Nuclear Energy

Weston M. Stacey
Callaway Regents' Professor
Nuclear and Radiological Engineering Program
Georgia Institute of Technology

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Outline

- Future Energy Needs and Resources
- Nuclear Power – An Established and Improving Technology
- Nuclear is Economically Competitive and Reliable
- Nuclear Reduces Greenhouse Gas Emission
- Technical Challenges
- Fusion – Nuclear Energy of the Future
- Summary and Conclusions
- Nuclear Energy at Georgia Tech

World Electricity Needs

(Annual Fuel Consumption[a], Units 10^{21} J/yr)

		2000	2050
Developed Nations[b] (USA)		0.089 (0.039)	0.171[c] (0.090)
Former Soviet Union		0.013	0.017
Developing Nations		0.046	0.230[d]
World		0.147	0.418

Source: MIT study of Future of Nuclear Power

[a-d] see Appendix A

Major Energy Resources (Proven Reserves[a], Units 10^{21} Joules)

Region	Coal[a]	Oil[a]	Nat. Gas[a]	Uranium LWR OTC[a,b]	Uranium U^{238} Conv.[c]	Thorium[d,e] Th^{232} Conv	Lithium D-T Fusion
Africa	1.6	0.4	0.4	0.3	34		
N America	7.6	0.4	0.3	0.4	38		167[f,g,h]
S. America	0.6	0.6	0.2	0.1	9		
Asia	7.4	0.3	0.6	0.4	45		
Europe	9.2	0.4	1.9	0.2	17		
Mideast	0.1	3.9	1.9	0.0	0		
Oceania	2.4	0.0	0.1	0.4	37		
World	28.8	6.0	5.5	1.8	179	202	2640[f,g,h]

Source: World Energy Institute, 1999

[a-h] See appendix B

Nuclear and Radiological Engineering and Medical Physics

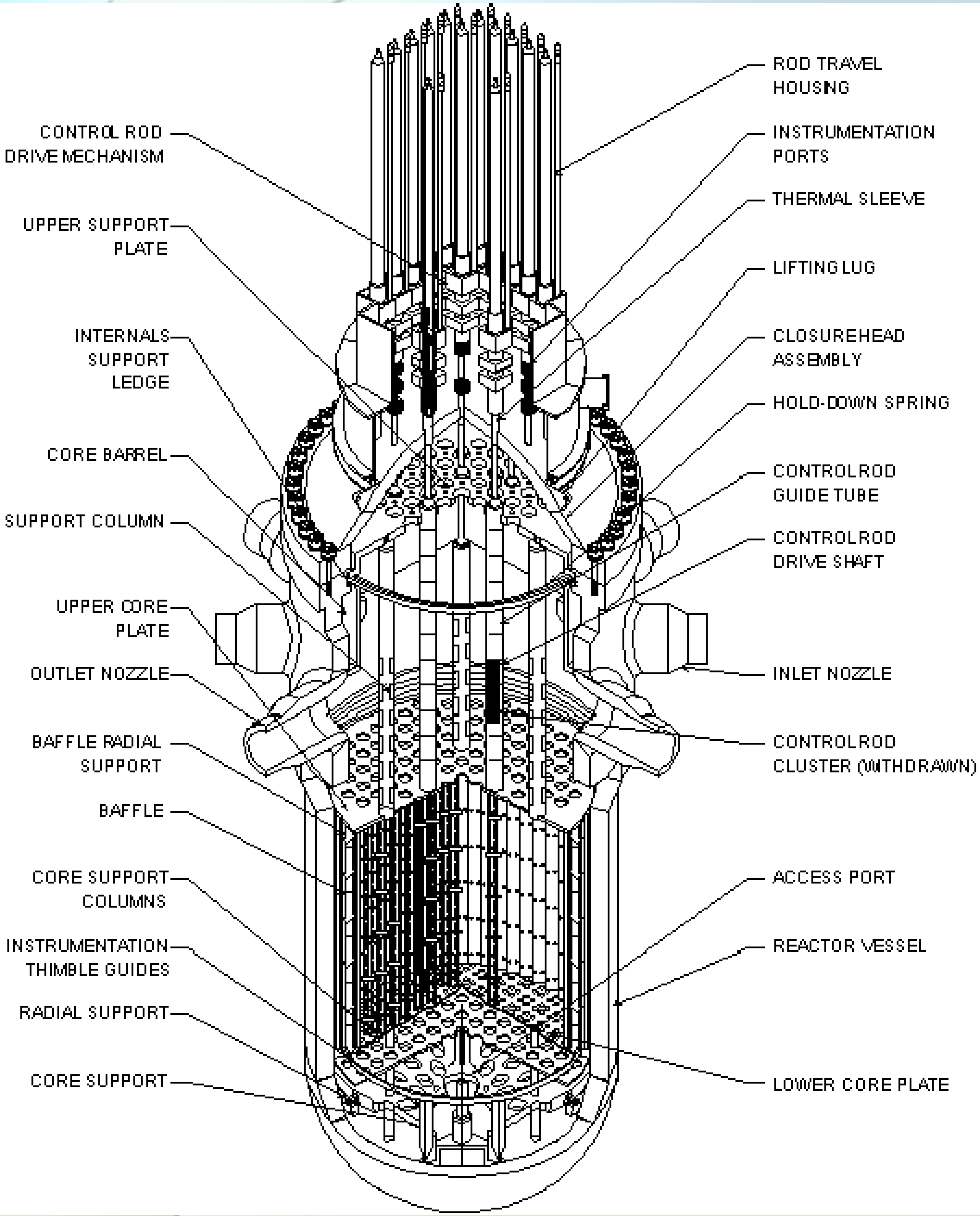
Nuclear Reactors

- Neutron chain reaction
- Nuclear energy from fission of uranium
- Nuclear to heat to electricity

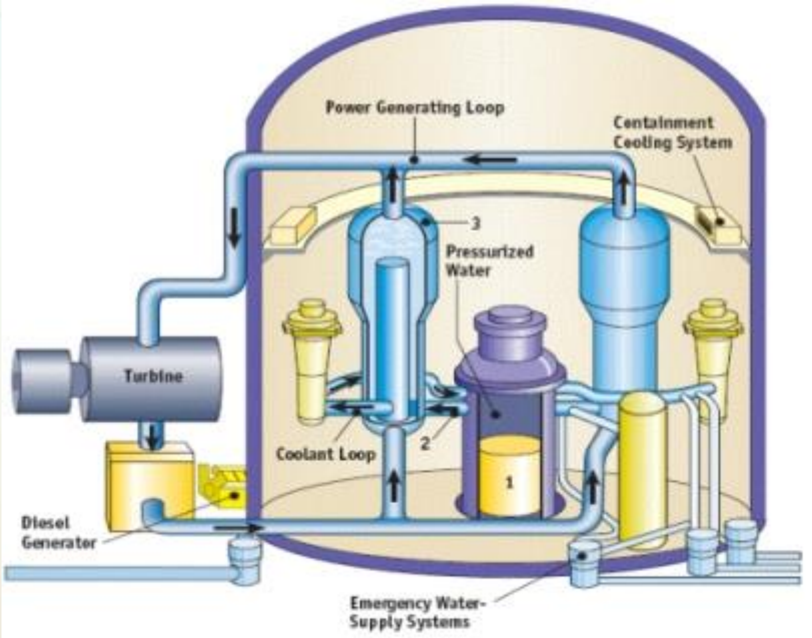
Predominant Commercial Nuclear Reactors

- PWR – Pressurized Water Reactor
- BWR – Boiling Water Reactor
- Others—Heavy Water Reactor, Gas Cooled Reactor, etc.

