Energy Future
(Summary of lectures 1, 2, 3)

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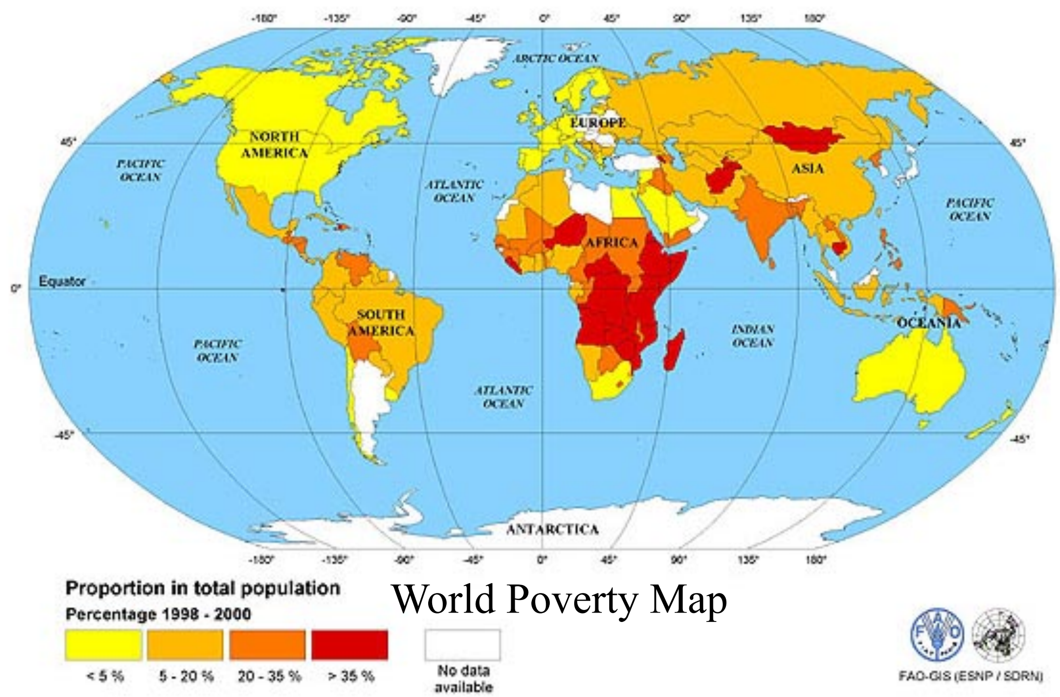


