Nuclear Energy 101

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Stanford University
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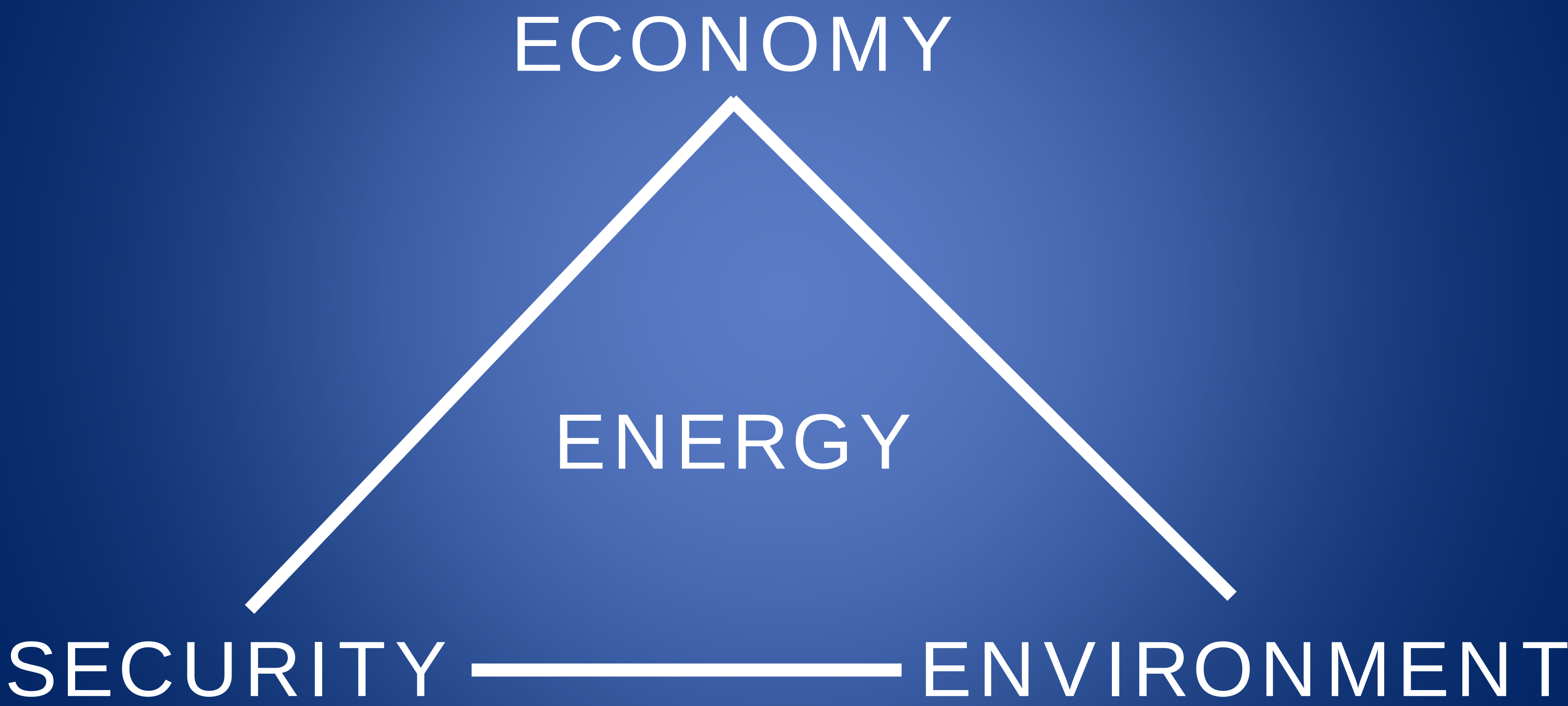
1. Energy in the 21st Century

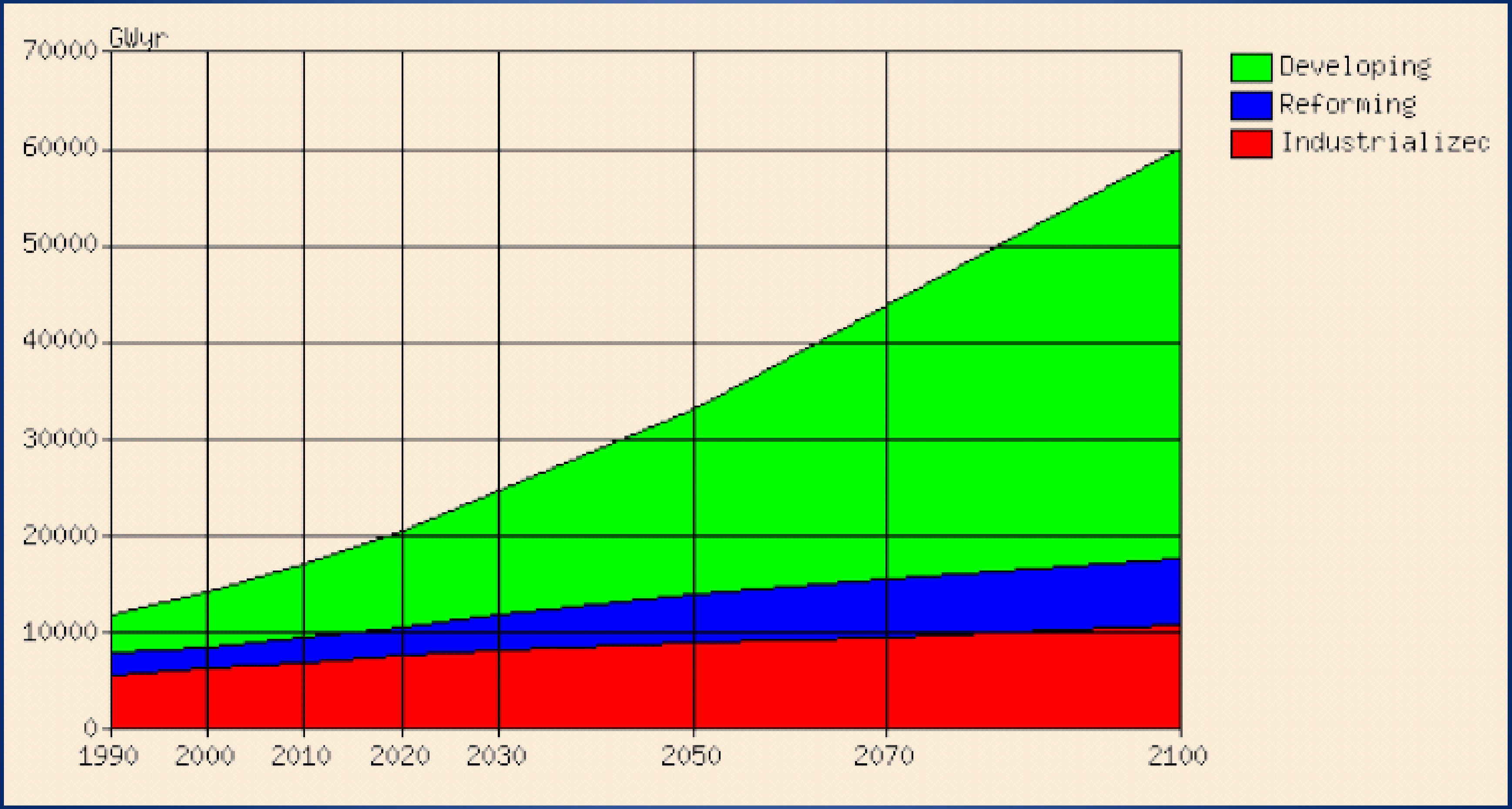
Energy and Society – 3 Dimensions



Energy and Emissions in a Growing World Economy

- Energy = (Population) x (GDP/Population) x (Energy/GDP)
- Emissions = Energy x (Emissions/Energy)
- World Population: 7 Billion now, projected to increase to 9 B by 2050 and 10 B by 2100
- World Per Capita Income is going up
- World Energy Demand and Emissions in "Business as Usual" case must go up to match the economic requirements

IIASA Projection of Future Energy Demand Scenario A1 (High Growth)



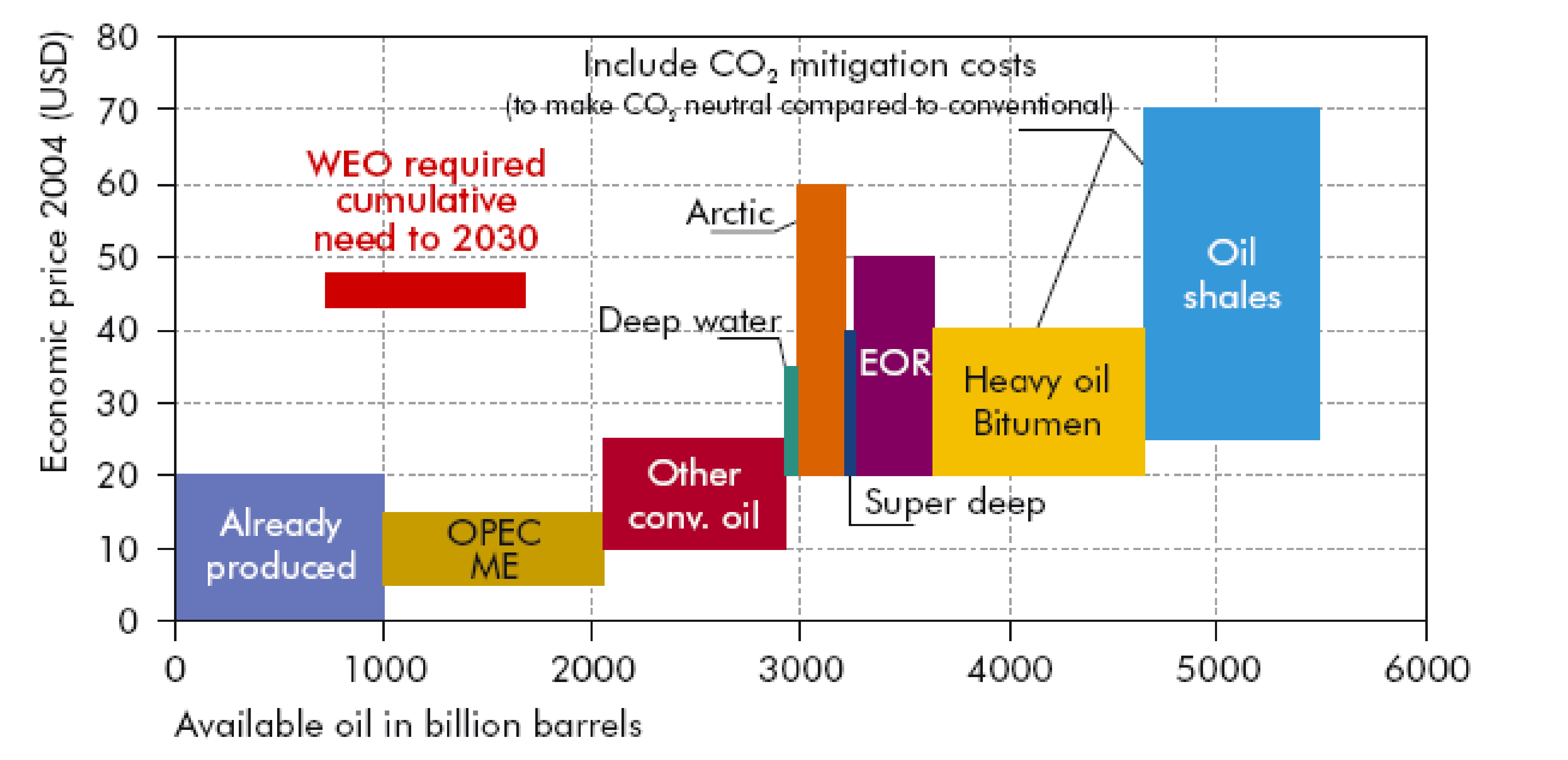
Percentage of Total Primary Energy Supply (TPES) and World CO_2 Emissions by Fuel

Energy Source	Percentage of TPES	Percent of World CO_2 Emissions
Oil	36	37
Coal	20	43
Natural Gas	25	20
Nuclear Power	10	0
Hydroelectric	2.5	0
Combustibles	5	0
Renewables	1.5	0