PWR

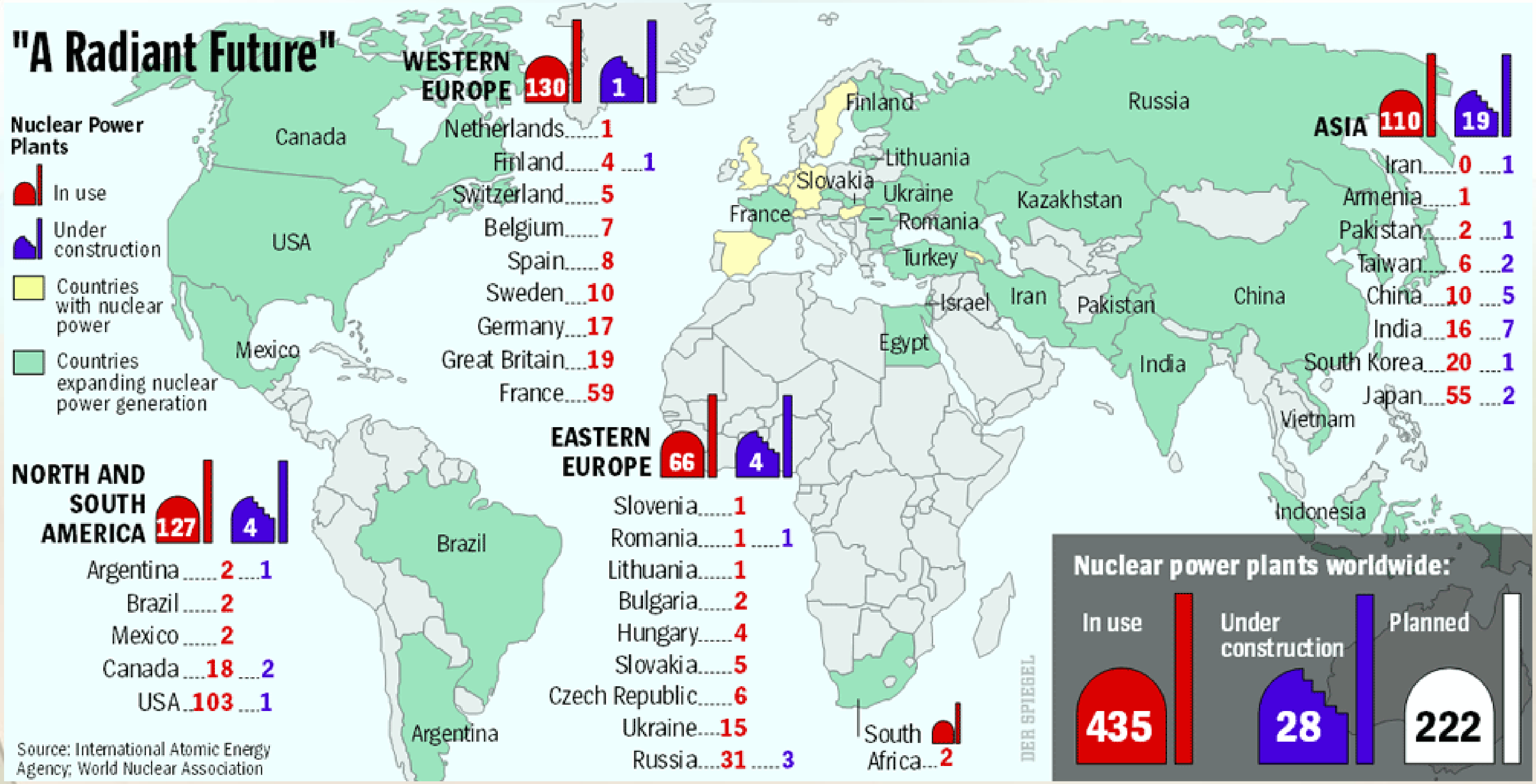


ROD TRAVEL HOUSING
INSTRUMENTATION PORTS
THERMAL SLEEVE
LIFTING LUG
CLOSUREHEAD ASSEMBLY
HOLD-DOWN SPRING
CONTROLROD GUIDE TUBE
CONTROLROD DRIVE SHAFT
INLET NOZZLE
CONTROLROD CLUSTER (WITHDRAWN)
ACCESS PORT
REACTOR VESSEL
LOWER CORE PLATE
CONTROL ROD DRIVE MECHANISM
UPPER SUPPORT PLATE
INTERNALS SUPPORT LEDGE
CORE BARREL
SUPPORT COLUMN
UPPER CORE PLATE
OUTLET NOZZLE
BAFFLE RADIAL SUPPORT
BAFFLE
CORE SUPPORT COLUMNS
INSTRUMENTATION THIMBLE GUIDES
RADIAL SUPPORT
CORE SUPPORT



Power Generating Loop
Containment Cooling System
3
Pressurized Water
Turbine
Coolant Loop
2
1
Diesel Generator
Emergency Water-Supply Systems

Nuclear Power Provides 367 GWe (16%) of the World's Electricity (France 79%, USA 19%)



