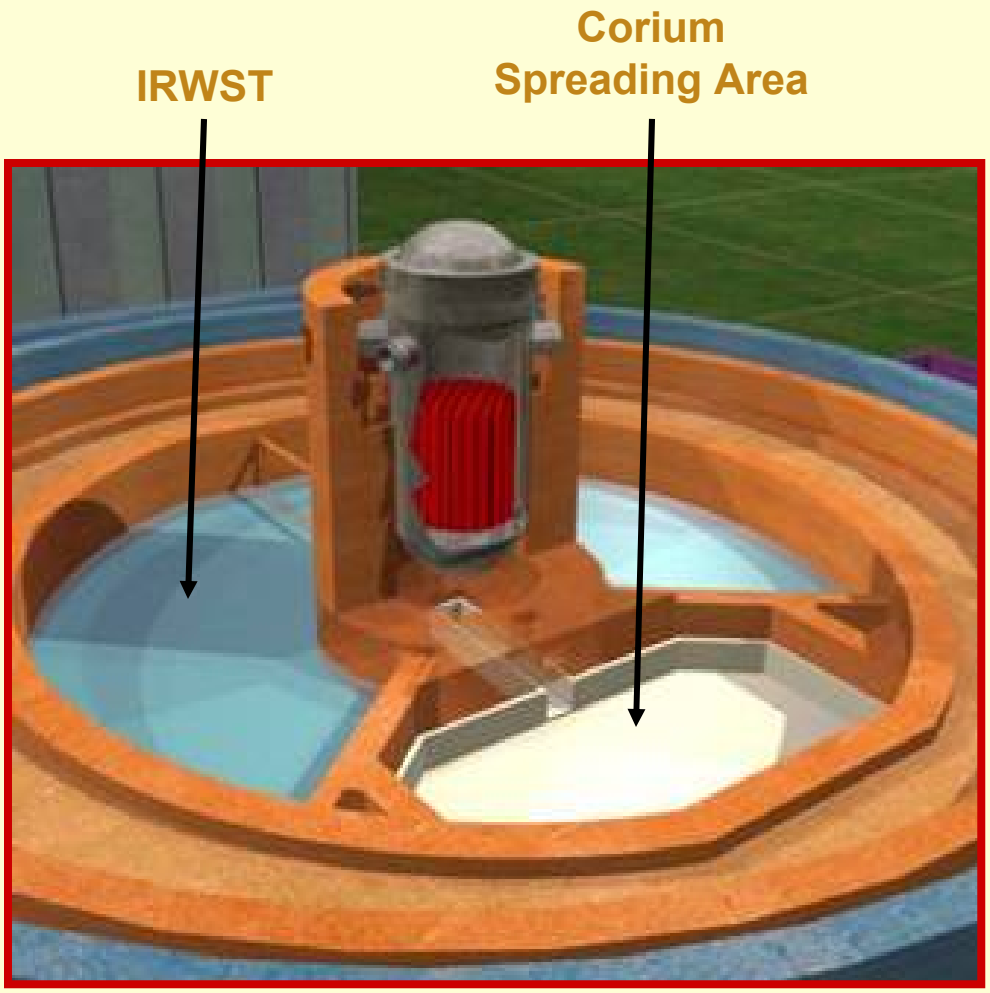
Passive safety systems (AP1000 Containment)



Passive safety systems (ESBWR ECCS and PCCS)



Severe accidents mitigation (EPR core catcher)



Ex-vessel core catcher concept (passive)

- Molten core is assumed to breach vessel

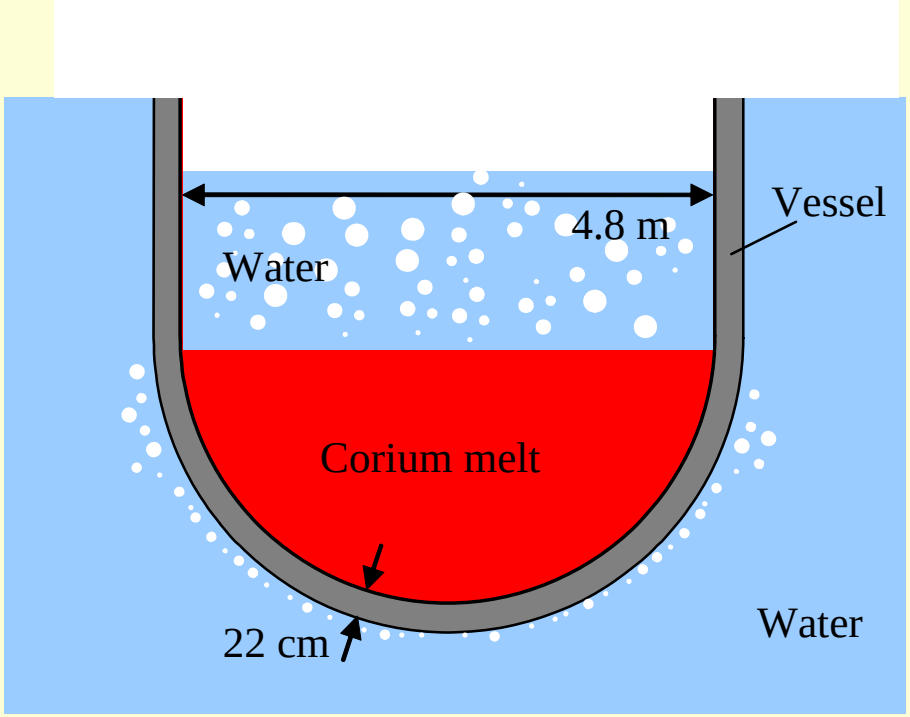
- Molten core flows into spreading area and is cooled by IRWST water