Source : IEA –Key World Energy Statistics 2012

Oil Supply and Cost

Availability of oil resources as a function of economic price



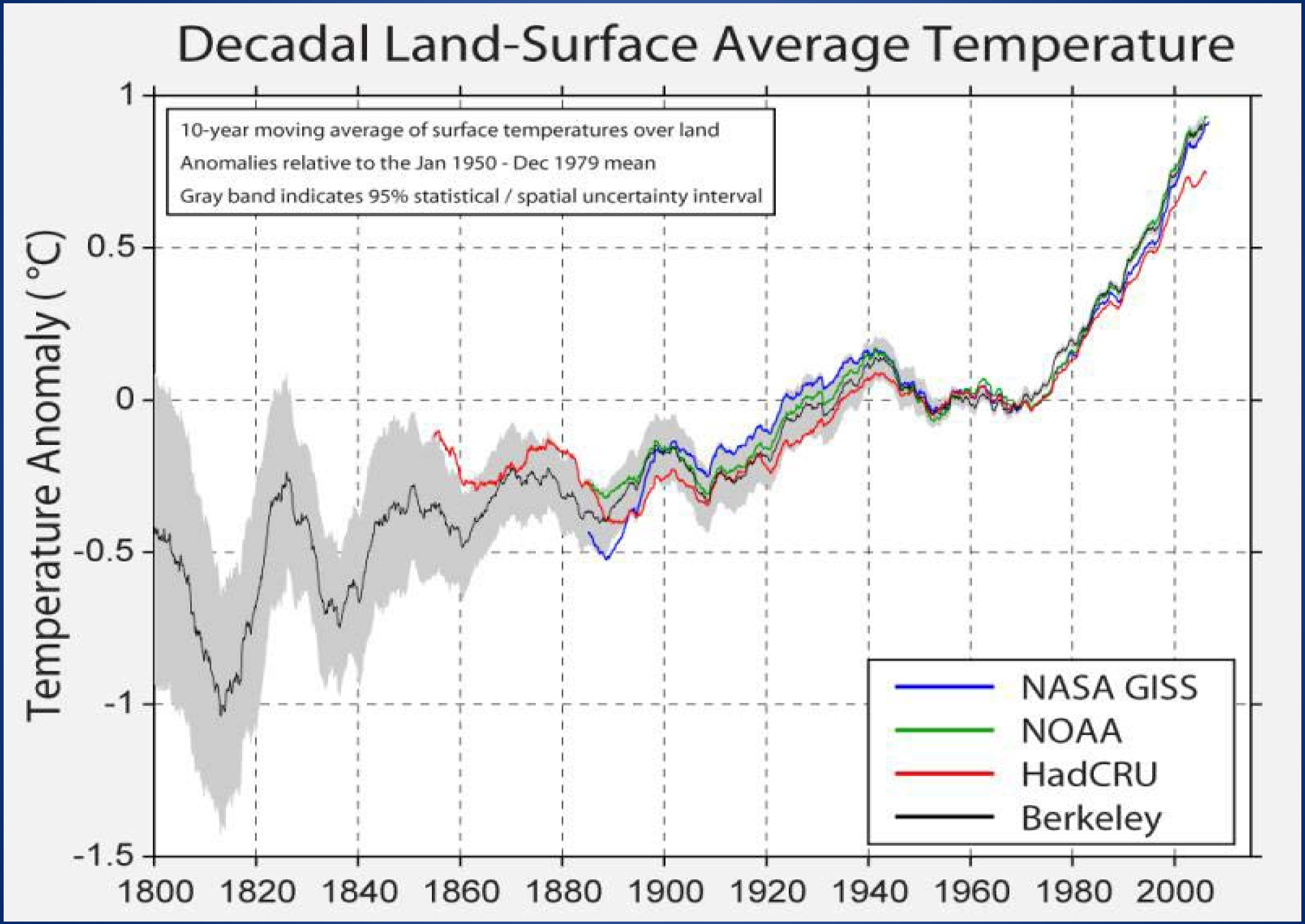
We won't run out of oil – we will run out of cheap oil

Source: IEA (2005)

Economic and Security Dimensions

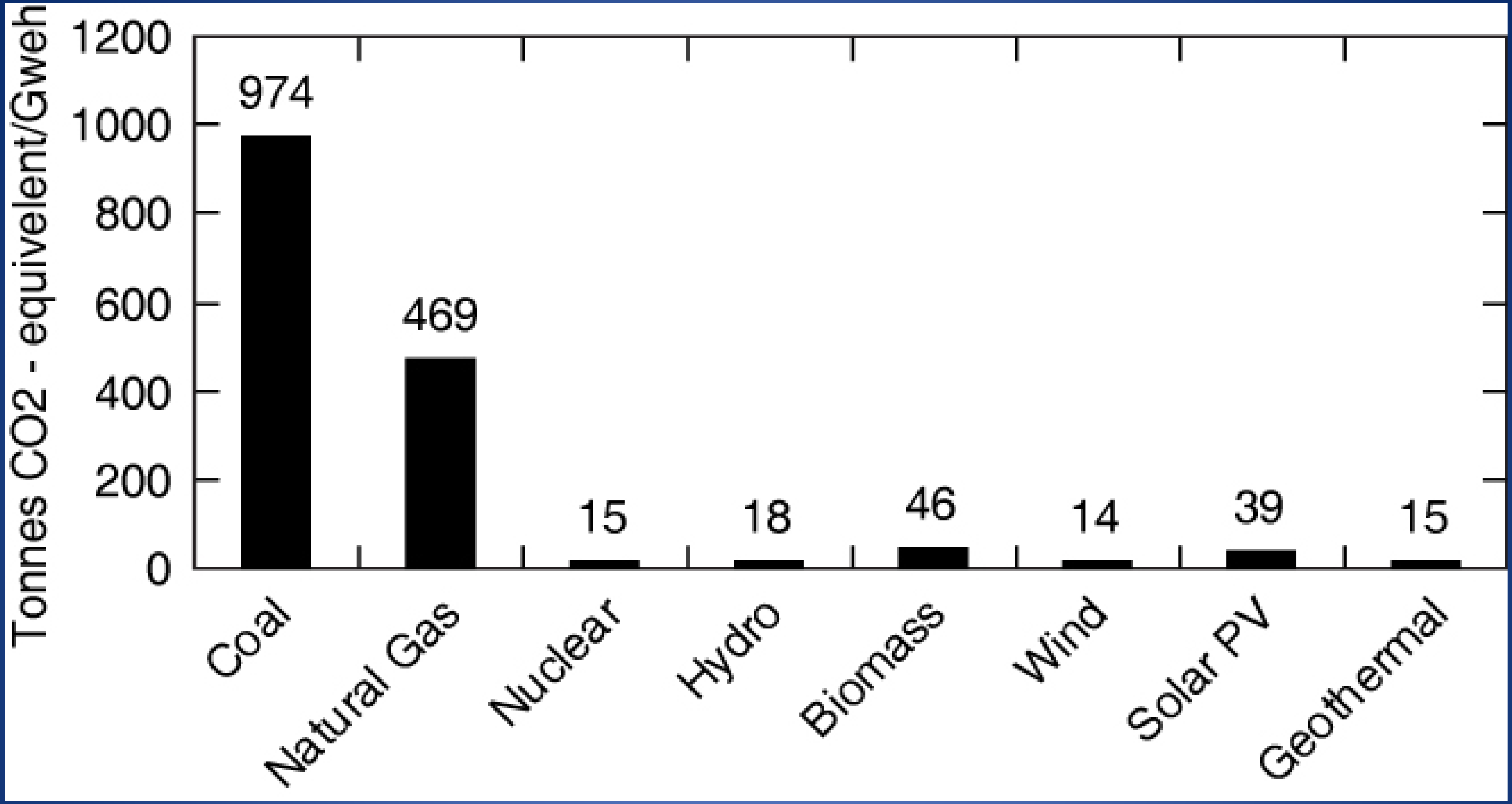
- Increase in population and increase in income are not compatible with ever increasing energy prices
- National security drives nations to look for supplies of energy that they can control
- Environmental issues also drive the move away from fossil

Global Warming



Source: http://berkeleyearth.org

Lifecycle Emissions for Various Electricity Generation Technologies



Comparison of Life Cycle Emissions in Metric Tonnes of CO_2e per GW-hour for various modes of Electricity Production; P.J. Meier, *Life-Cycle Assessment of electricity Generation Systems with Applications for Climate Change Policy Analysis,* Ph.D. dissertation, University of Wisconsin (2002); S. White, *Emissions form Helium-3, Fission and Wind Electrical Power plants,* Ph.D. Dissertation, University of Wisconsin (1998); M. K. Mann and P. L. Spath, *Life Cycle Assessment of a Biomass Gasification Combined-Cycle System*, (1997), www.nrel.gov/docs/legosti/fy98/23076.pdf *(ref 33).*

By 2100 The Energy Picture Must Change

- The countries we now call developing will use 85% of TPES, but the mix will certainly be different.
- They will have 6 times the population of those now called developed.
- These now poor countries will be most concerned about the cost of energy.
- The only low cost, steady renewable today is big hydro (and environmentalists don't like it).
- This is what is driving the interest in a big expansion of nuclear in the developing world, regardless of what happens in Europe and the U.S.

2. Nuclear Basics

Burning and Breeding Fuel

- Fissile nucleus
  - Add a neutron and it fissions releasing a large amount of energy
  - Uranium-233 & 235, and Plutonium-239 are Fissile
  - Only U235 exists naturally now
- Fertile nucleus
  - Capture a neutron and turn fertile into fissile
  - Uranium-238 + n makes Plutonium 239
  - Thorium-232 + n makes Uranium 233

How A Reactor Works

- A neutron hits U-235 (fissile) which fissions, turning into 2 lighter nuclei (fission products), releasing lots of energy (200 MeV), **AND** releasing 2.4 neutrons on average (200 MeV = 4000 miles of flashlight batteries; 1 pound of U = energy in 5000 tons of coal)
- Some neutrons are absorbed by coolant and structure
- Some are absorbed by U-238 (fertile), turning it into plutonium 239 (fissile)
- One has to be left to be captured by the fissile material which fissions to keep the cycle going.

Nuclear Basics

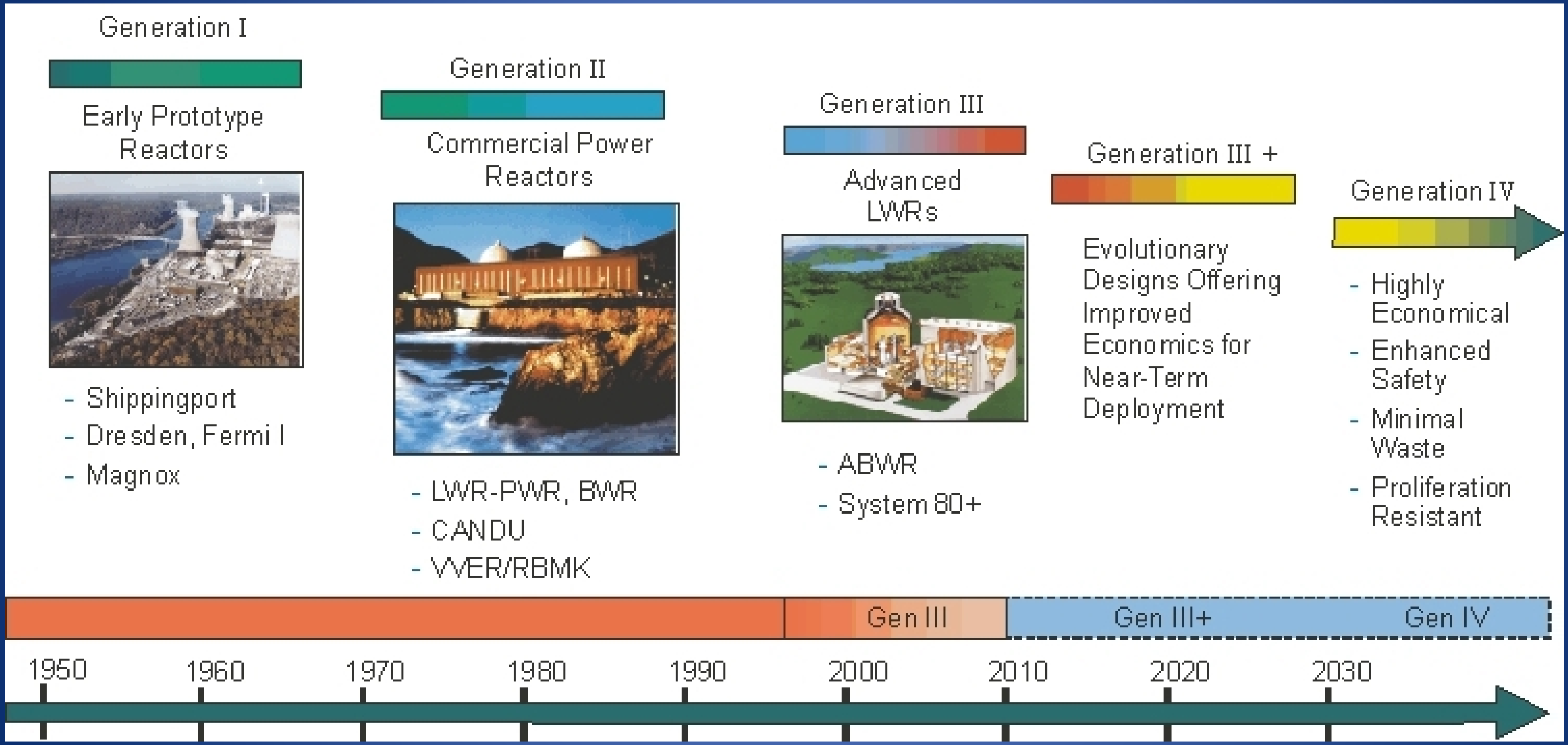
LWRs: Produce about 85% of nuclear power generation at about 35% thermodynamic efficiency