World Poverty Map

LA-UR 12-20205

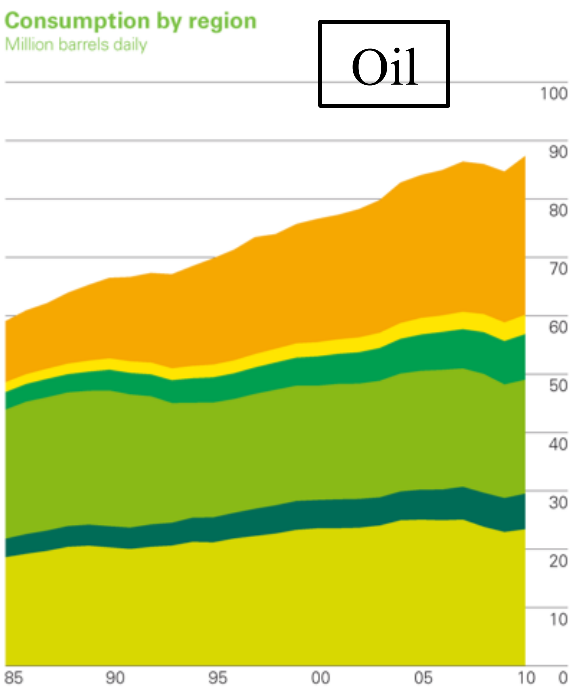
Abstract

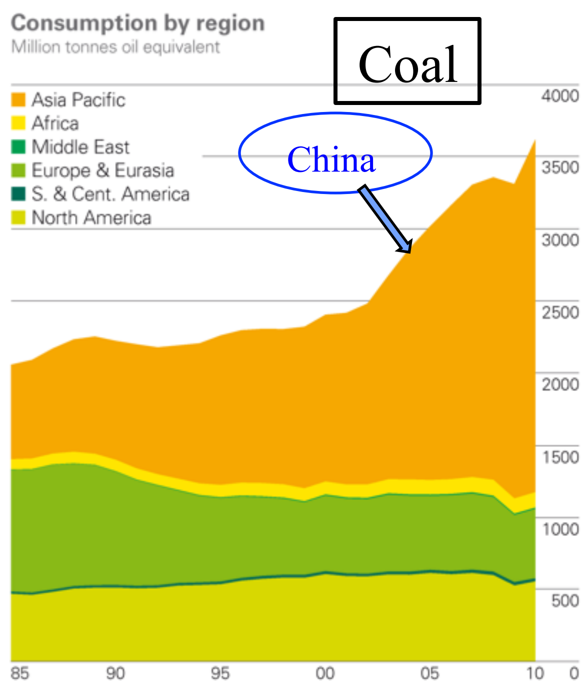
This talk will discuss the challenges of nuclear power and compelling reasons for why it has to be part of the mix for at least the next 50 years. The lecture will summarize the current situation with respect to deployment of power plants, economics of nuclear energy, nuclear manufacturing industry and R&D for next generation reactors. I will also discuss areas where research is needed to create a level of social acceptance of risk and environmental impact.

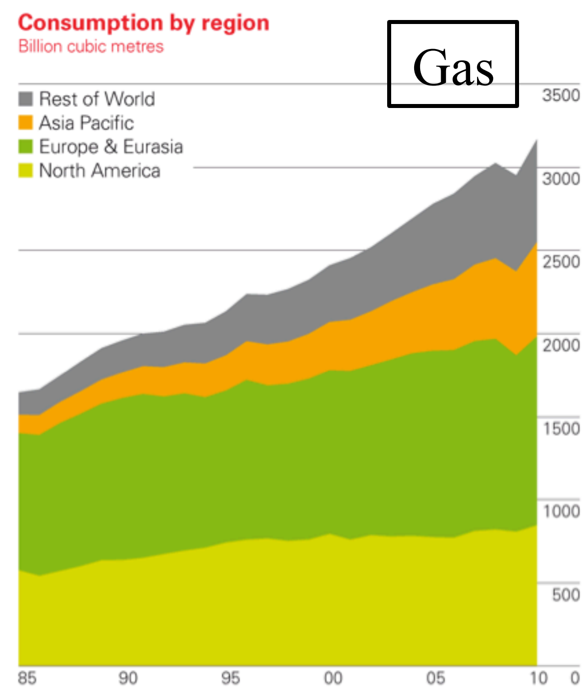
Historical (1985-2010) Growth trends:

driven by (a) demand (b) capacity for new additions

	Production 2010	Historical Growth	Historical growth as % of 2010 Prod.
Oil	86 MMbo/day	1 MMbo/yr	1.2%
Coal*	3.6 BToe	160 Mtoe/yr	4.4%
Gas	3150 B cum	60 B cum/year	1.9%