- Hydrogen recombiners ensure no detonation within container

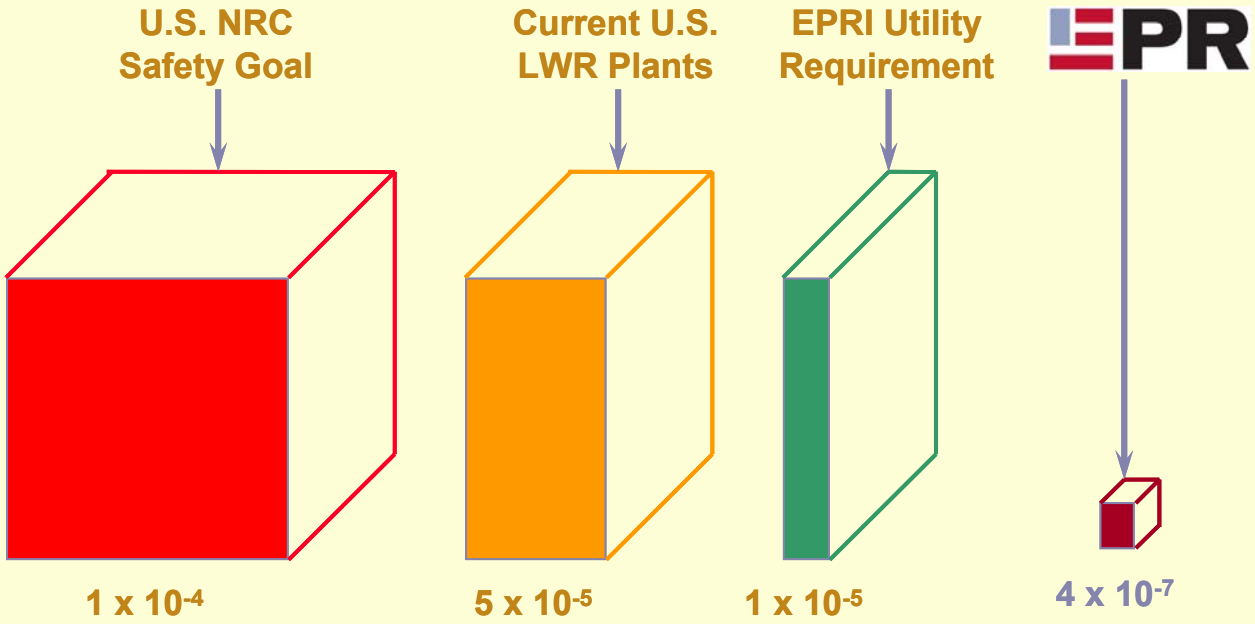
Severe accident mitigation (AP1000 IVR)

In-Vessel Retention (IVR) / ex-vessel cooling

- Reactor cavity is flooded with water
- Decay heat removed by boiling on outer surface of vessel



Overall improved safety (EPR and AP1000)



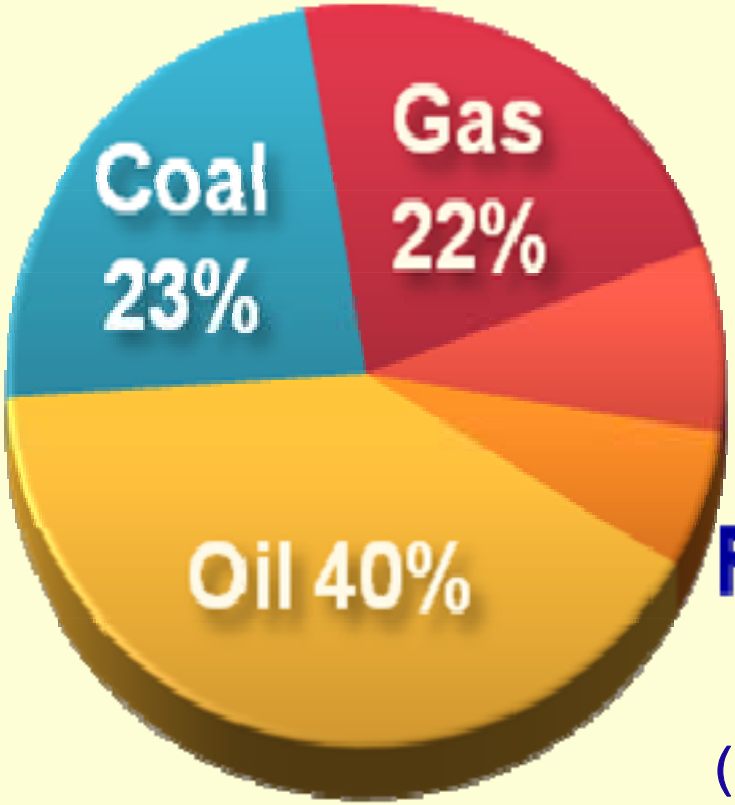
Core Damage Frequency Per Year

	Core Damage Frequency		Large Release Frequency	
	At-Power	Shutdown	At-Power	Shutdown
Internal Events	2.41E-07 /yr	1.23E-07 /yr	1.95E-08 /yr	2.05E-08 /yr
Internal Floods	8.80E-10 /yr	3.22E-09 /yr	7.10E-11 /yr	5.40E-10 /yr
Internal Fires	5.61E-08 /yr	8.52E-08 /yr	4.54E-09 /yr	1.40E-08 /yr
Sub-Totals	2.98E-07 /yr	2.11E-07 /yr	2.41E-08 /yr	3.50E-08 /yr
Grand-Totals	5.09E-07		5.92E-08	
NRC Safety Goals	1 E-4		1 E-6	

Can nuclear energy be used for more than just electricity production?