Fuel: 4.5% U-235, 95.5% U-238 (U ore is 0.7% U-235)

Moderator: H_2O; Collisions of neutron & hydrogen reduces neutron energy to thermal levels (about 0.05 eV)

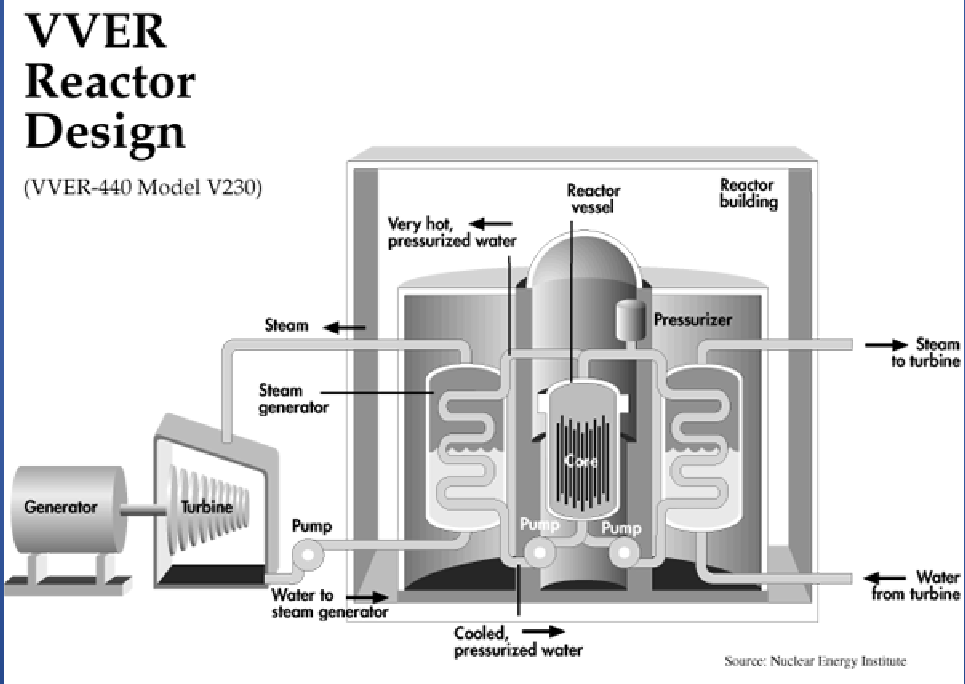
Coolant: H_2O at pressures of 155 Bars (PWR) or 70 Bars (BWR) and T of 350° C to 290° C

The Generations of Nuclear Power Reactors



Source: DOE Generation IV Project

Cartoon of a Pressurized Water Reactor (PWR)



From The Virtual Nuclear Tourist www://nucleartourist.com

Types of Power Reactors Today

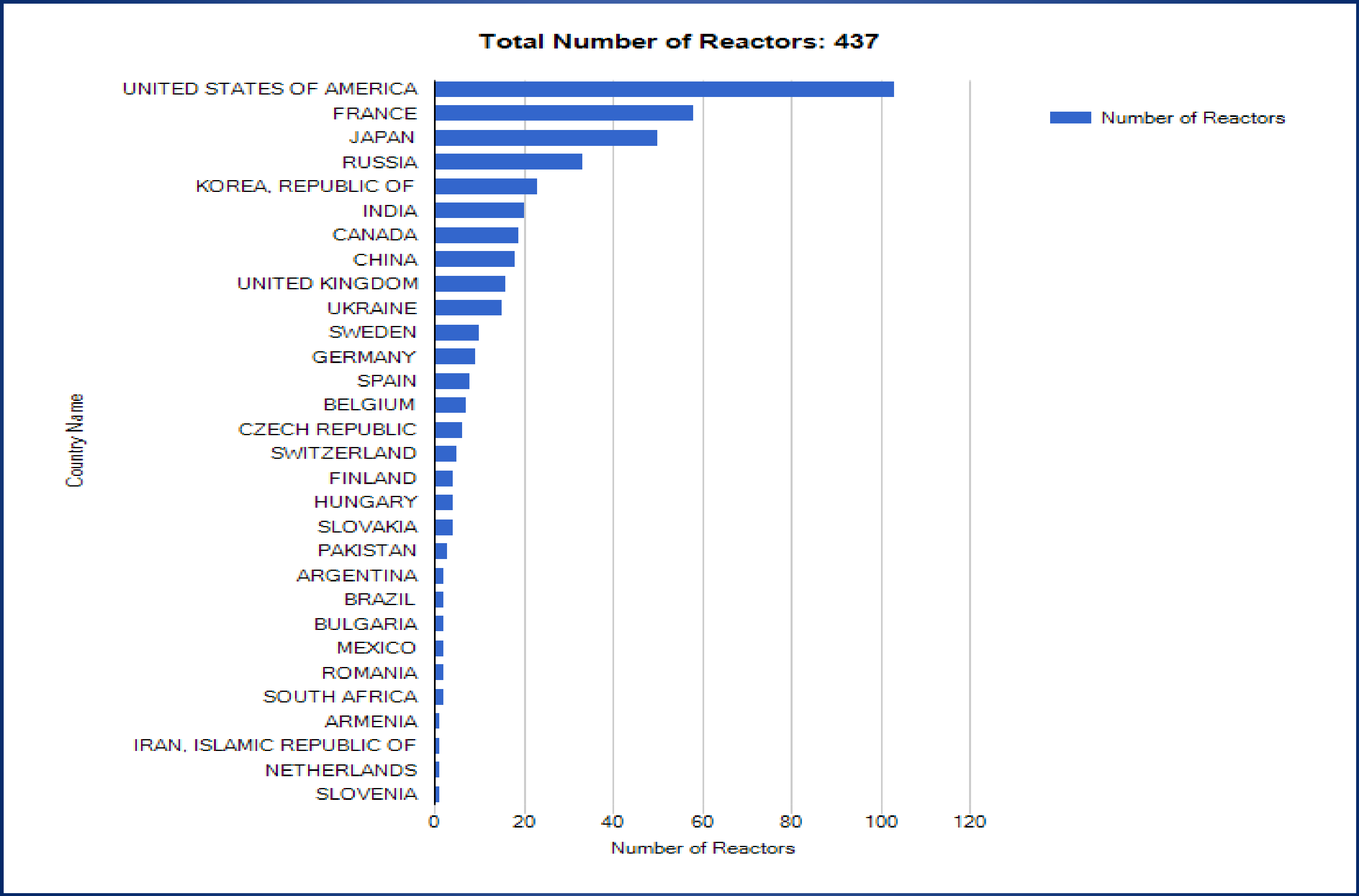
• Pressurized Water	270
• Boiling Water	84
• Gas Cooled	17
• Pressurized Heavy Water	47
• Graphite Moderated	15
• Fast Breeders	2
• Total	435

Fraction of Electricity Generation by Fuel 2010

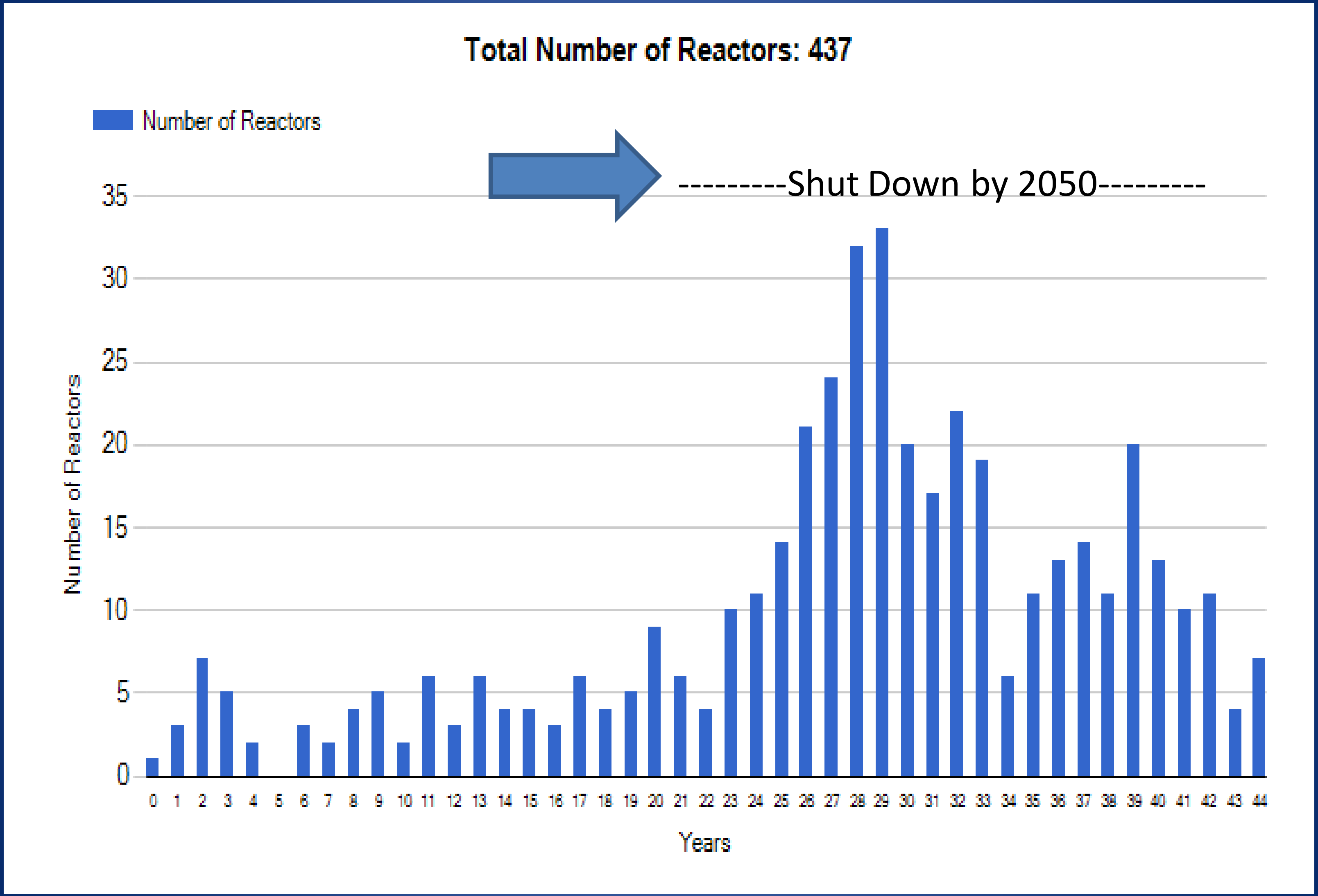
Fuel	U.S.	World
Coal	42%	40%
Natural Gas	25%	20%
Oil	1%	6%
Nuclear	19%	16%
Hydroelectric	8%	16%
Biomass	2%	1.3%
Wind	3%	0.5%
Geothermal	0.4%	0.3%
Solar	0.1%	0.02%

Source: EIA 2011; IEA World Energy Outlook 2008

Operating Reactors by Country



Number of Reactors by Age



Building a New Reactor

- Site License from NRC
  - At an existing site or a new site;
  - Public hearings required
  - In depth environmental review
- Design Certification of the Reactor
  - Only designs approved by NRC can be built in the US
- Construct – Operate License from NRC
  - Public hearings and comments before decision