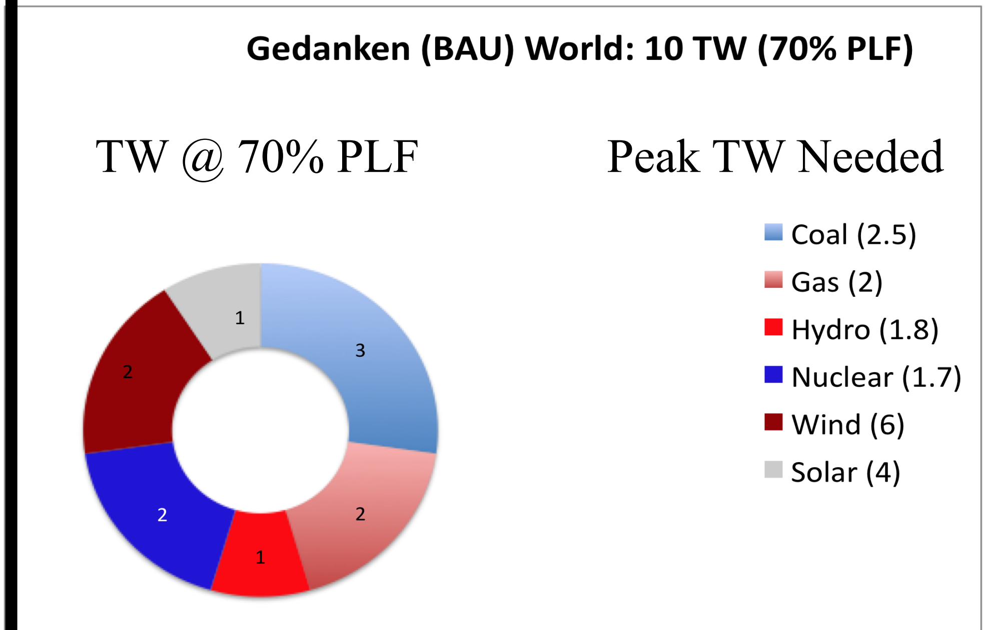




Source: BP Statistical Review 2011

Constructing Solution Wedges

- Need **10 TW** Electric Power:
  - ➢ **1 TW ←→ 6000 TWh**



- Need **85 mbo/day** Liquid Fuel:
  - ➢ **10** million barrels oil/day

Arithmetic and not wishful thinking

- Coal-fired capacity continues to increase
  → more coal consumption → more GHG
- Largest growth in fossil-fuels over the next 30 years will be in the use of natural/shale gas
- Solar, Wind, Bio-mass systems will benefit from R&D and continue to grow
- BAU: Solar & Wind unlikely to provide more than 25% of world demand for power by 2050
- BAU: Bio-mass unlikely to provide more than 15% of world demand for liquid fuels by 2050

To address climate change society must focus on efficiency and reduced use

Motivations for Nuclear Power

- Climate Change – GHG emissions from carbon based fossil-fuels
  - R&D leading to safe and cost-effective management of SNF and nuclear waste more likely than CCS
- Energy security: Many countries do not have adequate fossil-fuel resources
  - Nuclear power [ignoring waste issues] is cost-competitive with coal-fired generation [ignoring CCS & environmental impacts] for base load

Nuclear Power: High Hopes, Unfulfilled Promise

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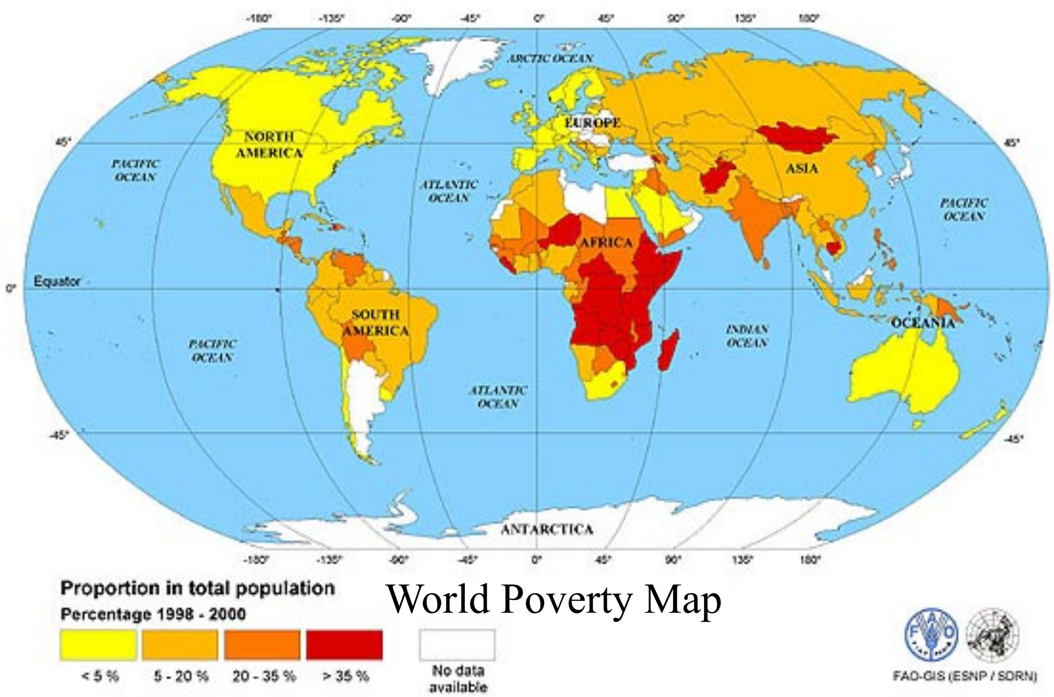