Total U.S. Energy Consumption

Oil is the Challenge



Nuclear
8%

Renewables
6%
(Primarily Hydro)

↑
Low Carbon
↓

U.S. data from EIA, Annual Energy Outlook 2008 Early Release, years 2006 and 2030; world data from IEA, World Energy Outlook 2007, years 2005 and 2030

Oil Is Used for Transportation. What Are the Other Transport Fuel Options?

- **Plug-in hybrid electric cars**
- **Liquid fuels from fossil sources (oil, natural gas and coal)**
- **Liquid fuels from biomass**
- Hydrogen
  - Long term option
  - Depends upon hydrogen on-board-vehicle storage breakthrough

Plug-In Hybrid Electric Vehicles (PHEVs)

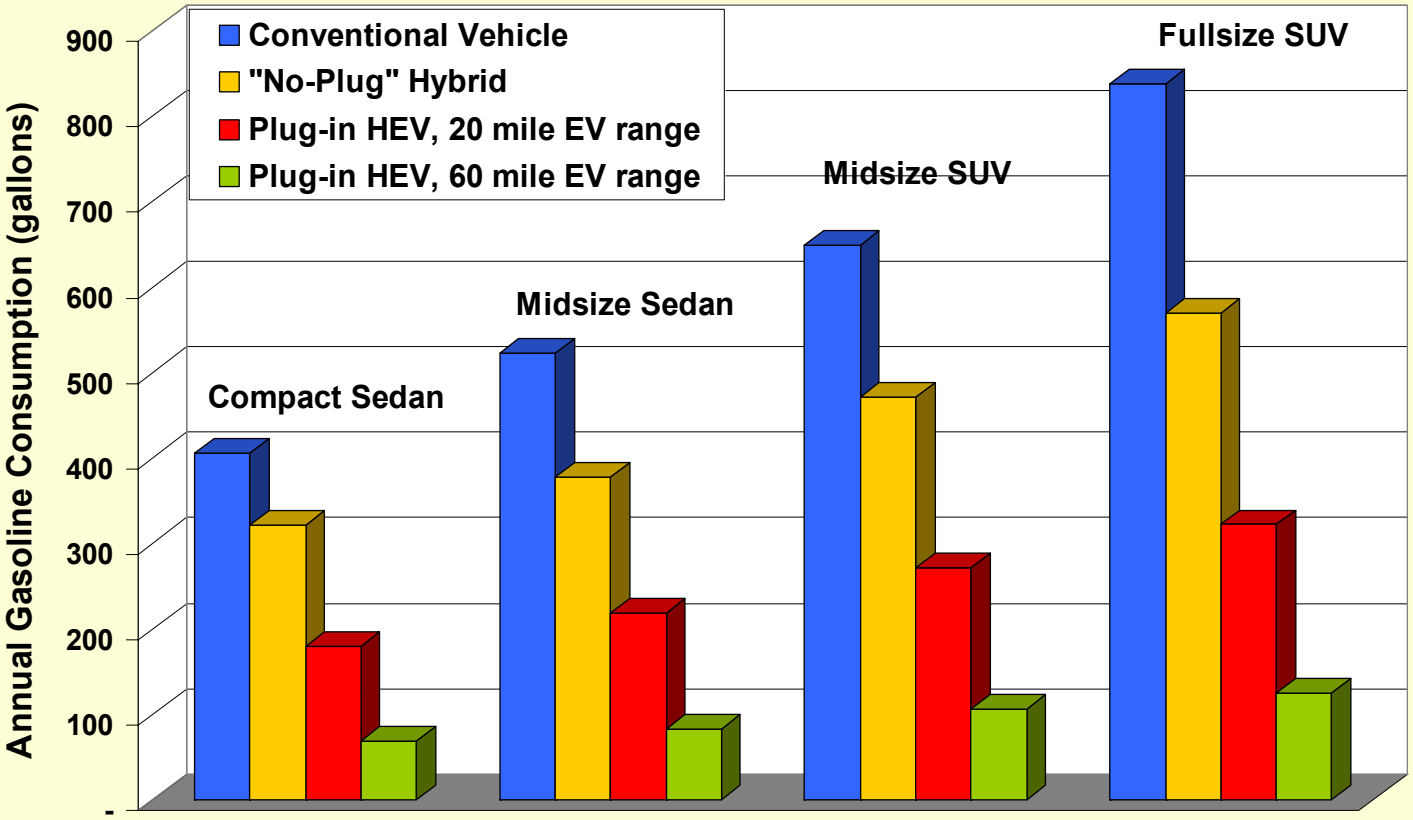
PHEVs: Recharge Batteries from the Electric Grid Plus Use of Gasoline