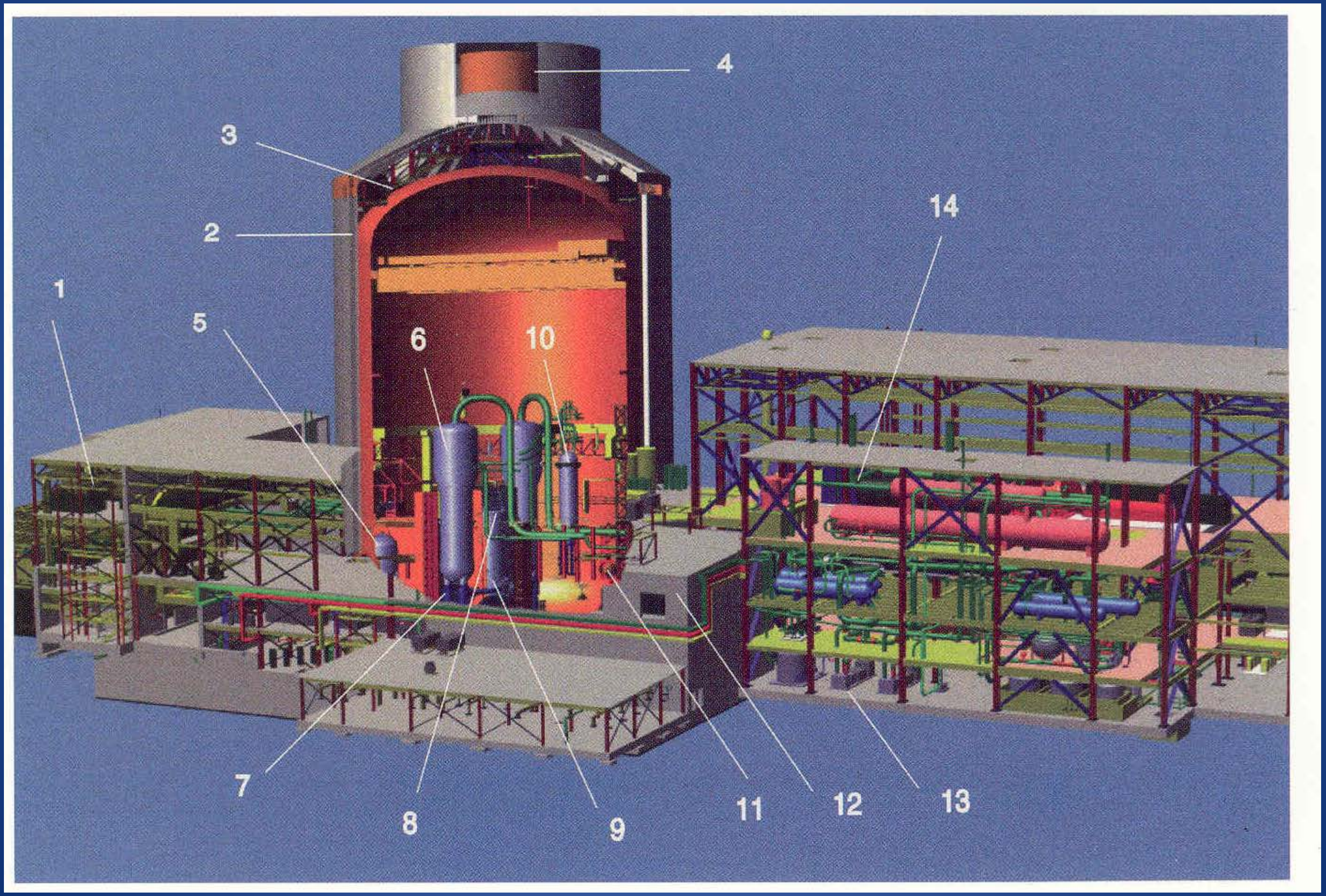
Vogtle Unit 3 Under Construction

Plant Vogtle Unit 3 containment vessel bottom head inside nuclear island

July 2013

Generation III+ Reactors

Westinghouse AP1000 PWR



Reactor Vessel 15 ft diameter; Containment building 100 ft. diameter

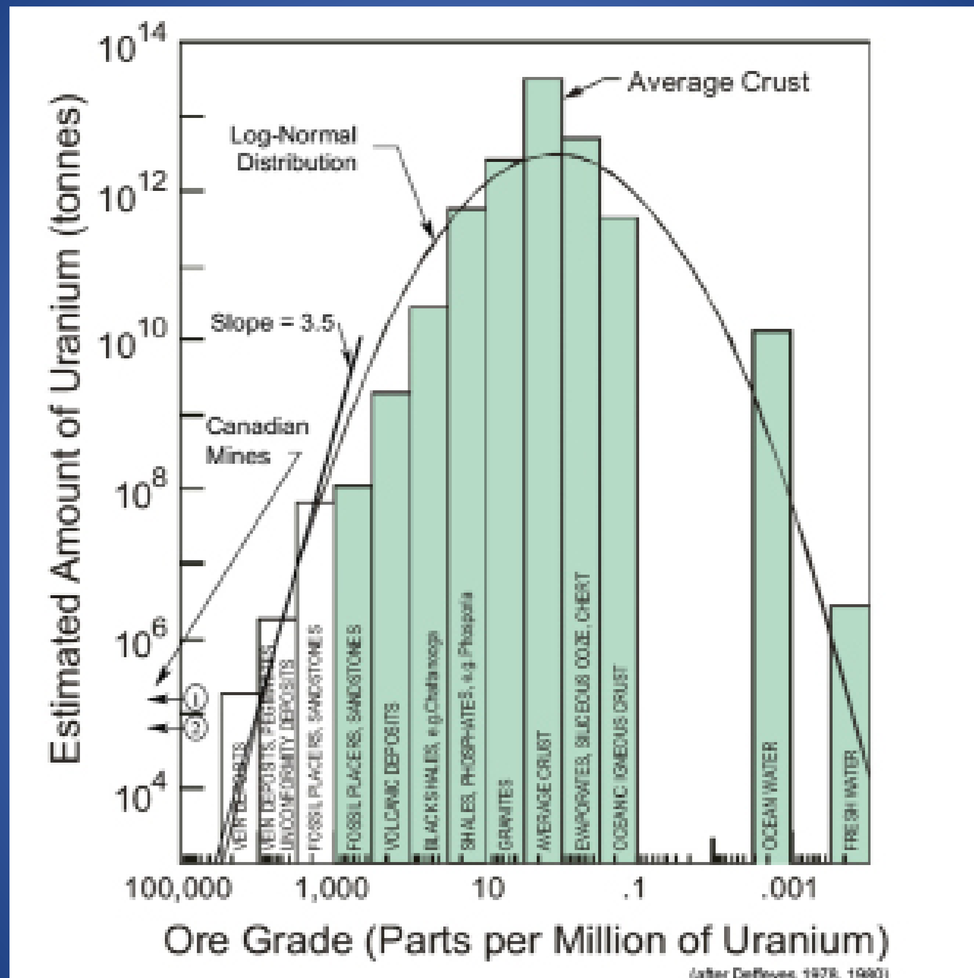
Summary – Nuclear Power Now

- 437 Reactors now supply 16% of world electricity
- 365 will shut down by 2050 because of old age
- Electricity demand will double by 2050
- To keep nuclear share the same (16%) we need about 800 new ones by 2050 or about 20 new ones turning on per year
- 68 new reactors are under construction now; 4 in the US

3. The Nuclear Fuel Cycle

- Mine Uranium ($U_3 O_8$)
- Enrich ($U F_6$)
- Burn in Reactor ($U O_2$)
- Extract and Cool Spent Fuel
- Dispose of Spent Fuel

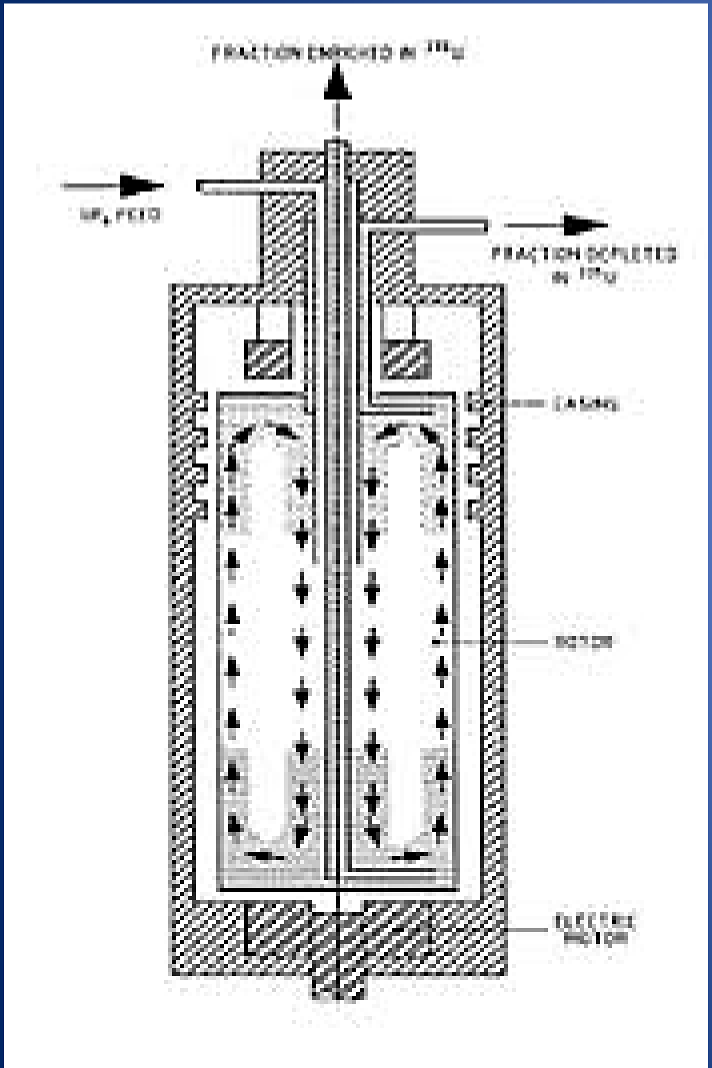
Uranium Availability



Distribution of Uranium in the Earth's Crust

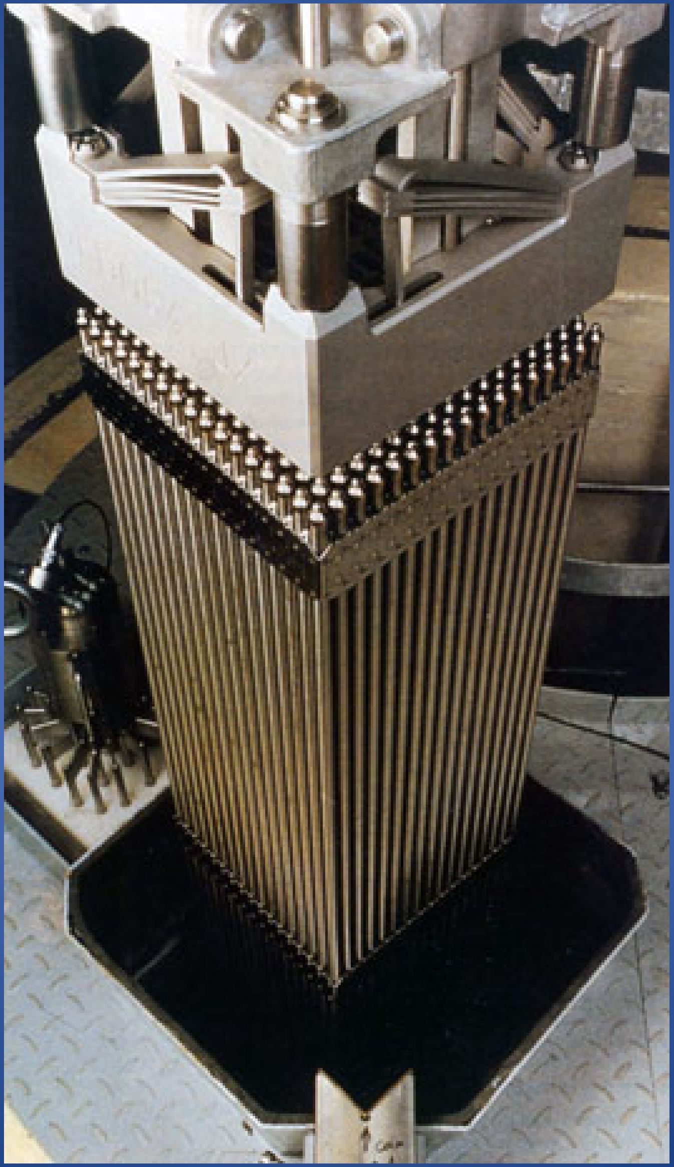
Deffeyes and Macgregor, Scientific American, 1980

Centrifuge Enrichment

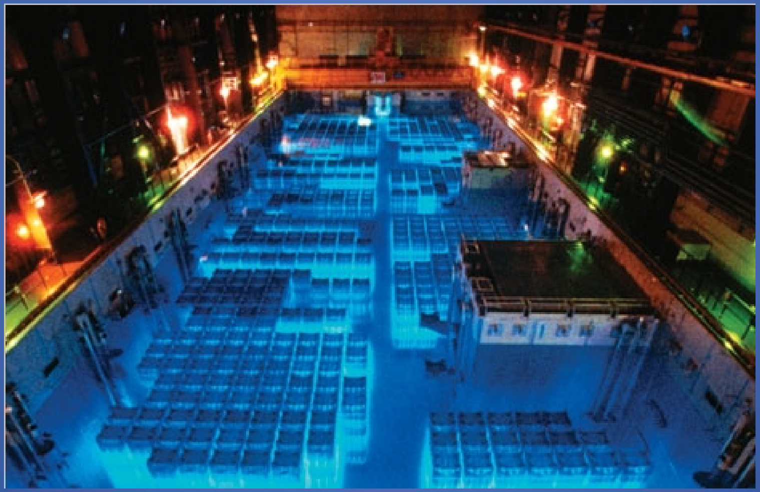


See www.fas.org/programs/ssp/nukes/index.html

Fuel Rod Assembly



Spent Fuel Cooling Pond



Source: http://www.energy-net.org

Dry Cask Storage

Source: Whole Earth Discipline; http://discipline.longnow.org

Yucca Mountain

4.Nuclear Power Issues

a) Is it Affordable?
b) What do we do with Used Fuel?
c) Is it Safe in Normal Operations?
d) What about Accidents?