http://www.spiegel.de/international/spiegel/0,1518,460011,00.html

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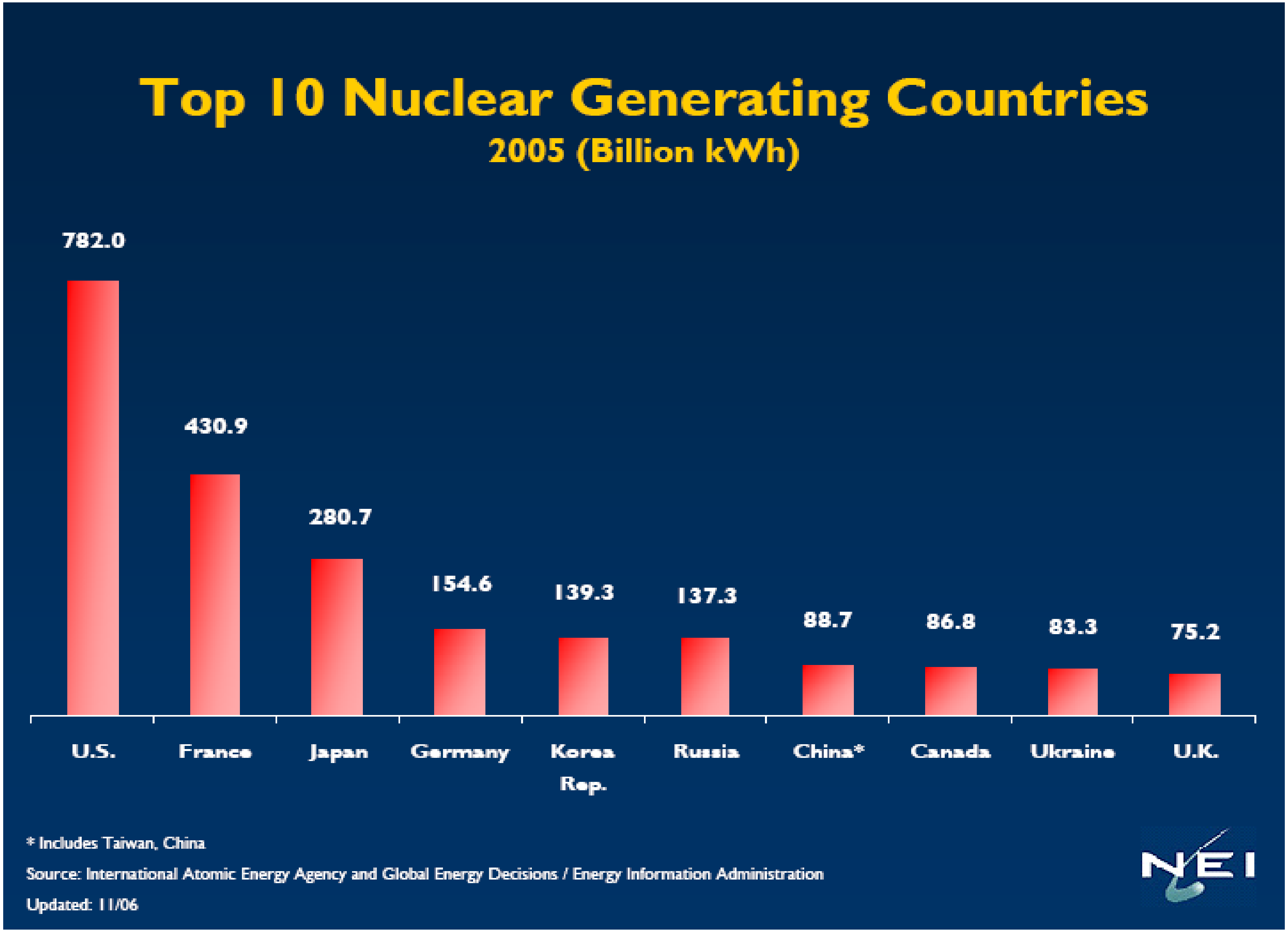
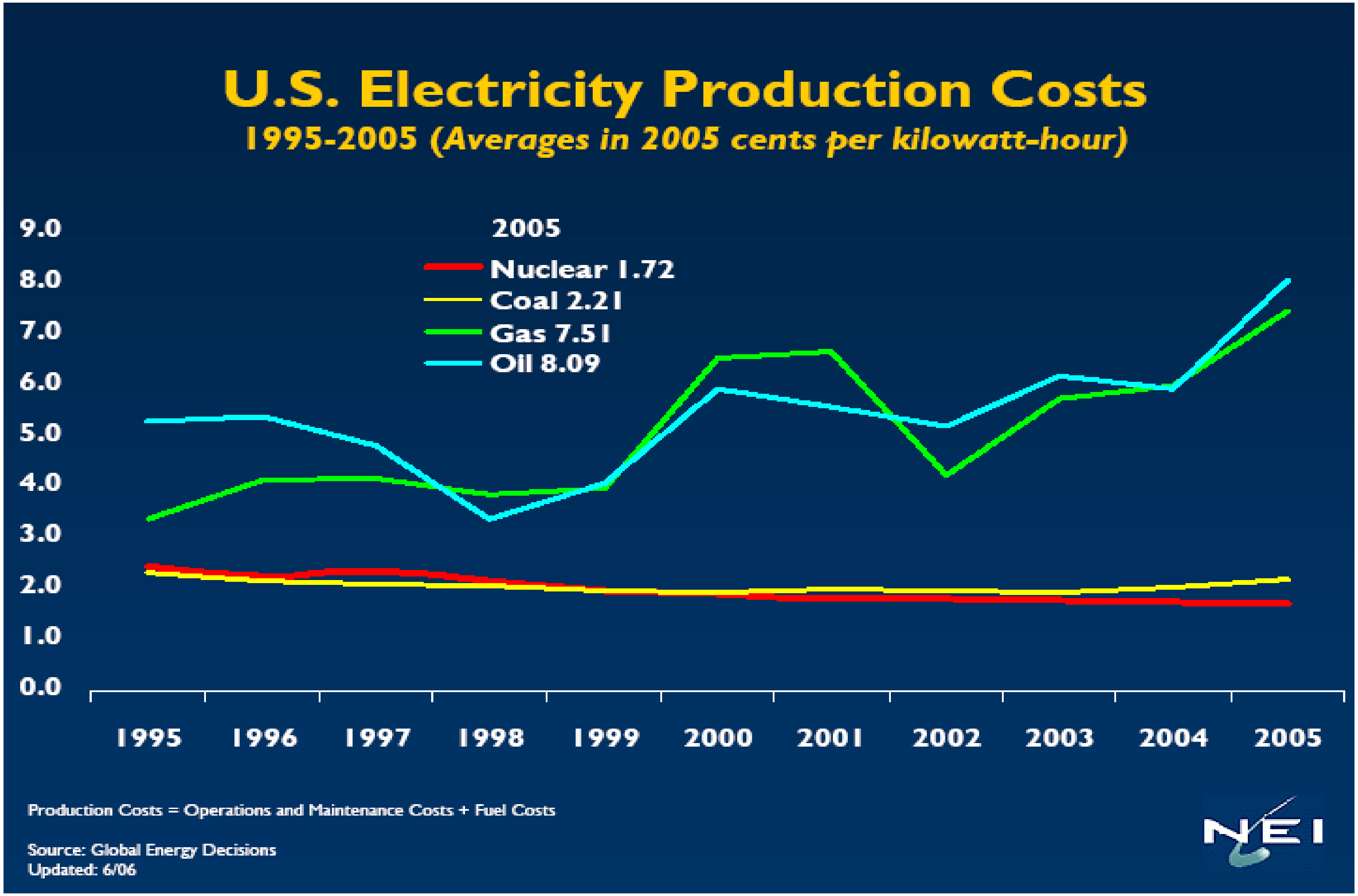

Top 10 Nuclear Generating Countries
2005 (Billion kWh)
782.0
430.9
280.7
154.6
139.3
137.3
88.7
86.8
83.3
75.2
U.S.
France
Japan
Germany
Korea Rep.
Russia
China*
Canada
Ukraine
U.K.
* Includes Taiwan, China
Source: International Atomic Energy Agency and Global Energy Decisions / Energy Information Administration
Updated: 11/06
NEI

Nuclear Power is Economical



Nuclear and Radiological Engineering and Medical Physics

Nuclear Plants are Reliable
Capacity Factors – US Power Plants (2005)