- Electric car limitations
  - Limited range
  - Recharge time (Gasoline refueling rate is ~10 MW)
- Plug-in hybrid electric vehicle
  - Electric drive for short trips
  - Recharge battery overnight to avoid rapid recharge requirement
  - Hybrid engine with gasoline or diesel engine for longer trips
- Connects cars and light trucks to the electrical grid

Courtesy of the Electric Power Research Institute

PHEVs: Annual Gasoline Consumption

Substituting Electricity for Gasoline



Courtesy of the Electric Power Research Institute

Need 150 to 200 Nuclear Plants Each Producing 1000 MW(e)

Liquid Fuels Production from Fossil Sources

Refineries Consume ~7% of the Total U.S. Energy Demand

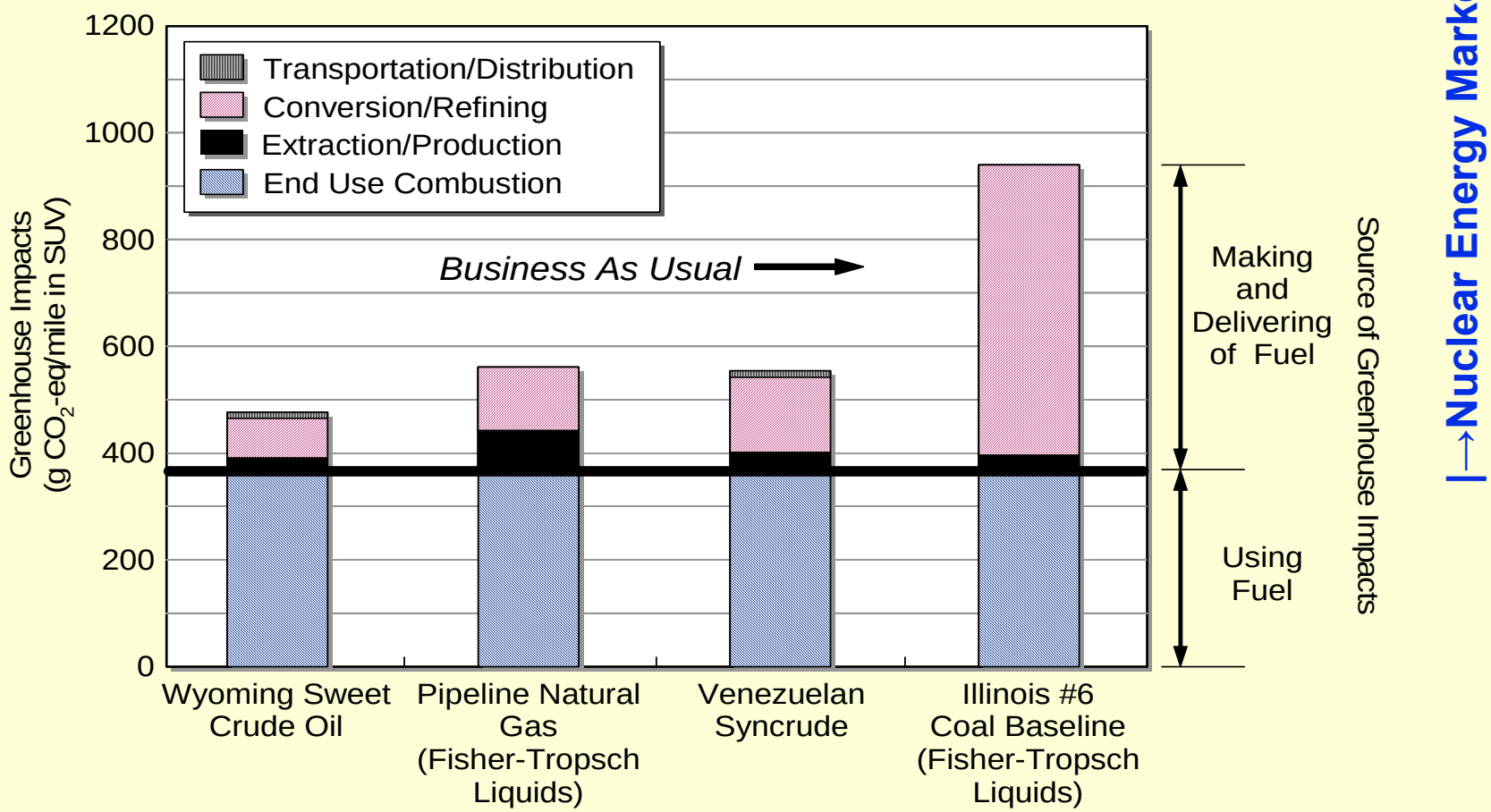
Column Cracker

Traditional Refining

- Energy inputs
  - Primarily heat at 550°C
  - Some hydrogen
- <u>High-temperature gas reactors could supply heat and hydrogen</u>
  - Market size equals existing nuclear enterprise