4a: Cost of 1 Kilogram of Fuel

Uranium:	**8.9 kg U_3O_8 x $146**	**US$ 1300**
Conversion:	**7.5 kg U x $13**	**US$ 98**
Enrichment:	**7.3 SWU x $155**	**US$ 1132**
Fuel fabrication:	**per kg**	**US$ 240**
Total:		**US$ 2770**

Fuel costs amount to
0.7 cents/kw-hour of electricity

Source: World Nuclear Association 2011

Some US Capital and Electricity Costs

	EPC cost	capacity	Electricity cost
Gas combined cycle, gas @ $3.70/GJ	$1000/kW	90%	$44.00/MWh
Gas combined cycle, gas @ $5.28/GJ	$1000/kW	90%	$54.70/MWh
Gas combined cycle, gas @ $6.70/GJ	$1000/kW	90%	$61.70/MWh
Gas combined cycle, gas @ $6.70/GJ, 50-50 debt-equity	$1000/kW	90%	c $70/MWh
Supercritical pulverized coal, 1300 MWe	$3000/kW	85%	$75.70/MWh
Integrated gasification combined cycle coal, 1200 MWe	$3800/kW	85%	$94.30/MWh
Nuclear, 1400 MWe (EIA's EPC figure)	$5500/kW	90%	$121.90/MWh
Nuclear, 1400 MWe (NEI suggested EPC figure)	$4500-5000/kW	90%	$85-90/MWh
Wind farm, 100 MWe	$1000/kW	30%	112.90/MWh

Sources: Nuclear Energy Institute and DOE Energy Information Agency 2013

Cost Conclusion

- Capital cost in US about $5000/KW-hr
- Capital cost in Japan and S. Korea $ 2900/KW for last 7 reactors built (2009 dollars, why so low?)
- MIT 2009 estimate of nuclear electricity cost from a new plant (at the plant):

  6 – 8 cents/KW-hr with loan guarantees

  8 – 11 cents/KW-hr without loan guarantees
- Two new reactors in US are under construction now. Two more are starting. If they come in on time and on budget nuclear will continue to expand

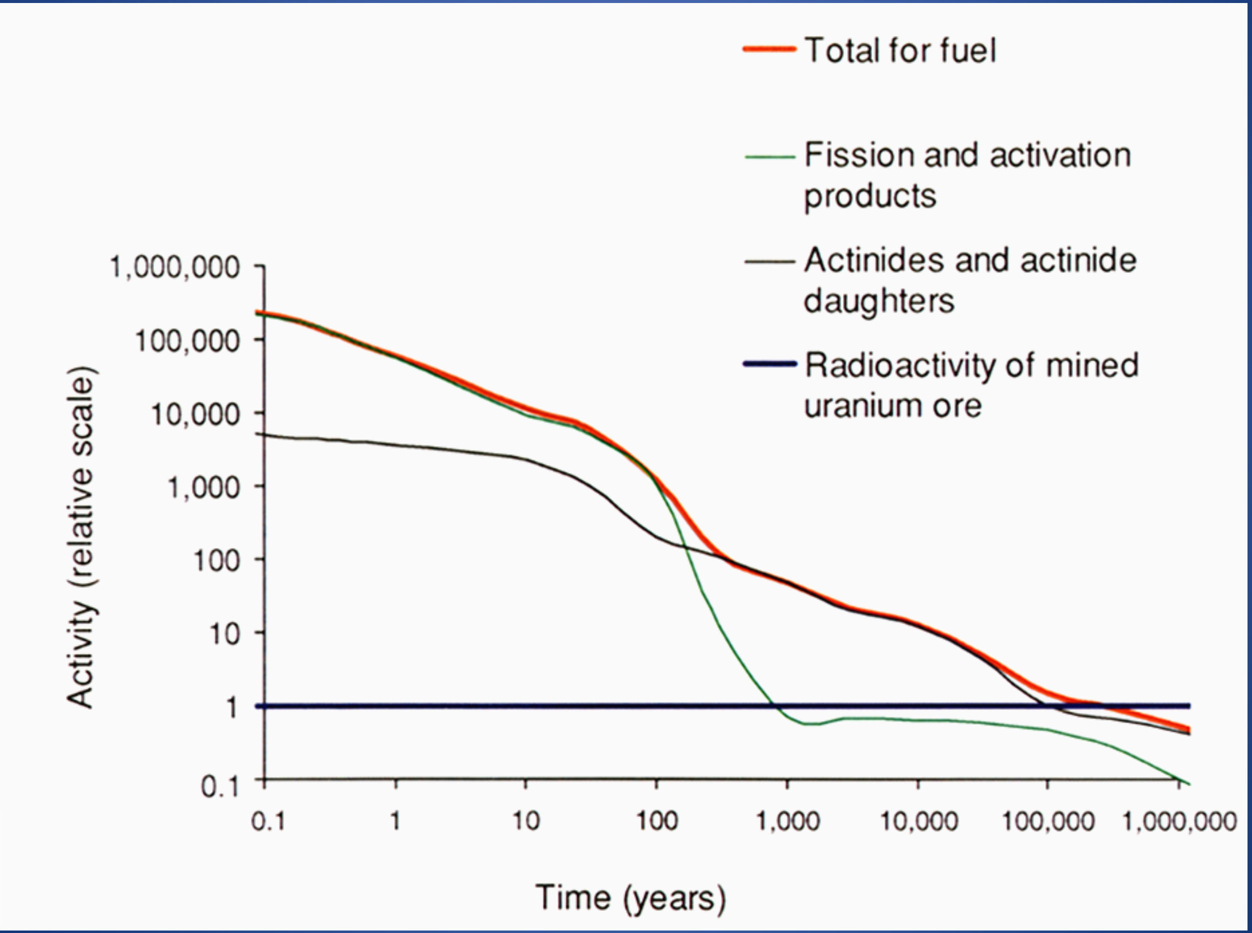
4b: What to do with Used Fuel

- Love It or Hate It We Have It: What to do with It is the Issue
- We have about 70,000 tonnes now
- Current reactors will produce 60,000 tonnes more over their lifetimes
- Disposal costs are built into nuclear electricity costs at 0.1 cent/KW-hr ($20 Billion in fund now; will take in $50 billion from current reactor fleet)

Components of Spent Reactor Fuel

Component	Fission Fragments	Uranium	Long-Lived Component
Percent Of Total	4%	95%	1% (Pu, Np, Am, Cm)
Radioactivity	Intense	Negligible	Medium
Untreated required isolation time (years)	500	0	300,000

Radioactivity vs. Time



Strategies for Disposition of Pu & Minor Actinides (Np, Am, Cm)

- **Geologic Answer:** Geologic disposal of spent nuclear fuel and/or immobilization of actinides in *durable solids*.

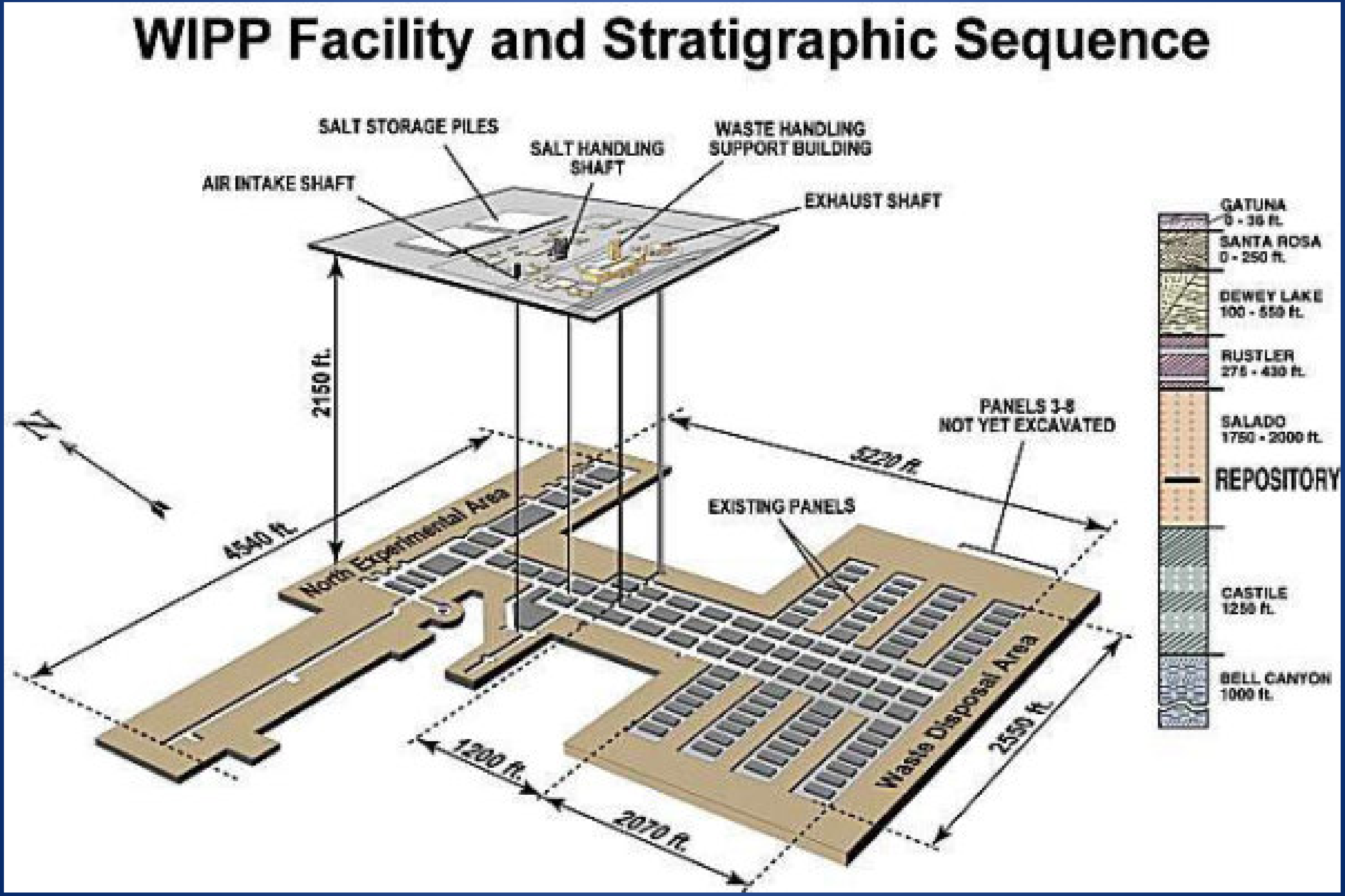
- **Nuclear Answer:** Use nuclear reactors to “burn” or reduce inventories of plutonium and minor actinides in advanced reactors.

The Geological Answer - History

- 1982 – Congress says spent fuel disposal is a federal responsibility, sets an amount utilities have to pay, tells DOE to find a site
- 1987 DOE comes up with 3 (Texas, Washington state, and Nevada)
- GHW Bush is VP so Texas is out; Tom Foley is House majority leader so Washington is out, and Nevada is it
- Nevada has fought it ever since