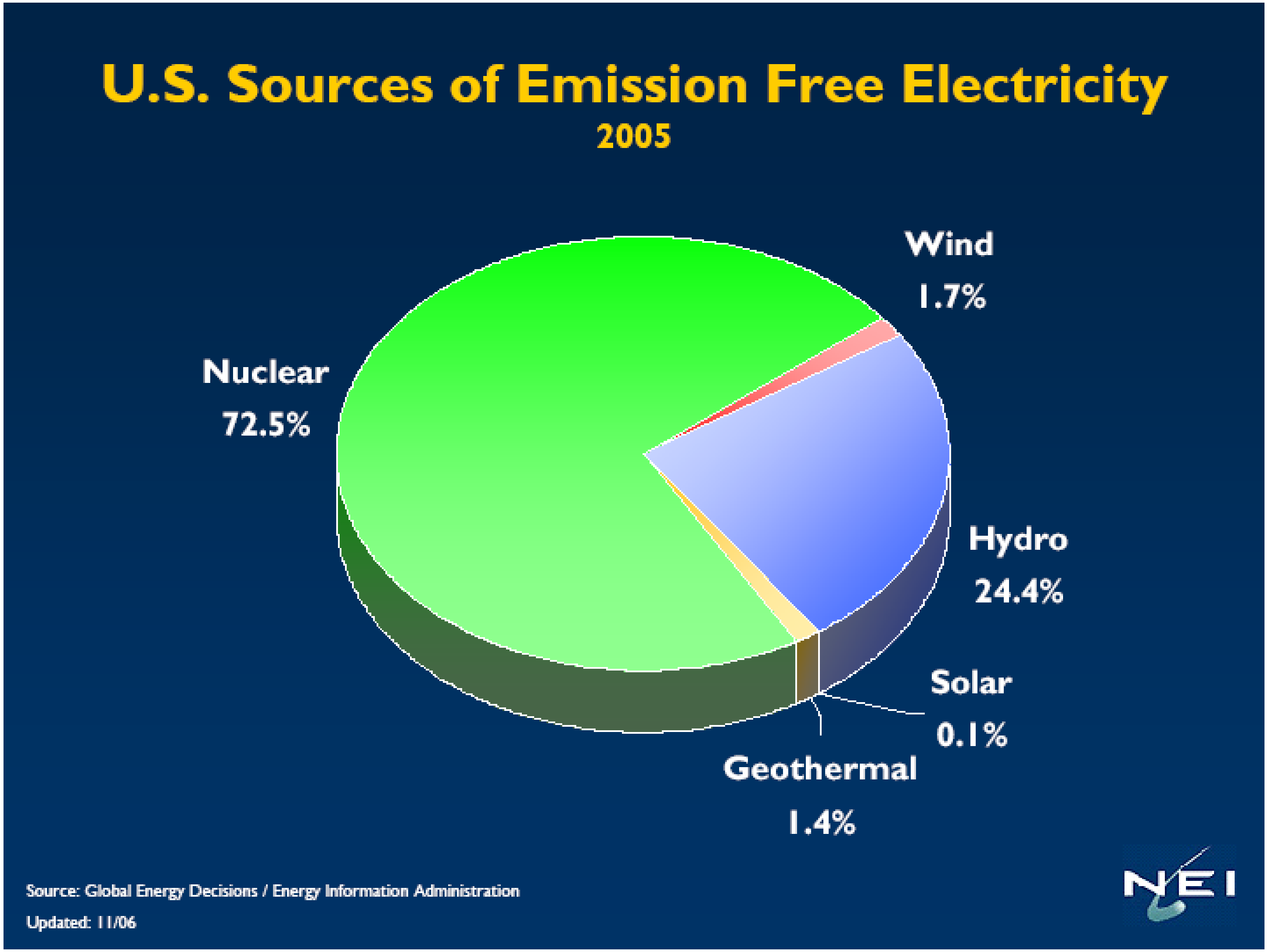
Plant Type	Capacity Factor
Nuclear	89.3
Geothermal	75.5
Coal	72.6
Natural gas	15.6-37.7
Heavy oil turbine	29.8
Hydro	29.3
Wind	26.8
Solar	18.8

Capacity factor = electricity produced/electricity that could be produced
Source: NEI

Nuclear Power Protects the Environment

- In 2005 U.S. Nuclear plants displaced fossil plants that would have emitted into the atmosphere
  - 3.32 Million Tons of SO_2
  - 1.05 Million Tons of NO_x
    - Equivalent to 41% of total passenger auto emission
  - 682 Million Metric Tons of CO_2
    - Equivalent to 96% of total passenger auto emission
- Nuclear power plants accounted for >1/3 of voluntary reductions in greenhouse gases in 2005

Source: NEI


U.S. Sources of Emission Free Electricity
2005
Wind
1.7%
Nuclear
72.5%
Hydro
24.4%
Solar
0.1%
Geothermal
1.4%
Source: Global Energy Decisions / Energy Information Administration
Updated: 11/06
NEI

Nuclear Units Under Construction Worldwide

Country	Units	Total MWe
Argentina	1	692
Bulgaria	2	1,906
China	5	4,220
China, Taiwan	2	2,600
Finland	1	1,600
India	7	3,112
Iran	1	915
Japan	1	866
Pakistan	1	300
Romania	1	655
Russia	5	4,525
S. Korea	1	960
Ukraine	2	1,900
Total	**30**	**24,251**

Source: International Atomic Energy Agency PRIS database

Updated: 2/07

Advanced Reactor Status in USA Regulatory Design Certification

Certified:

- **Advanced Boiling Water Reactor** design by GE Nuclear Energy (May 1997);
- **System 80+** design by Westinghouse (formerly ABB-Combustion Engineering) (May 1997);
- **AP600** design by Westinghouse (December 1999); and
- **AP1000** design by Westinghouse (February 2006)

Active Reviews:

- **ESBWR** – GE Nuclear Energy (2005)
- **EPR** – AREVA (expected in 2007)
- **PBMR** – PBMR Pty Limited (expected in 2008)
- **US APWR** – Mitsubishi (expected in 2008)

New Reactor Status in USA
Utility Permit & License Preparation

- 15 Utilities are spending serious money
  - To prepare ESP and COL requests for submittal in the 2007-2009 time-frame
  - NRC approval for a COL costs $50-$90M (over 3-4 years)
  - At least 36 new nuclear power reactors are expected

- Reactor types to be licensed
  - 15 advanced PWRs (10 AP100,5 EPR)
  - 7 advanced BWRs (4 ABWR, 3 ESBWR)
  - More than 17 TBD

Source: NEI **ESP: Early Site Permit** **COL: Construction and Operating License**

Future Challenge for Nuclear Technology Closing the Nuclear Fuel Cycle

- Natural uranium
  - 0.72% fissionable U^{235} + 99.28% "Fertile" U^{238}
- LWRs use uranium enriched to 3-4% U^{235}
- ~ 1% of the potential energy content of uranium is recovered in the LWR "Once-Through Cycle" (OTC) in the US
  - ~ 3% is in the mining "tails"
  - ~ 2% is in the discharged "spent" fuel as U^{235} and transuranics (TRU) produced from neutron transmutation of U^{238}
  - >90% is in the depleted uranium from the enrichment process and in the U^{238} in the spent fuel

Closing the Nuclear Fuel Cycle (cont.)