Conversion of Fossil Fuels to Liquid Fuels Requires Energy

Greenhouse Impacts from Vehicle and Fuel Production Cycle

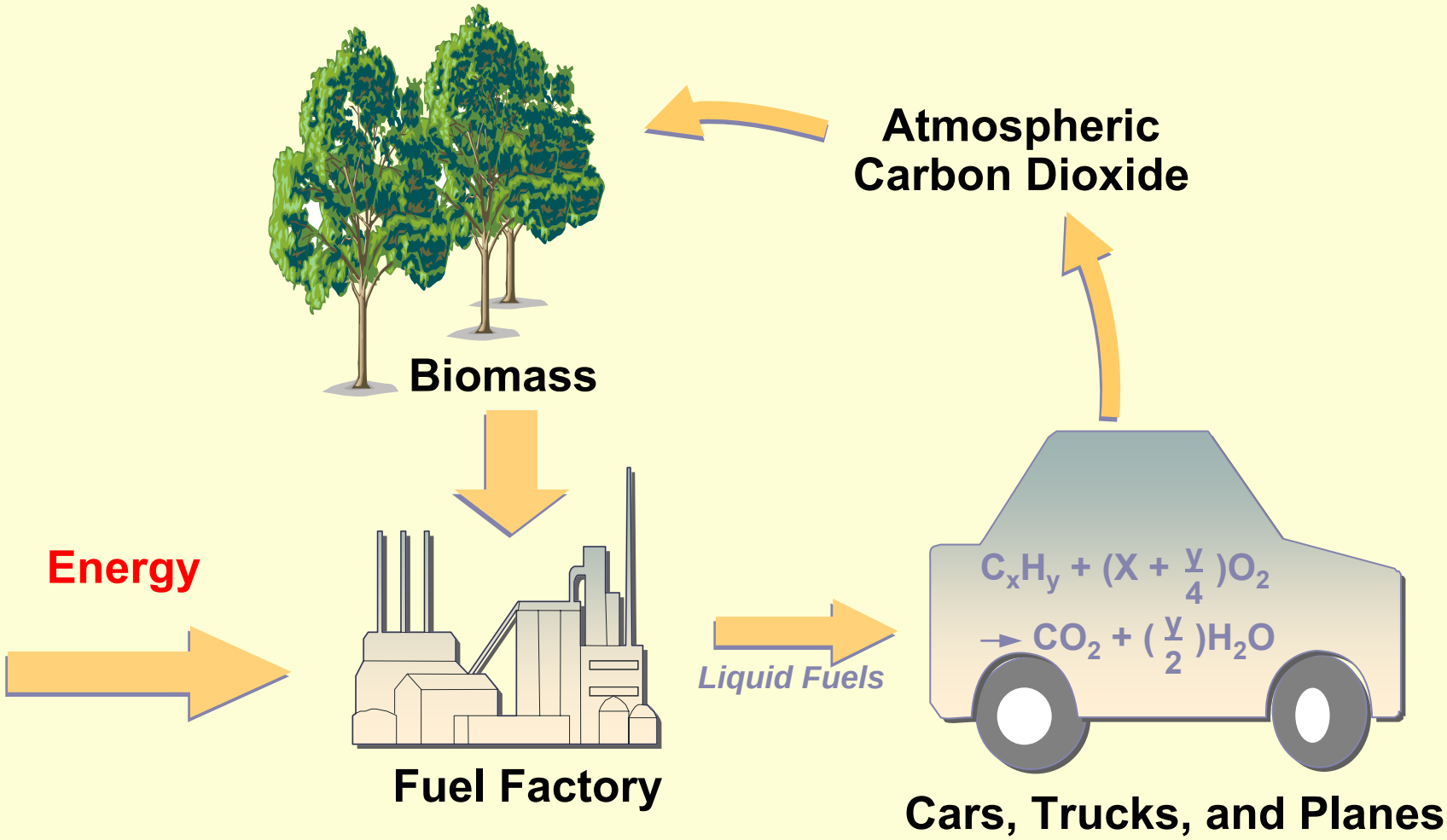


Liquid Fuels Production from Biomass

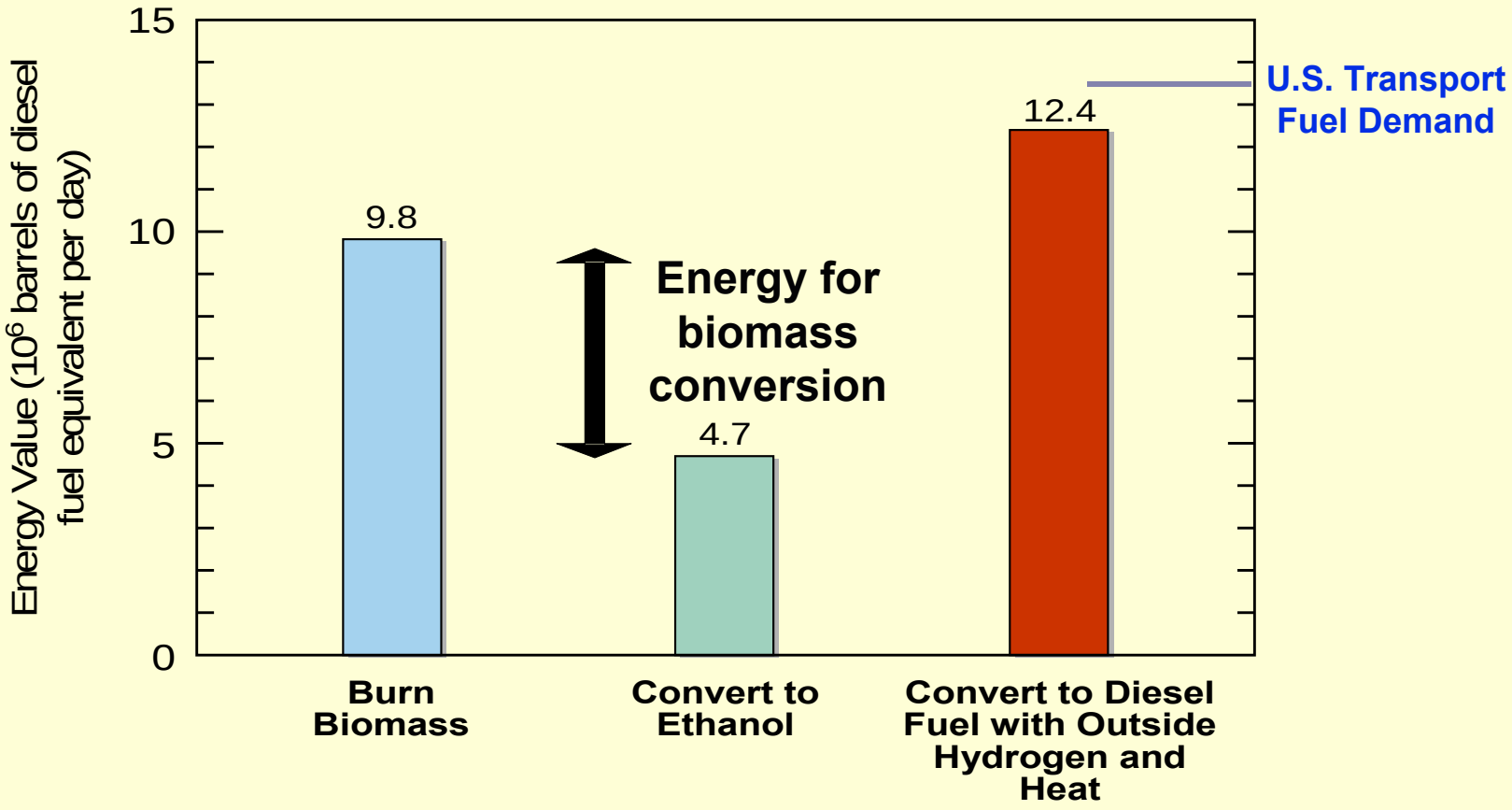
Biomass: 1.3 Billion Tons per Year

Available Biomass without Significantly Impacting U.S. Food, Fiber, and Timber

Conversion of Biomass to Liquid Fuels Requires Energy

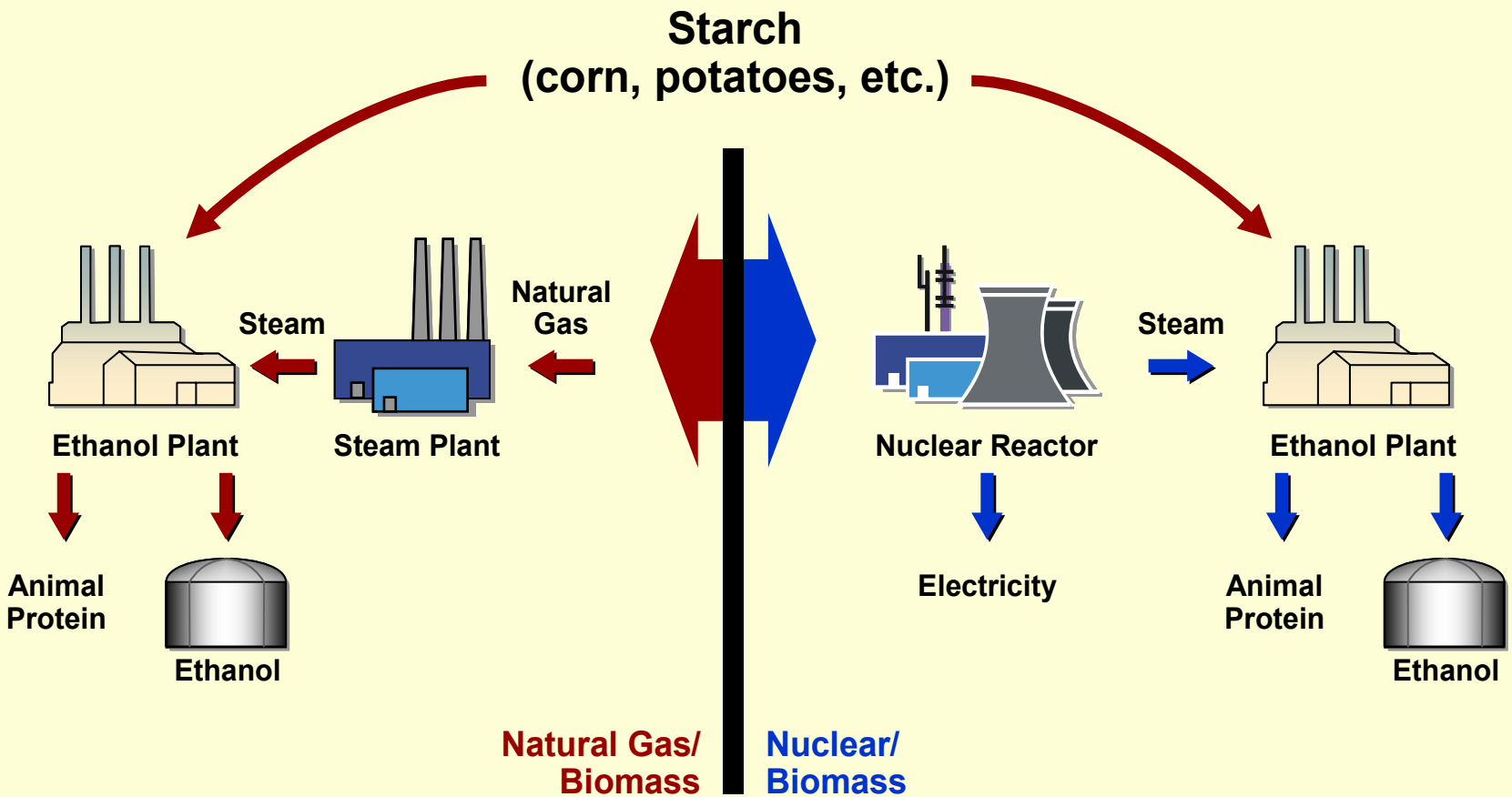


Biomass Conversion to Liquid Fuel Requires Energy



Energy Value of 1.3 Billion Tons/year of U.S. Renewable Biomass Measured in Equivalent Barrels of Diesel Fuel per Day