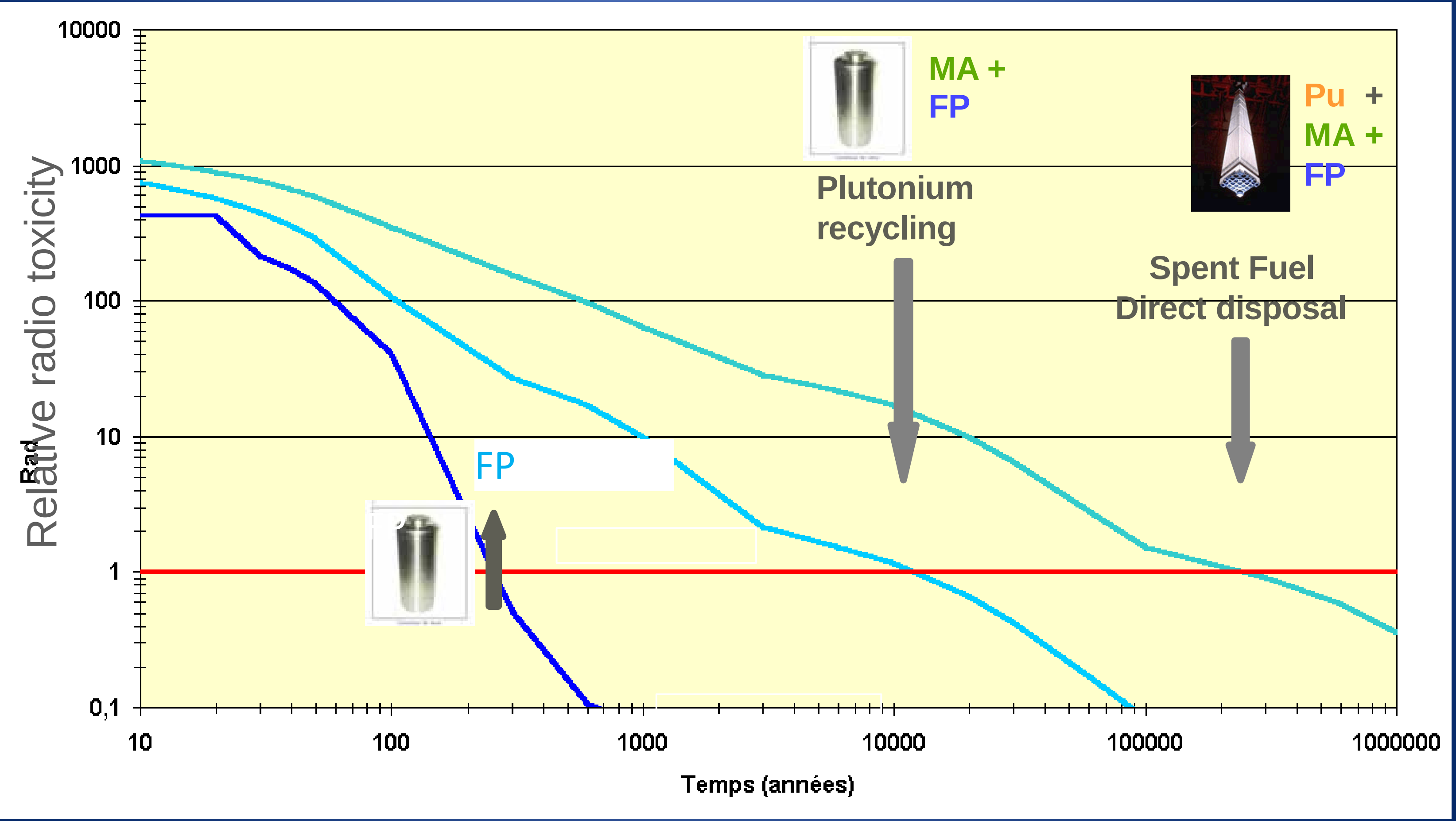
Waste Isolation Pilot Project

We have a Working Repository at Carlsbad NM



The Nuclear Answer

Closing the Fuel Cycle by Burning the Long Lived Component



Spent Fuel Disposal - Summary

- We always need a Repository – 500 years for Nuclear Disposal, 500,000 for Geological Disposal
- This is a Political Problem, Not a Technical One
- Other Counties have used a Consent Based System (Sweden, Finland, France)
- Blue Ribbon Commission Recommends Consent Based System (http://brc.gov)
- We have one in New Mexico – WIPP
- If politics do not intervene (dream on), we can solve this problem in a few years.

4d : Nuclear Accidents

Three Mile Island (1979) – A Partial Core Meltdown

- LWRs have containment building
- Offsite impact - negligible

Chernobyl (1986) – World's Worst

- Reactor type not used outside of old Soviet bloc (can become unstable) – no containment
- Deliberately taken into unstable region
- Lots of radiation offsite

Fukushima (2011)

- Midway between – probably about 10% of Chernobyl; still being evaluated

Three Mile Island

Source: Japan Times

After TMI

- Major changes in safety regulation and incident reporting
- Many costly modifications of plants to prevent or handle loss of coolant events
- Institute of Nuclear Power Operations (INPO) set up by industry to:
  - effect prompt exchanges of safety experience
  - establish more rigorous operating standards
  - inspect plants for compliance with new rule
  - Intense focus on operational reliability, increasing from 65% average availability to 92% today.

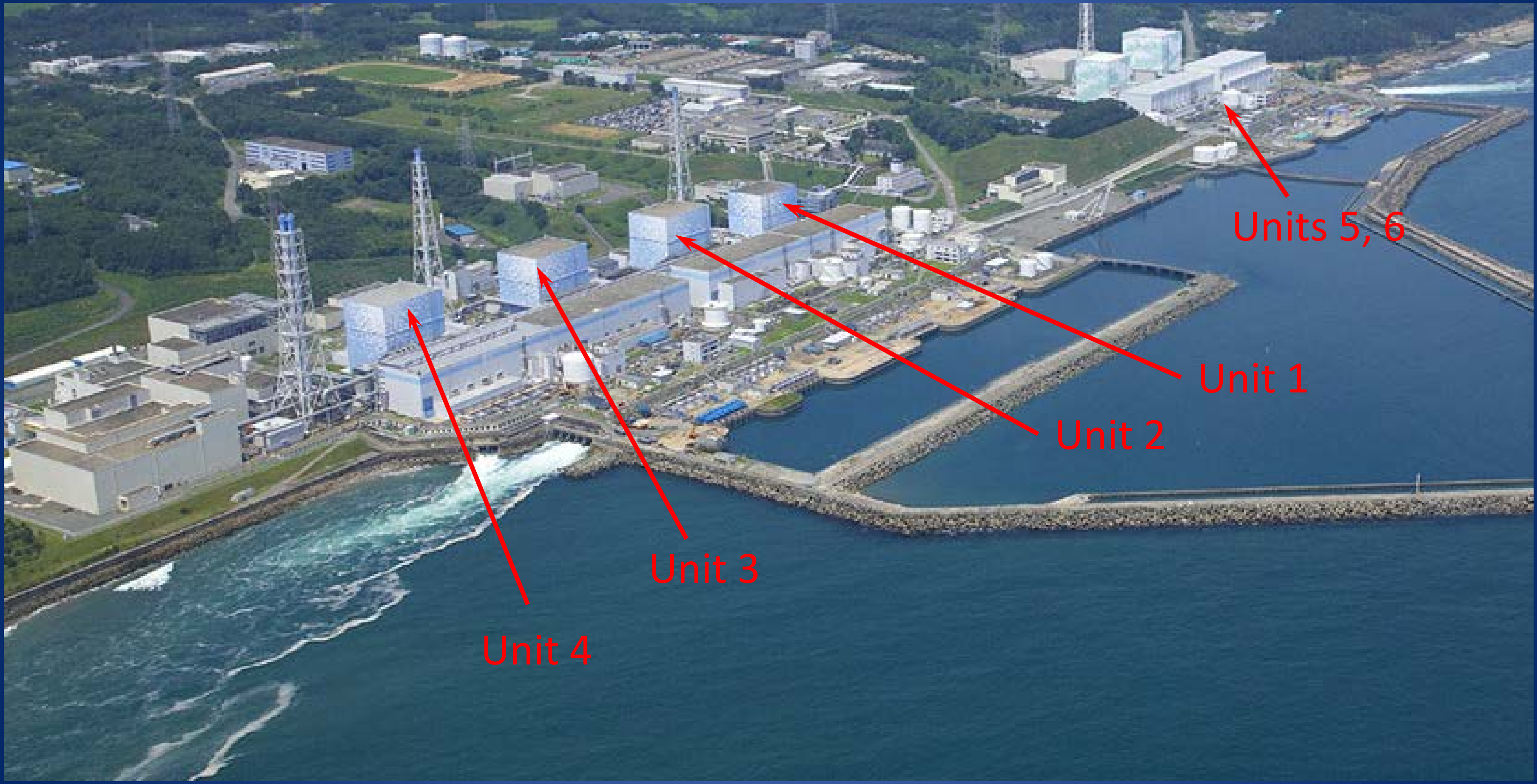
Chernobyl

Source Wikipedia

After Chernobyl

- Safety reviews and improvements in RMBK reactors (Chernobyl style) undertaken by Russia and the IAEA
- Many RMBKs shut down – others modified to improve safety systems
- Chernobyl reactor design never used for power outside of old Soviet Block - no longer being built
- INPO's went international by establishing the World Association of Nuclear Operators (WANO)

Fukushima Dai-ichi Nuclear Power Plant Before the Accident



Tsunami 40 minutes after earthquake

Radioactive Heat After Reactor Shutdown (% of thermal power)

• Immediately after shutdown	7%
• 3 hours after	1%
• 5 days after	0.5%
• 2 months after	0.1%
• 1 year after	0.01%

- 4 years after – water cooling no longer needed

Fukushima After

Pre-Fukushima Expectation

- Large expansion in Asia
- Expansion in EU and US
- 1600 operating by 2050
- Fraction of world electricity doubled to 32%

Fukushima Impact

- Fukushima was and still is a serious incident.
- There is an ongoing rethinking of reactor safety and the setting of “design basis” threats.
- Regulators will be given more power (India, Japan, China, S. Korea).
- The actual impact of Fukushima compared to that of other conventional electricity sources is small, but radiation is feared and it is too soon to see the impact on public perception.
- Personal opinion – world wide impact will be small.

Public Health Impacts per TWh*

	Coal	Lignite	Oil	Gas	Nuclear	PV	Wind
Years of life lost:							
Nonradiological effects	138	167	359	42	9.1	58	2.7
Radiological effects:							
Normal operation					16		
Accidents					0.015		
Respiratory hospital admissions	0.69	0.72	1.8	0.21	0.05	0.29	0.01
Cerebrovascular hospital admissions	1.7	1.8	4.4	0.51	0.11	0.70	0.03
Congestive heart failure	0.80	0.84	2.1	0.24	0.05	0.33	0.02
Restricted activity days	4751	4976	12248	1446	314	1977	90
Days with bronchodilator usage	1303	1365	3361	397	86	543	25
Cough days in asthmatics	1492	1562	3846	454	98	621	28
Respiratory symptoms in asthmatics	693	726	1786	211	45	288	13
Chronic bronchitis in children	115	135	333	39	11	54	2.4
Chronic cough in children	148	174	428	51	14	69	3.2
Nonfatal cancer					2.4		

*Krewitt et al., "Risk Analysis" Vol. 18, No. 4 (1998).

Fukushima Mortality Comparison

Years of life that would have been lost had electricity generated by nuclear been generated by coal or gas fuels;

B. Richter, Energy Environ. Sci., 2012, DOI: 10.1039/C2EE22658H

Fuel	1 Twh[1]	898 Twh[2]	6097 Twh
Coal	**138**	**124,000**	**840,000**
Gas	**42**	**38,000**	**260,000**
Nuclear - normal operations	*25*	*22,000*	*153,000*
H-J Fukushima meltdown	*5.4*	*4,800*	*4,800*
Total Nuclear	**30**	**26,800**	**157,800**

1 W. Krewitt *et al. Risk Analysis,* Vol. 18, No. 4, 1998

2 Total Generation at Fukushima and total nuclear in Japan up to 3/11/2011

Safety Philosophy:

- Nuclear power plants must prepare for extreme events with a defense in depth
- Maximum credible earthquakes and floods
- Loss of off-site power and on-site power
- Hydrogen generation as a result of fuel damage during loss-of-coolant accidents
- Post 9/11: aircraft impact, loss of large areas of the plant
- Note that regulators in each country set their own requirements – no universal code

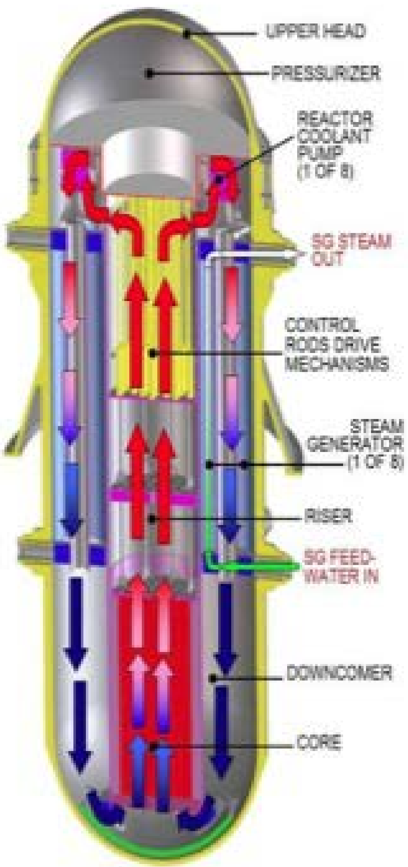
5: Reactors of Tomorrow

- Already Deployed – mostly Gen II
- Being Deployed Now – Gen III & III+
- Deployable in the 2020s – Small Modular Reactors (SMRs)
- Deployable in the 2040s – GEN IV Advanced Reactors (fast spectrum, thorium, liquid metal cooled, molten salt cooled, etc.)