- The long lived TRU (Pu, Np, Am, Cm, Cf) in spent fuel are the main reason that spent fuel must be stored in geological repositories for 100,000s of years
- These TRU are all fissionable in a fast reactor
- The >93% of uranium energy content in U^{238} can be recovered in fast reactors by
  - Neutron transmutation of U^{238} into TRU
  - Neutron fission of the TRU

DOE Global Nuclear Energy Partnership (Deployment 2020-2030)

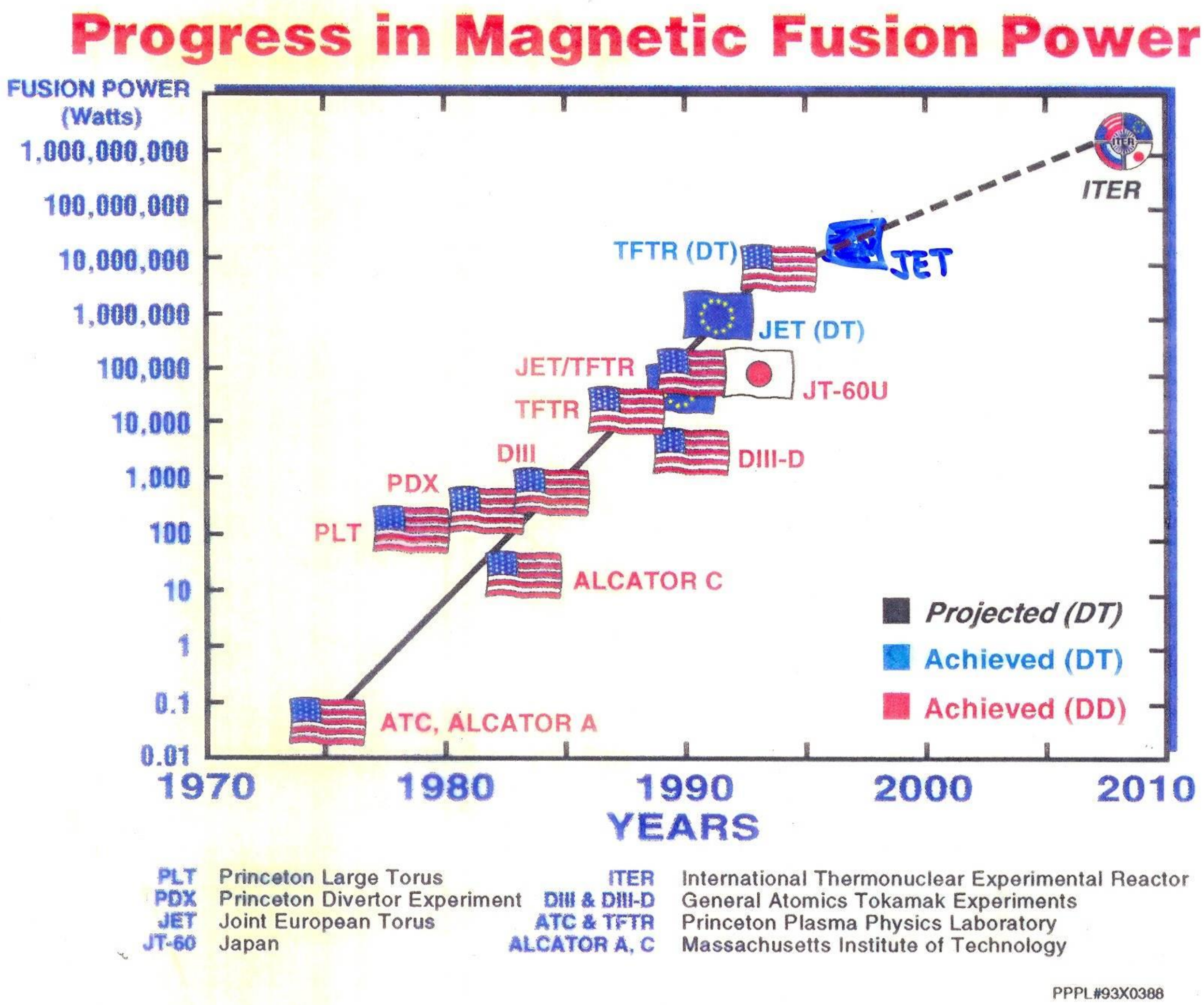
- Purpose
  - To develop a fuel recycling capability to enable fissioning the long-lived transuranic elements (Pu, Np, Am, Cm, Cf) in spent LWR fuel
- Components
  - Advanced burner reactor (ABR)
    - A fast reactor fueled with transuranic nuclei from LWR spent fuel
  - Consolidated fuel treatment center
    - A recycling facility that would separate the transuranics from the fission products
  - Advanced fuel cycle facility
    - For reactor fuels research
- Promise
  - Reduce high-level waste repository requirements by 10-100
    - a new Yucca Mountain every 300 years instead of every 30 years (at present nuclear power level)
  - Reduce proliferation possibilities

International Generation-IV Studies Possible Future Reactors

- Reactor Types
  - Sodium cooled fast reactor – closed fuel cycle for uranium conversion and transuranic fission (2020)
  - Lead cooled fast reactor – closed fuel cycle for uranium conversion and transuranic fission (2025)
  - Gas-cooled fast reactor – closed fuel cycle for uranium conversion and transuranic fission (2025)
  - Very high temperature reactor – gas cooled thermal reactor for hydrogen production (2020)
  - Supercritical water reactor – high temperature thermal reactor (2025)
  - Molten salt reactor – circulating fuel epi-thermal reactor with transuranic recycle (2025)

Fusion

- Major advances have been made in both magnetic and inertial fusion research
- The Tokamak magnetic fusion concept has reached the threshold of the physics parameter range needed for a fusion reactor
- Fusion technology that would support a fusion experimental reactor has been developed


Progress in Magnetic Fusion Power
FUSION POWER (Watts)
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0.1
0.01
1970
1980
1990
2000
2010
YEARS
ITER
JET
TFTR (DT)
JET (DT)
JET/TFTR
JT-60U
TFTR
DIII
DIII-D
PDX
PLT
ALCATOR C
ATC, ALCATOR A
Projected (DT)
Achieved (DT)
Achieved (DD)
PLT Princeton Large Torus
PDX Princeton Divertor Experiment
JET Joint European Torus
JT-60 Japan
ITER International Thermonuclear Experimental Reactor
DIII & DIII-D General Atomics Tokamak Experiments
ATC & TFTR Princeton Plasma Physics Laboratory
ALCATOR A, C Massachusetts Institute of Technology
PPPL#93X0388

INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

- Construction of the first fusion experimental reactor (ITER) is beginning in 2007
  - Initial operation is planned for 2016
  - ITER will
    - produce 400 MW_{th} power
    - produce fusion power= 10 x external power to heat plasma
    - demonstrate & test reactor-relevant fusion technology
- ITER will serve as
  - A test-bed for a demonstration fusion power reactor, and
  - A prototype for a fusion neutron source to drive a sub-critical fast reactor to fission TRU fuel or convert U238 into TRU