Option Today: Steam From Existing Nuclear Plants to Starch-Ethanol Plants



Fossil Energy Input 70% of Energy Content of Ethanol

50% Decrease in CO_2 Emissions/Gallon Ethanol
50% Reduction in Steam Cost

Now, for the bad news…

Outstanding issues that could slow the expansion of nuclear power

- Capital intensity of plant construction projects:

  -New plants remain very expensive to build (G$/unit)

  -Loan guarantees in 2005 energy bill will help to soften the financial risk

- Proliferation concerns:

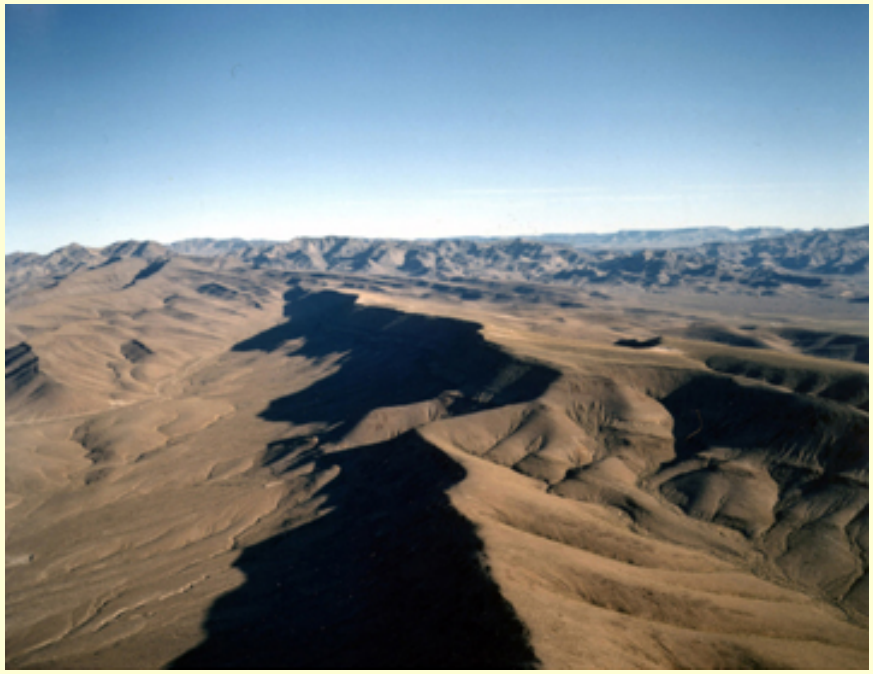