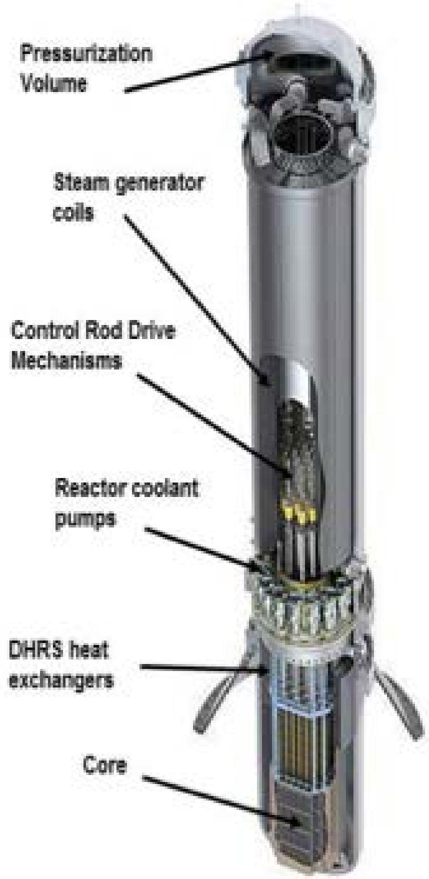
SMRs – Why?

- Less capital per module
- Distributed power makes for more reliable grid
- Factory built small can match economies of scale of large so cost/kw same, say proponents
- More applications – off grid places, developing nations, process heat (desalinization), distributed power, …

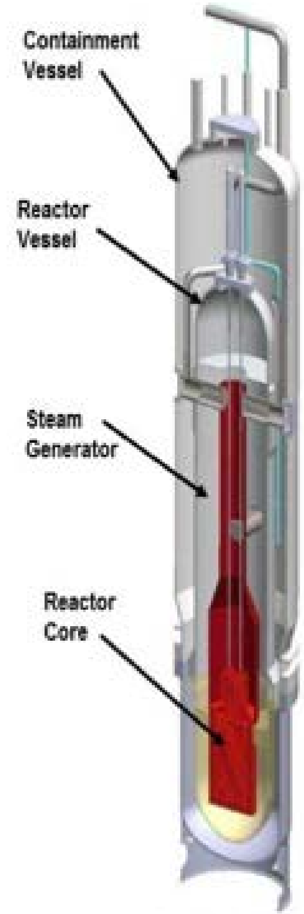
Examples of Light Water SMRs



IRIS (Westinghouse)
335 MWe



mPower (Babcock & Wilcox)
125 MWe



NuScale (NuScale)
45 MWe

SMR Status

- Going through early stages of NRC design certification
- Full cost to get there - \$300 – \$500 million each
- DOE cost sharing competition – mPower wins first round
- Second round in process
- Cost and learning curve issue

Evaluation Criteria for Gen IV Reactors

- **Safety** – how long are they "walk away" safe?
- **Capital Cost** – how much per kilowatt of capacity?
- **Cost of Electricity** – how much per kilowatt-hour?
- **Waste Management** – simpler to dispose of used fuel?
- **Proliferation Risk** – harder to make a weapon from the fuel cycle?
- **Fuel Availability** – is there a supply problem?
- **Environmental Impact** – besides radiation, are there other issues (water, for example)?
- **Development Risk** – do the R&D issues look tractable?

GEN IV Advanced Reactors

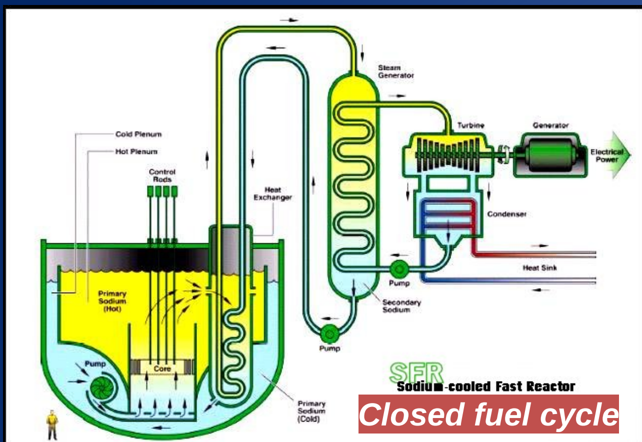
Fuel Cycle Options

- Once Through
- Partial Recycle (Pu - MOX)
- Full recycle (All TRU)
- Fast Spectrum
- Thermal Spectrum
- Intermediate Spectrum
- Breeders
- Critical or Subcritical

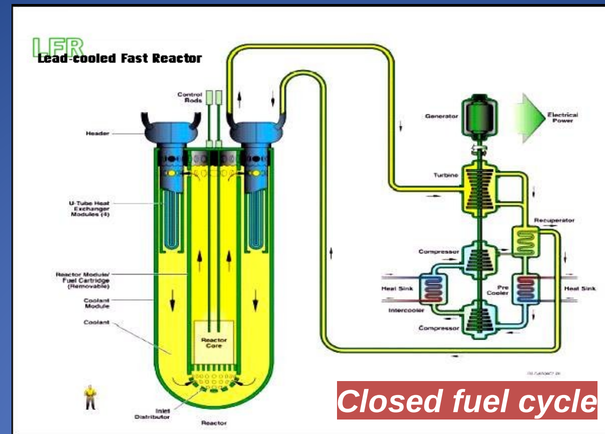
Reactor Options

- Thorium
- Lifetime Core
- Sodium Cooled
- Lead Cooled
- High Temperature Gas
- Very High Temperature Gas
- Molten Salt Cooled

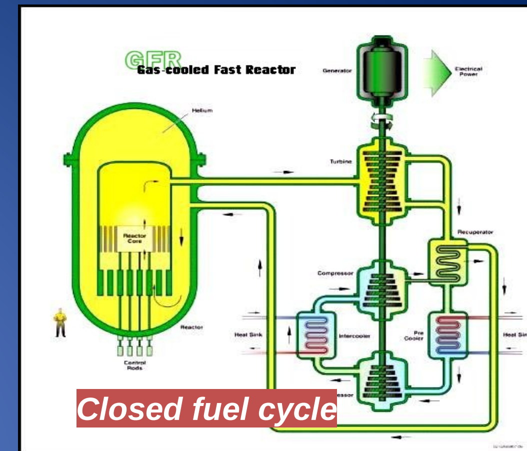
The GIF selected concepts



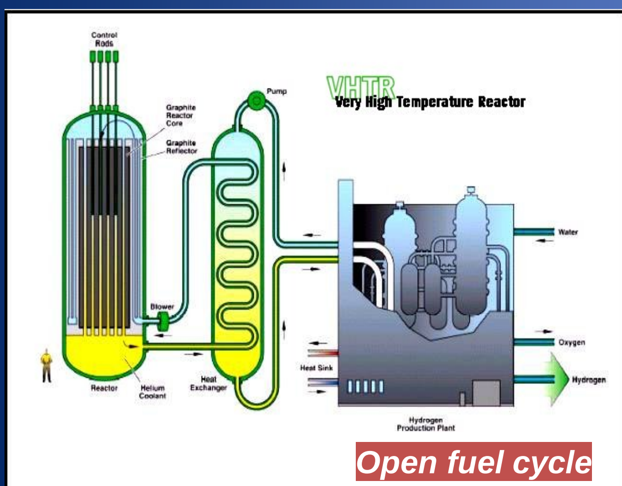
Sodium Fast Reactor



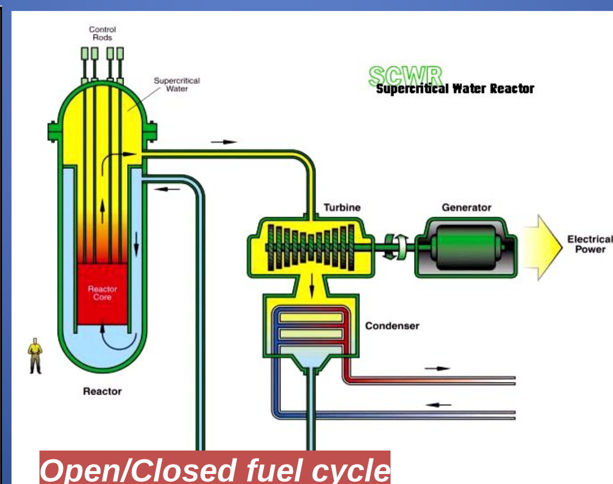
Lead Fast Reactor



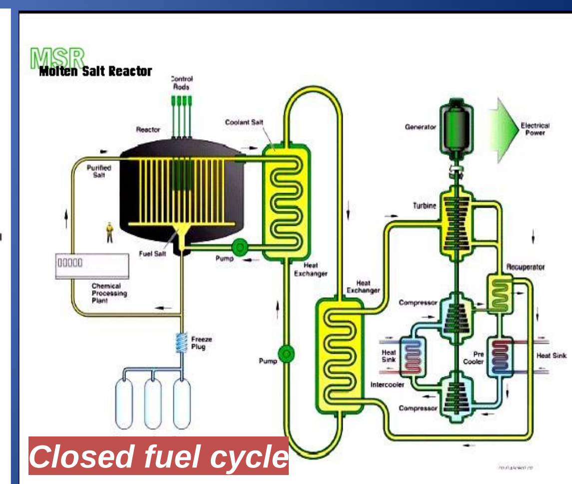
Gas Fast Reactor



Very High Temperature Reactor



Super Critical Water Reactor



Molten Salt Reactor

Who is doing what

- **China** – TerraPower (Bill Gates - fast spectrum with sodium cooling and 30 year refuel); molten salt cooled; sodium cooled fast spectrum
- **France** – sodium cooled multiple recycle to be deployed commercially about 2040
- **India** – thorium breeders; uranium breeders all with recycle
- **Russia** – fast spectrum lead and/or sodium cooled
- **S. Korea** – multiple recycle LWR
- **U.S.** – twiddling our thumbs; in collaborations as junior partner

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Multi-Lateral Collaborations

- **Generation-IV multi-lateral agreements developed since 2000**
  - Current SFR participants are Japan, Korea, U.S., France, Euratom
  - New members are China and Russia
- **Several specific activities sponsored by IAEA and OECD/NEA**
  - IAEA Technical Working Group on Fast Reactors (TWGFR)
  - IAEA Coordinated Research Projects
  - OECD Studies of Fuel Cycle and Technology Options
- **Trilateral MOU signed with France (CEA) and Japan (JAEA) for SFR development being renewed**
  - Original focus on harmonizing SFR prototype no longer valid
  - Collaborative R&D and infrastructure sharing, being explored

Conclusion

- Lots going on in the world.
- The US is in the minor leagues, although much of the technology was developed here.
- We can buy advanced systems made by others rather than selling our own.
- But, the less of a role we play in the future of nuclear energy the less our influence will be on controlling safety and proliferation.

6: Nuclear Energy Summary

- Nuclear Renaissance is Alive and Well in Asia and perhaps Middle East
- European Situation is Mixed
  - Most of Europe is Holding Fast to nuclear
  - German and Belgium are in a Phase Out
  - Italy has Abandoned Plans to go Nuclear
- South America is Expanding
- Africa is Thinking about it
- North America May be Expanding

Summary

- SMRs will begin operation around 2020 and if they live up to Promise may become a large factor
- Safety is being improved in Gen III+ and SMRs
- Advanced Reactors are in development, but best choice is not yet clear
- Deployment of Gen IV might begin around 2040

Summary

- Waste disposal will be geological for current reactors and may be nuclear for Gen IV, and is not a technical problem
- Keeping nuclear at he same fraction of world electricity requires about 20 new big reactors per year to turn on (total of 800). 68 are in construction today

Summary

- New methods of regulation and inspection of operations need to be developed
- International systems of enrichment and reprocessing need implementation to lower proliferation risk, as well as costs for smaller nations
- The driver for all this is a burgeoning population and the desires of the poor to become less poor.
- ***Business As Usual Is Not An Option***

Useful References

- *Nuclear Energy,* David Bodansky, Springer 2004
- International Atomic Energy Agency (www.iaea.org)
- World Nuclear Association (www.world-nuclear.org)
- Nuclear energy Agency (www.nea.fr)
- Department of Energy (www.energy.gov)
- International Energy Agency (www.iea.org)