Summary and Conclusions

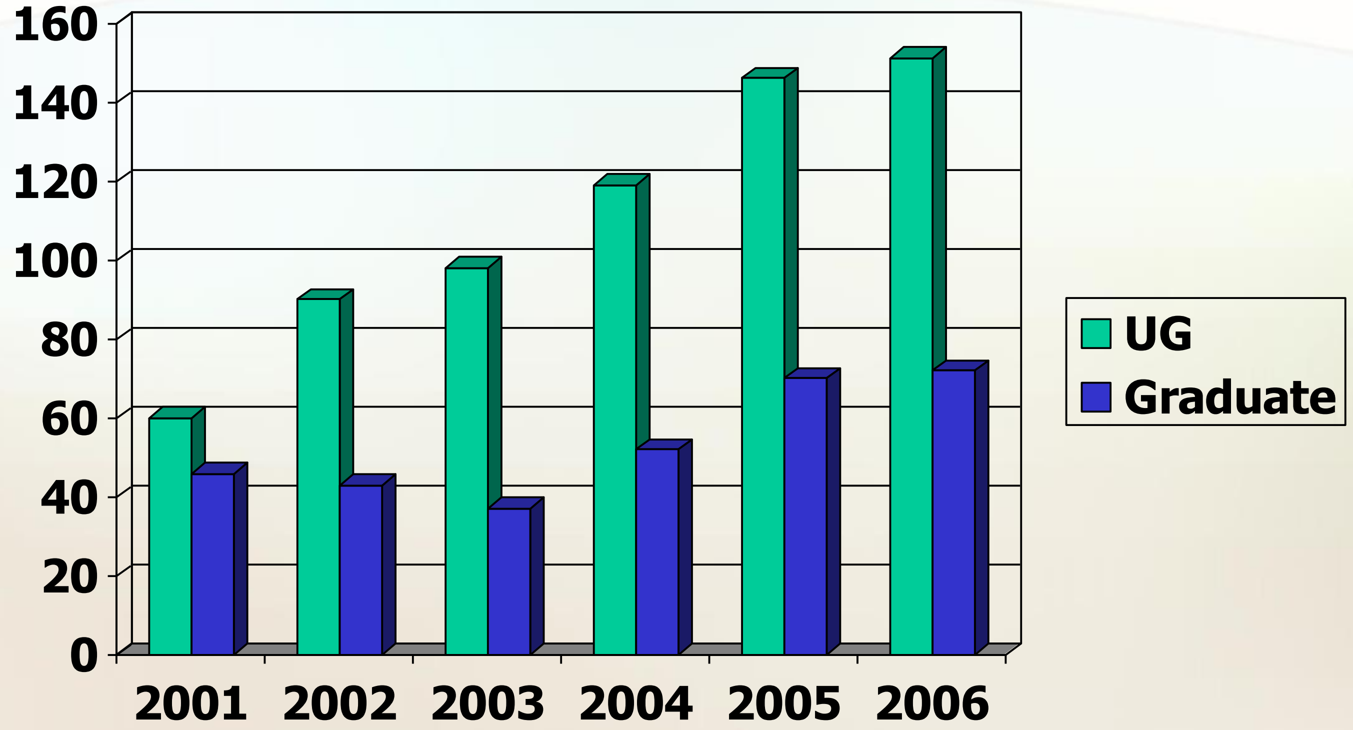
- Nuclear Energy is an established technology that is
  - Reliable
  - Economical
  - Emission-free
  - Provides 16% of the World's Electric Power
- The World's Uranium (and Thorium) resources would support a substantial expansion of the emission-free nuclear energy component of the World's growing electrical power production

Summary and Conclusions (cont.)

- The technical challenge for Nuclear Energy is closing the Nuclear Fuel Cycle by
  - Fissioning rather than burying the TRU discharged from LWRs
  - Transmuting the fertile U^{238} into TRU that can be fissioned to recover energy
- This challenge is being addressed – GNEP, GEN-IV
- In the longer term (>2050)
  - Fusion will enable the World's Lithium resources and ultimately seawater to provide an unlimited resource for emission-free electrical power

Student Interest in Nuclear Energy is Increasing

NRE Enrollment Trend at Georgia Tech



Nuclear Energy Research at Georgia Tech

- Advanced Nuclear Reactor Design
  - Generation-IV & Advanced Burner Reactor Design
  - Analyses of Closing the Nuclear Fuel Cycle
- Nuclear Reactor Core Simulation Methods
  - Improved Computational Models for Advanced water reactors, VHTRs, ABR
  - Advanced Radiation Transport Code (neutron, photon & electron transport)
- Fusion Plasma Physics and Technology
  - Plasma Theory & Exp. (D-III National Tokamak Team)
  - Conceptual Design of Neutron Sources & Reactors
- Heat Removal from Fission & Fusion Reactors
- Radiation Detection and Protection

Questions?

Appendix A

a J thermal fuel consumption = 1/3 J electrical

b > 4000 kWh per capita per year PER

c **Population growth rat 0.1 – 1.0% per year**

d Population growth rate 1% per year

Appendix B

[a] Source: World Energy Institute, 1999

[b] 1 tonne U = 13,000 toe in LWR OTC @ 1% utilization = 5.46e14 J

[c] 100% utilization via transmutation of U238 into Pu239

[d] Source: US Geological Survey Mineral Commodity Summaries, 2005

[e] **1** ton Th232 = 2.7e28 atoms U233 on neutron capture, which yields 8.1e16 J when fissioned

[f] Source: US Geological Survey Mineral Commodity Summaries, 2001

[g] 1 ton Li = 7.8e28 atoms T on neutron capture, which yields 2.2e17 J when fused with D

[h] For D-D fusion, the fuel is seawater, which is virtually an unlimited energy resource