  -Technical features of fuel cycle can hinder proliferation (e.g., high burnup, no Pu separation, use of thorium, etc.)

  -Ultimately it is an issue of political nature; probably best managed through international oversight (IAEA?)

- Unresolved issue of spent fuel management (waste)

Spent fuel management (direct disposal)

- Underground geological repository is the current approach in the US
- Yucca Mountain site selected, President approved and license application submitted to NRC in 2008

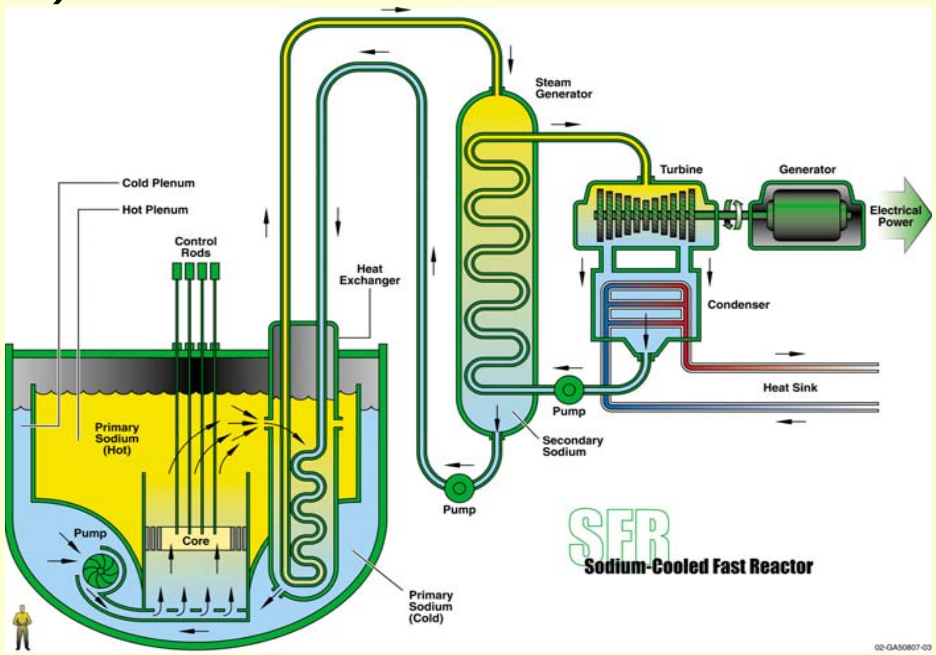


However, many think it is unlikely it will open any time soon.