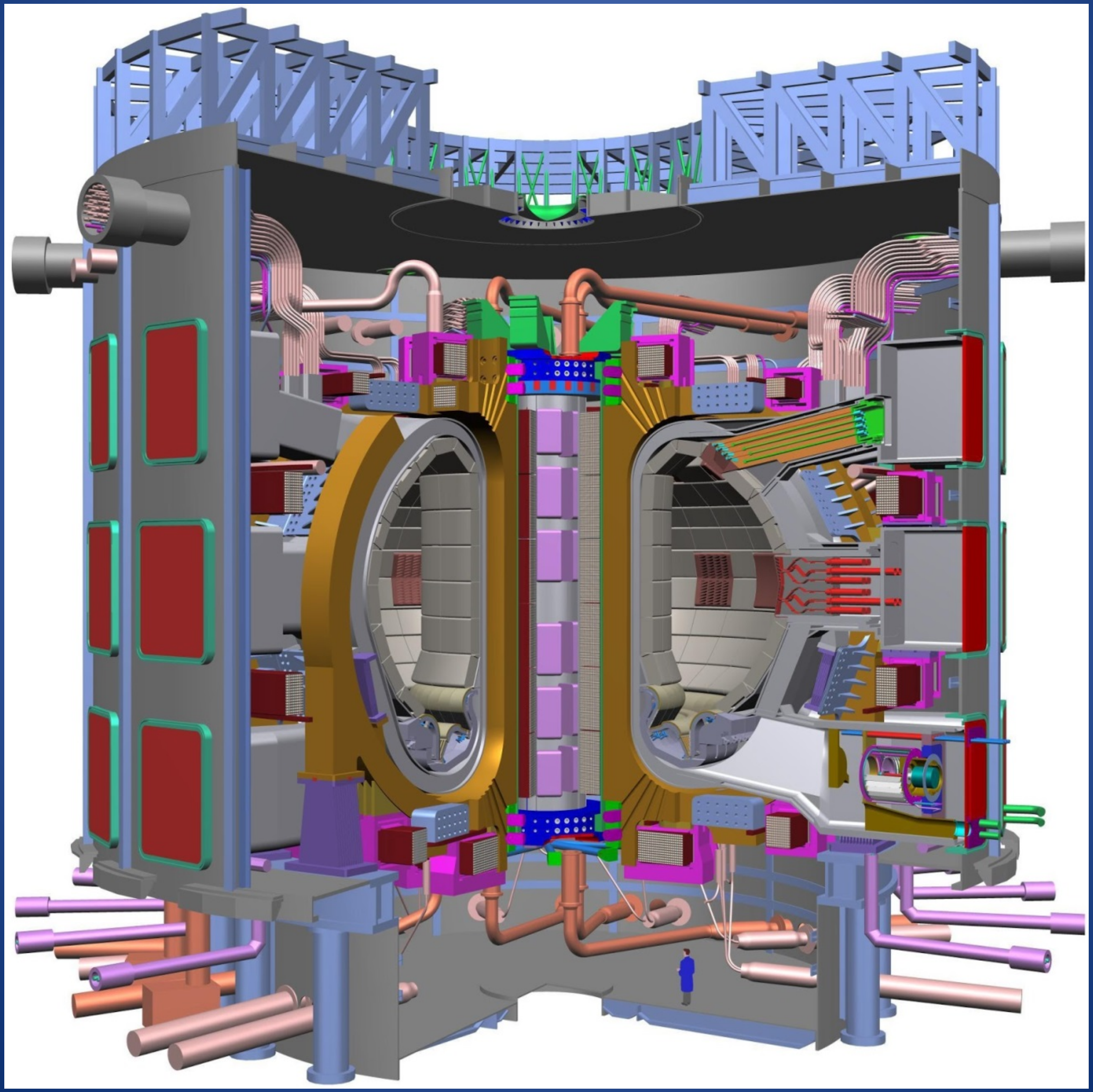
Backup

Fusion Energy

- Deuterium + Tritium = Helium + Neutron + 17.6 MeV

  (1 n+1p) + (2n+1p) = (2n+2p+3.6MeV) + (1n+14MeV)
- Heat the D&T high enough to make the reaction go
- Convert the energy released into heat and then to electricity
- Make the Tritium which does not exist in nature
- Do it all using less energy than is produced and not destroy the machine
- Two variants – Magnetic and Inertial

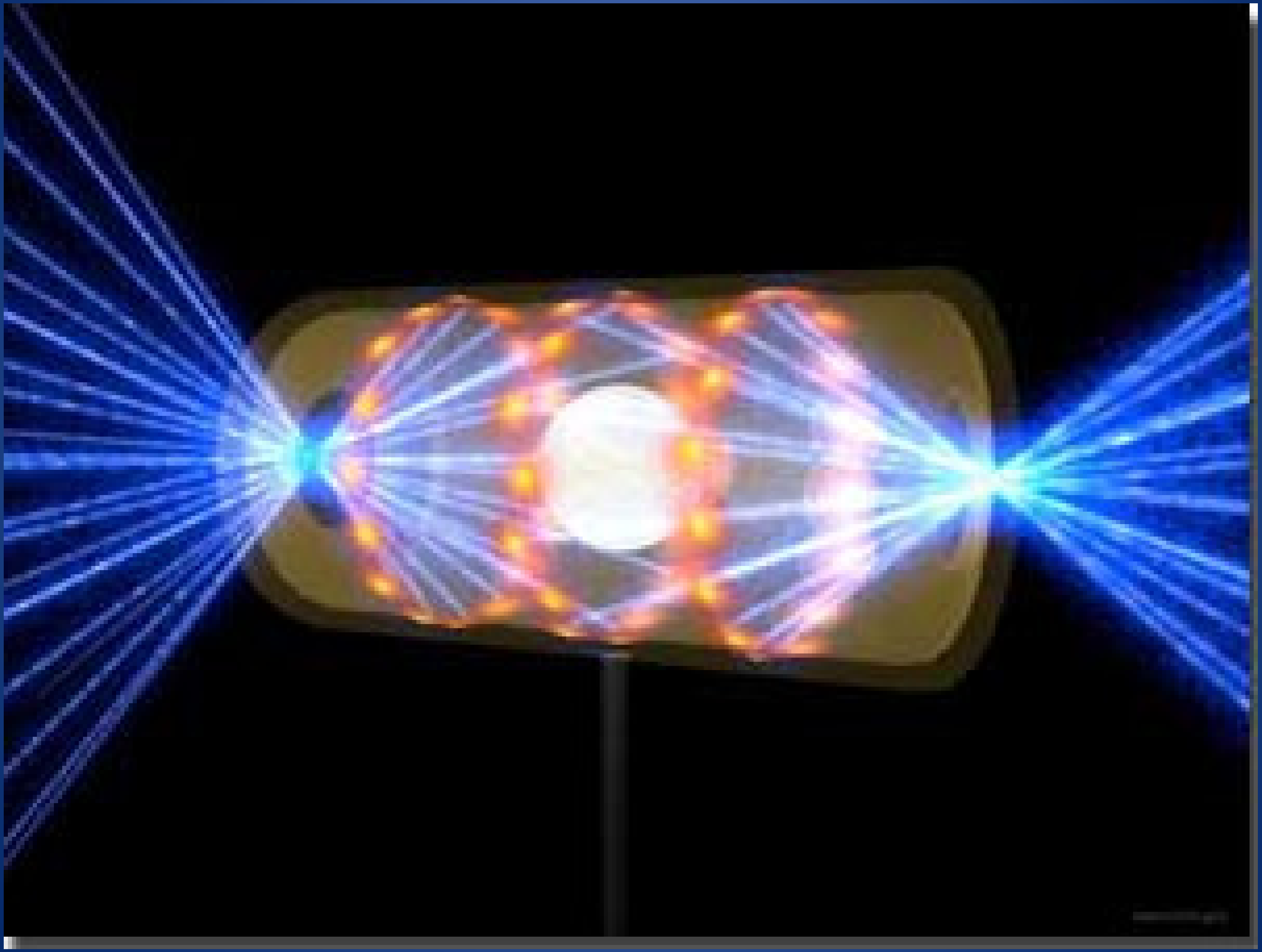
ITER



ITER Status

- Original Schedule –Startup 2020 for € 5Billion ($6.5 billion)
- Current Schedule – Startup D-T 2027 for € 13 billion ($17 Billion)
- New Cost Review – Rumor is € 30-50 Billion
- Goal 500 MW (thermal) for 50 MW of Drive Power (would produce about 150 MWe if fully equipped)
- If Successful to be followed by a Demo supposedly cheaper (better be because ITER would price out at more than $100,000 per KW at $17 billion cost)
- May be pricing itself out of the market

Inertial Confinement Fusion



The Business End

NIF Status

- Has Failed to Achieve Ignition (making the micro-bomb go off)
- Lasers work better than design
- Performance Does Not Agree with Model Predictions
- Trying to Understand What is Wrong with Model
- For a Power Plant need micro-bombs equivalent to 100 pounds TNT at rate of 15/second and target gain of at least 30

Fusion Summary

- Both Magnetic and Inertial are in Trouble
- Magnetics problem is delays and cost overruns that may price it out of the power plant world even if it works
- Inertial finds that what happens to the micro-bombs does not agree with what they think should happen
- It was once said "Practical fusion energy is 50 years in the future and will always be so."

General conversion factors for energy

To: / From:	TJ	Gcal	Mtoe	MBtu	GWh
	multiply by:				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

Useful Reference: Key World Energy Statistics 2012
International Energy Agency

Coal Reserves and Consumption

Country	Known Reserves (2003) billions of tons	Consumption (2007) billions of tons
U.S.	271	1.1
Russia	173	0.26
China	126	2.3
Indonesia	102	0.51
Australia	87	0.15
South Africa	54	0.20
Rest of World	188	2.7
WORLD Total	1001	7.2

Source: DOE Energy Information Agency

Current Reactor License Applications

	UTILITY	SITE/LOCATION		REACTOR/ NO. UNITS		COLA DATES			REVIEW PHASE IN PROGRESS	
						Submitted	Docketed	Issued	Safety [4]	Environ.[5]
Issued	Southern Nuclear	Vogtle	GA	AP1000	2	03/31/08	05/30/08	02/10/12	Completed	Completed
Issued	SCE&G	V.C. Summer	SC	AP1000	2	03/27/08	07/31/08	04/10/12	Completed	Completed
Active COL Applications	Progress Energy	Levy	FL	AP1000	2	7/30/08	10/6/08	-	Ph. D	Completed
Active COL Applications	STP Nuclear Operating Co.	South Texas Project	TX	ABWR [1]	2	9/20/07	11/29/07	-	Ph. 4	Completed
Active COL Applications	Luminant (TXU)	Comanche Peak	TX	US-APWR [1]	2	9/19/08	12/2/08	-	Ph. 2	Completed
Active COL Applications	UniStar	Calvert Cliffs	MD	US-EPR [1]	1	3/14/08	6/3/08	-	Ph. 2	Completed
Active COL Applications	DTE Energy	Fermi	MI	ESBWR [1]	1	9/18/08	11/25/08	-	Ph. B	Completed
Active COL Applications	Duke Energy	William States Lee	SC	AP1000	2	12/13/07	2/25/08	-	Ph. B	Ph. 4
Active COL Applications	Florida Power and Light	Turkey Point	FL	AP1000	2	6/30/09	9/4/09	-	Ph. A	Ph. 2
Active COL Applications	PPL (UniStar)	Bell Bend	PA	US-EPR	1	10/10/08	12/19/08	-	Ph. A	Ph. 2
Active COL Applications	Progress Energy	Shearon Harris	NC	AP1000	2	2/19/08	4/17/08	-	Ph. B	Ph. 2
Active COL Applications	Dominion Energy	North Anna	VA	US-APWR	1	11/27/07	1/28/08	-	Ph. A	Ph. 2

[1] Reference COL Application (R-COL)

[4] Safety Review: *R-COL→* *Ph 1* Issue RAIs *Ph 2* SER w/Open Items *Ph 3* ACRS Review *Ph 4* Advanced SER/ No OI *Ph 5* ACRS Review *Ph 6* Final SER

S-COL→ *Ph A* Issue RAIs and supplemental RAIs *Ph B* Advanced SER/ No OI *Ph C* ACRS Review *Ph D* Final SER

[5] Environmental Review Phases: *Ph 1* Environmental Scoping Report *Ph 2* Draft EIS *Ph 3* Public comment *Ph 4* Final EIS

Generation IV Reactor Summary

System	Neutron Spectrum	Fuel Cycle	Size (MWe)	Major Design Options	Missions
Very-High-Temp. Reactor (VHTR) [850-1000C helium]	Thermal	Open	600 MWt (or up to 300 MWe)	Prismatic or pebble fuel; thermochemical or high temperature electrolysis for H2	Hydrogen Production, Process Heat, Electricity
Supercritical-Water Reactor (SCWR) [550C water]	Thermal or Fast	Open, Closed	1700	Pressure vessel or pressure tube designs; several moderator designs	Electricity
Gas-Cooled Fast Reactor (GFR) [850C helium]	Fast	Closed	288	Three fuel options, active vs passive post-accident cooling; large system alternative for economics	Actinide Management, Electricity, Hydrogen Production
Lead-Cooled Fast Reactor (LFR) [550C Pb/Bi - 800C Pb]	Fast	Closed	50-1200	Transportable 'battery' with long life core, or large plant; Pb or Pb/Bi eutectic coolants	Electricity, Hydrogen Production
Sodium Cooled Fast Reactor (SFR) [550C sodium]	Fast	Closed	150-1500	Oxide or metal fuel; Aqueous or pyro processing; Loop or tank designs; supercritical CO2 turbine	Actinide Management, Electricity
Molten Salt Reactor (MSR) [700C molten salts]	Thermal	Closed	1000	Choice of salts (Na/Zr/F for burning; Li/Be/F for breeding) and fuels (238U or 232Th fertile feed)	Actinide Management, Electricity, Hydrogen Production