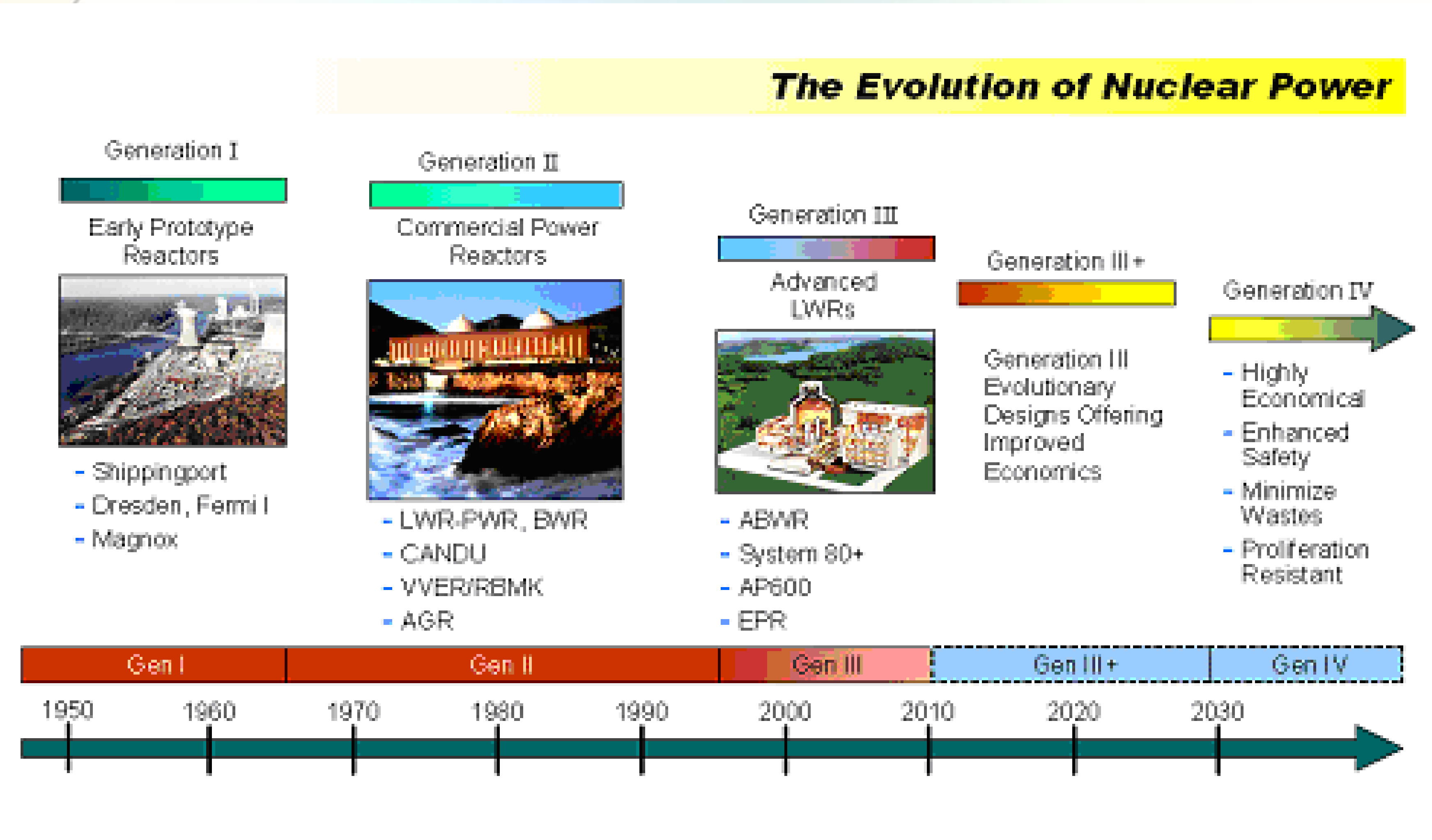
NOTES

1. Heavy oils and bitumen resources comparable to Mideast oil reserves, but recoverability is an issue.
2. Methane hydrates exceed conventional gas reserves, but recoverability is an issue.
3. Windpower comparable to electricity demand is technically feasible, but land use is an issue.

Nuclear Reactors

- Nuclear reactors are assemblages of fuel, coolant, structure, shielding, etc
- Controlled neutron chain reaction is maintained by fissioning heavy mass nuclei (e.g., U^{235})
- The thermal energy is then removed and converted to electricity or process heat
- Reactors are characterized by
  - Neutron energy distribution, e.g.,
    - Thermal
    - Fast
  - Energy distribution is mainly determined by the coolant (moderator) type, e.g.,
    - Water (thermal reactors)
    - Sodium (fast reactors)

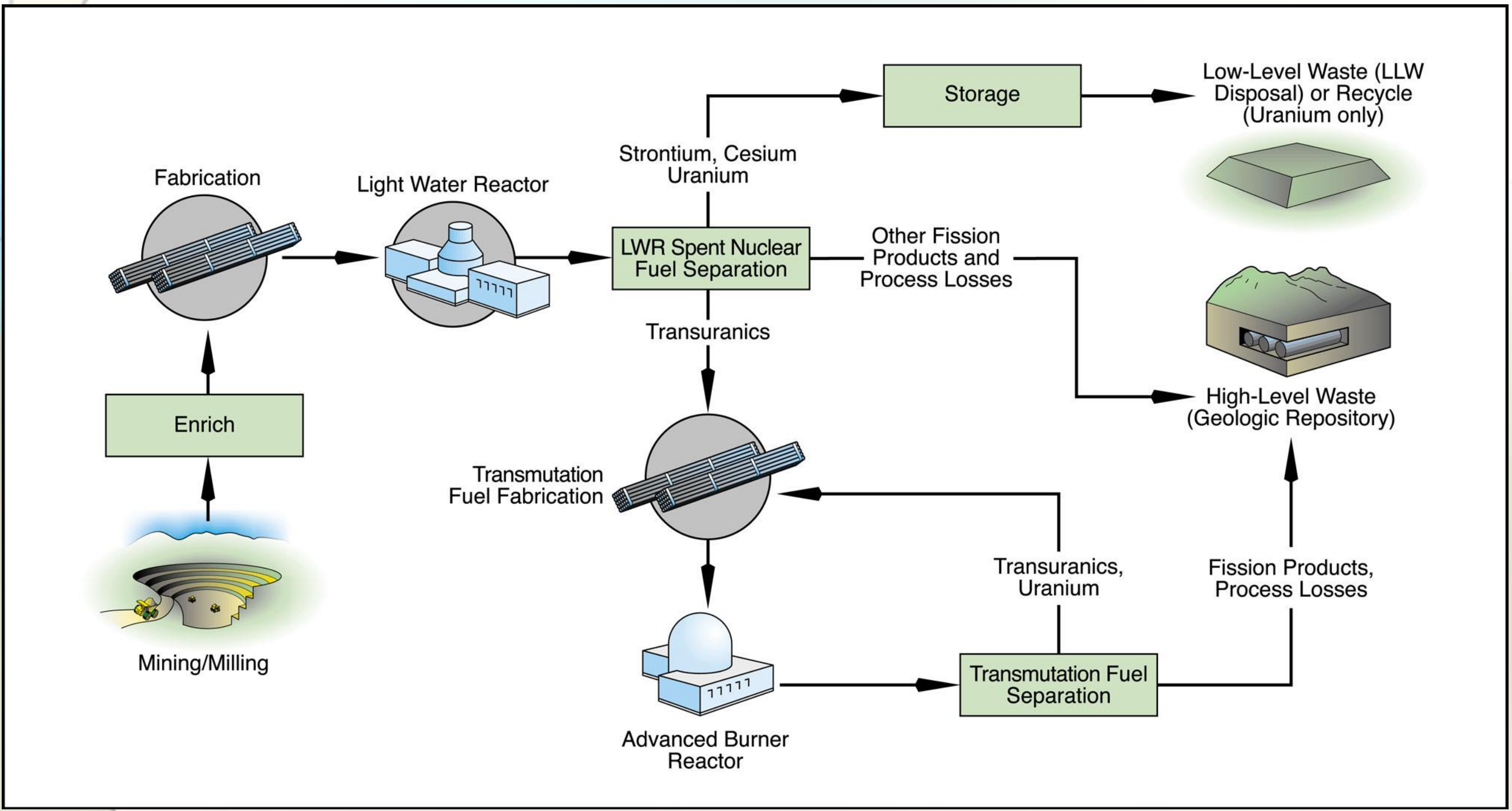
Nuclear Reactor Evolution



World Nuclear -- Electricity Production (Source: NEI)

Country	#	MWe (1/07)	%
Belgium	7	5,801	55.6
Canada	18	12,584	14.6
China	16	12,456	2.0
France	59	63,363	78.5
Germany	17	20,339	31.0
India	16	3,483	2.8
Japan	55	47,593	29.3
Korea	20	16,810	44.7
Russia	31	21,743	15.8
Spain	8	7,450	19.6
Sweden	10	8,909	46.7
Switzerland	5	3,220	32.1
Ukraine	15	13,107	48.5
U.K.	19	10,982	19.9
U.S.	103	98,466	19.3
Other	36	21,487	
Total	435	367,793	16.0