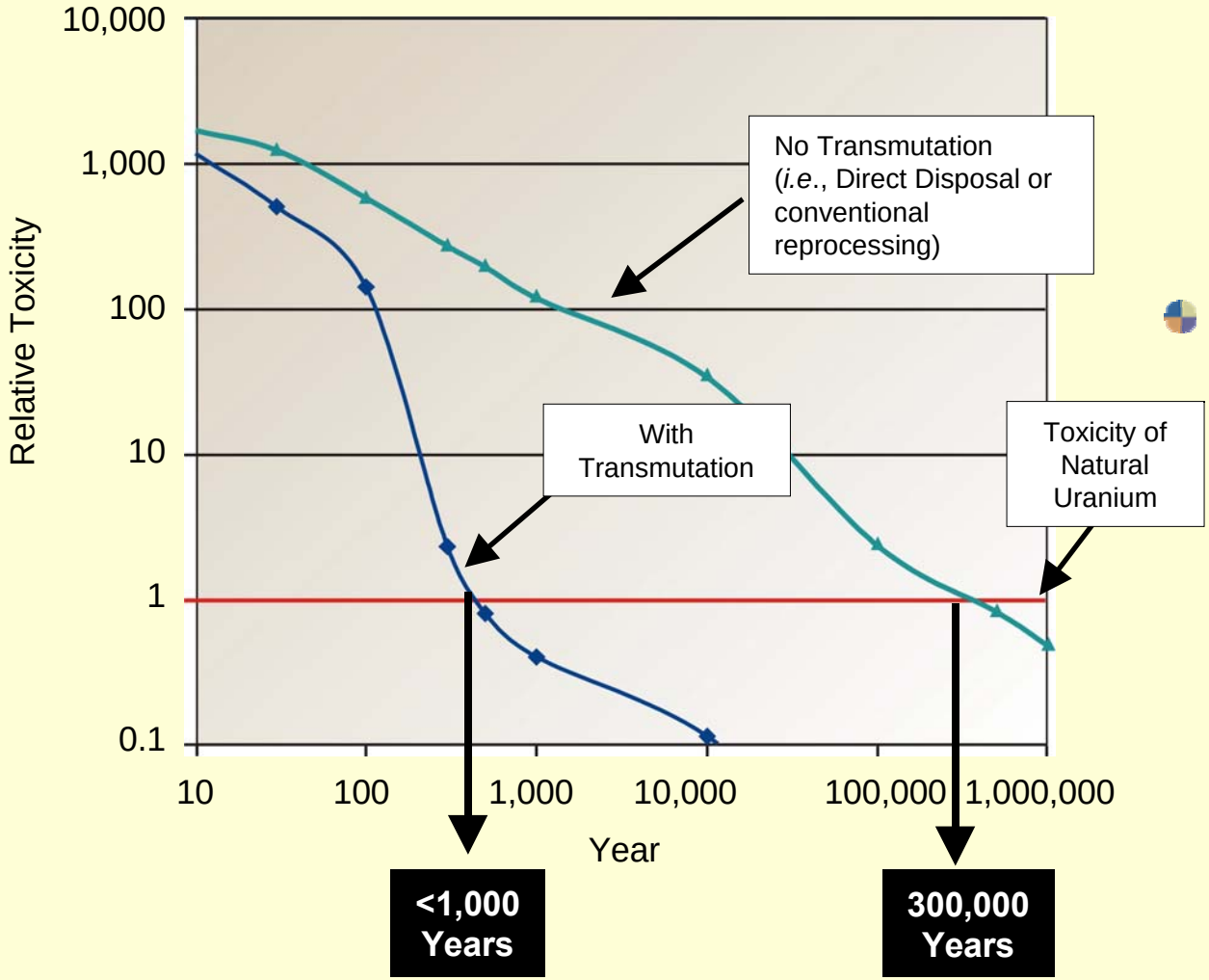
Interim storage at plants (wet pools and dry casks)

Spent fuel management (recycling)

- Spent fuel from LWRs is reprocessed and:
  - Separated Pu is recycled in LWRs (MOX approach, done in France and Japan)
  - Pu+U recycled in (sodium-cooled) fast reactors (being reconsidered in Russia, Japan, France and US under GNEP umbrella)



Spent fuel management (transmutation)



- "Deep" burning could be done with accelerator-driven subcritical reactors

Conclusions

- New nuclear plants underway in the US for first time in 30 years
- New plants feature higher level of safety through increased redundancy and use of passive safety systems
- Nuclear could be used (today!) to reduce oil consumption in transportation
- Toughest unresolved issue is long-term disposal of spent fuel