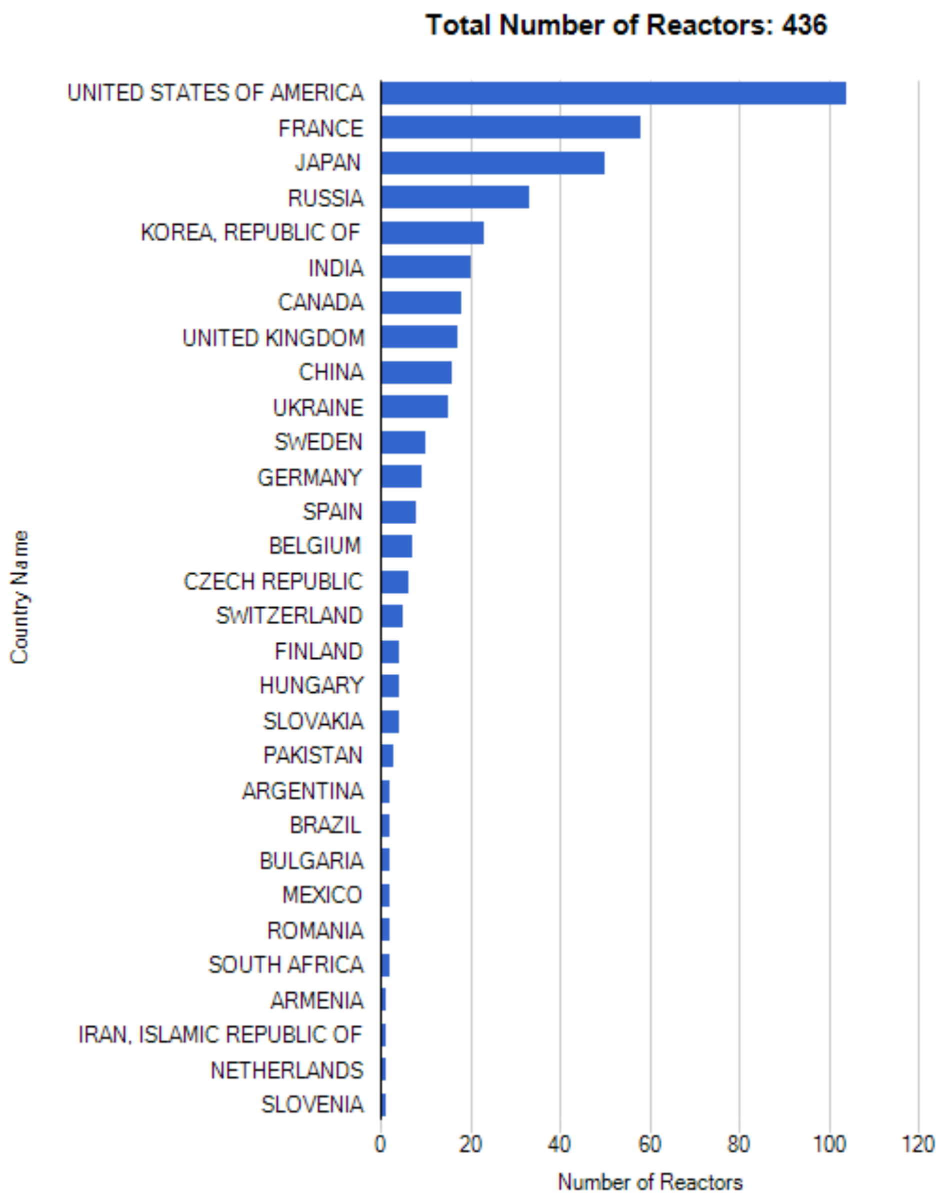
World Poverty Map

LA-UR 12-20205

Nuclear Power: Major Events

- 1955-57: Adm. Rickover oversees technology transfer from Naval reactors to civilian PWR in the US. UK and Russia develop their own capability
- 1965-1975: The golden age of nuclear power in the US
- 1979: Three mile island – core meltdown but containment vessel/building hold radiation in. Public opinion shifts.
  - Price escalation due to regulations, safeguards, and long build time
  - Rate of increase of annual electricity demand drops from ~9% to ~2.5%
  - Gas-fired power plants provide an alternative to coal
  - No more reactors ordered in the US
- 1986: Chernobyl – Russian RBMK reactors did not have a containment building + poorly trained operators. Large release & impact.
  - 11 RBMK reactors commissioned in Russia in 1970-1984 still in service
  - Public opinion against nuclear grows and fear becomes visceral
- 2001/9/11: Nuclear terrorism creates further fear
- 2011: Fukushima – core meltdown and heat up of stored spent fuel rods
- Waste disposal, safeguards, proliferation remain a challenge (mostly political)