GNEP Deployment System



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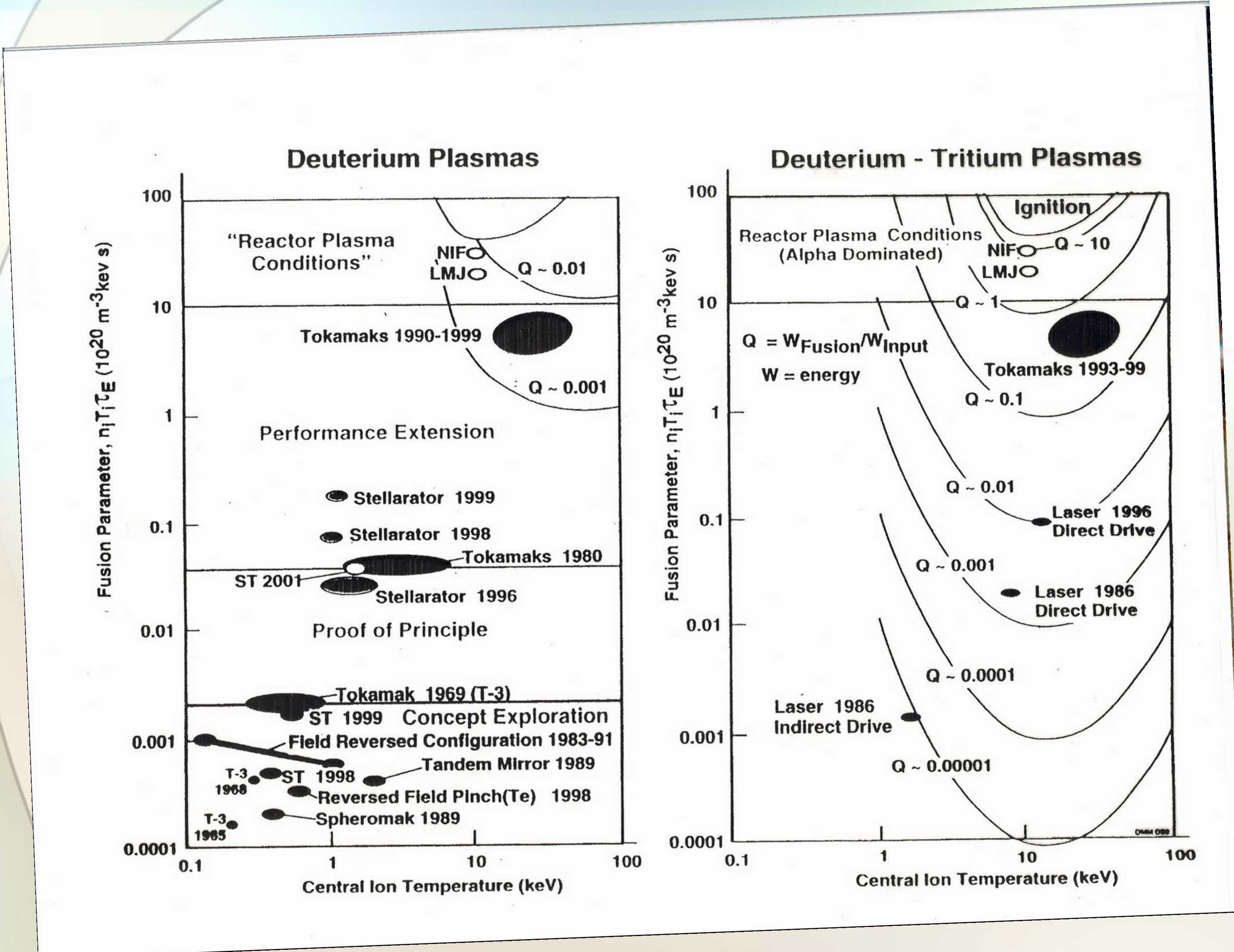
Generation-IV Studies of Possible Future Reactors

- Purposes is to achieve
  - better uranium utilization
  - minimum nuclear waste discharge
  - enhanced safety
  - reduced cost
  - enhanced proliferation resistance
  - produce energy and/or hydrogen

- Potential deployment in 2030-2040



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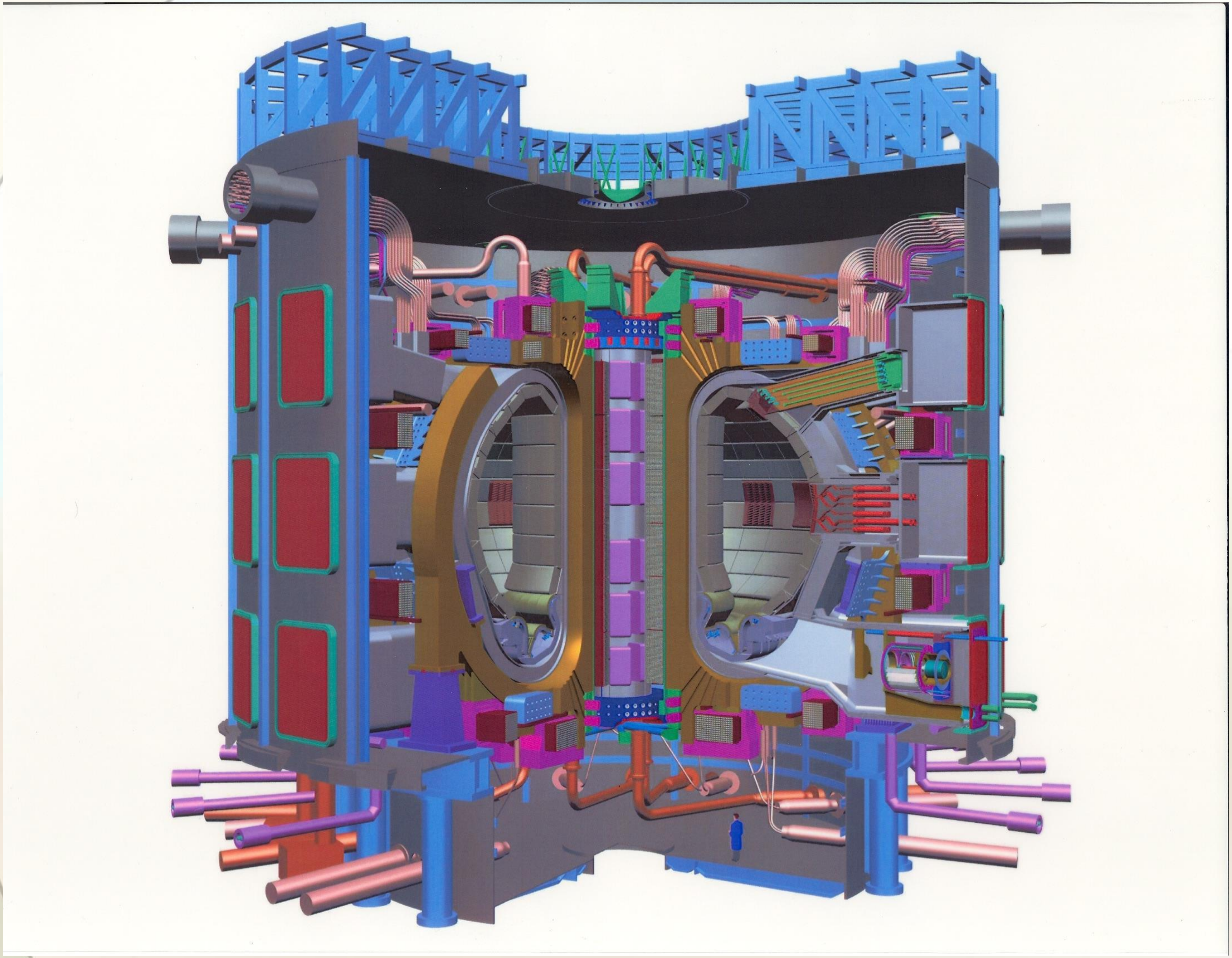

Nuclear Energy Education at Georgia Tech

- Nuclear and Radiological Engineering Program offers the following degrees
  - BSNRE
  - MSNE
  - PhD

- One of the largest NE enrollments in the US