Current Status



# OP.	# Con.	GW	# Closed
104	1	101.24	28
58	1	63.12	12
50	2	44.215	9
33	10	23.643	5
23	3	20.671	
20	7	4.391	
18		12.624	3
17		9.703	28
16	26	11.688	
15	2	13.107	4
10		9.326	3
9		12.068	27
8		7.567	2
7		5.927	1
6		3.766	
5		3.263	1
4	1	2.736	
4		1.889	
4	2	1.816	3
3	2	0.725	
3	1	0.935	
2	1	1.884	
2	2	1.906	4
2		1.300	
2		1.300	
2		1.83	
1		0.375	
1		0.915	
1		0.482	1
1		0.688	

Source: IAEA Pris database; world-nuclear

Nuclear Profile

- 138 reactors shut down
  - 9 reactors shut down due to accidents (1+4+4)
  - Lithuania closed two RMBK (Chernobyl type) reactors
- Most of the shutdown reactors were built before 1970 and were Gen I and II of <400 MWe capacity
- Germany has shut down all reactors built before 1980. All 9 operating reactors were built in the 1980s and will be shut down by 2022
- LWR Dominate: PWR (66%); BWR (22%)
- General trend: Lifecycle extension, capacity upgrades
- Many countries aiming for 30-60% power from nuclear

To achieve 1.7 TW capacity by 2050

- Construction start of **50** GW/year of nuclear capacity during 2012-2046
  - Almost all existing reactors will have been decommissioned
- Only four countries (China, India, Russia, USA)
  - Will want/need more than 100 GW capacity
  - Require they develop the infrastructure & safety culture to scale up to 100s of GW?
- 1.7 TW can be achieved only if many more countries acquire/build nuclear power plants. Increased risk of
  - Proliferation – theft and diversion of nuclear material
  - Accidents
- Goals & Hope: Gen IV / Modular reactors that are cost-competitive
  - Standardized
  - Increased safety / Passively safe
  - High burn rate / reducing the amount of spent fuel requiring disposal
  - Proliferation resistant: prevent theft/diversion of nuclear material
  -
  - A utility can add capacity incrementally
  - Reduced one time capital cost and build time
  - Plants can be sited closer to load centers

GEN IV

Advantages of small modular

What will new capacity look like?

Generation III and III+ reactors will dominate installations over the next 30-40 years

Who will be the major players?

- US/Japan, Russia, France, South Korea, China, India

Standard Design Certification LWR

WH AP-1000
2-loop PWR

Simplified Design → Passive safety

China
AP-1000
CAP-1400

WH AP-600 →

C-E/WH System 80+ →

South Korea KNGR APR-1400
RoK 2 units u.c. UAE: 4 units

GE ABWR (Gen III) →

GE Hitachi Nuclear Energy (GEH)
Toshiba Nuclear Energy Corp

Kashiwazaki-Kariwa-6 and 7 (96/97)
Hamaoka-5 (2004), and Shika-2 (06)
Lungmen (Taiwan); Shimane-3

Standard Design Certification LWR

Under review

GE ESBWR → Economical Simplified / Passive safety (1600) → [ ]

Mitsubishi APWR → 1700 MW → Tsuruga 3 and 4 ??

Areva EPR → 1600 MW →

4 reactors:	construction start
Olkiluoto 3	(2005-08-00)
Flamanville 3	(2007-12-06)
Taishan 1 and 2	(2009-11-18, 2010-04-15)

Atmea PWR (Areva+MHI) → 1000 MW → [ ]

China & India
The Build Period – 2005-2050

- Both will be highly dependent on import of oil and natural gas
- Ignoring constraints on emissions, domestic coal can support
  - China: 600 GW with ~100B Tonnes Reserves
  - India: 300 GW with ~50B Tonnes Reserves
- Both countries have plans for 500+ GW nuclear capacity
- China is aggressively targeting solar and wind as a business opportunity
- India needs a much larger R&D base, capital and investment in education

China (1TW 2011→ 2 TW by 2030)

- Coal (~0.7 TW coal fired capacity)
  - 3.5 gigatons/year coal mined and consumed
  - Dongfang, Shanghai, Harbin, … are major global suppliers of Coal PP
- Natural Gas -- CCGT
  - Rapidly increasing domestic gas and imported LNG capacity. Shale Gas?
  - Shanghai, Dongfang, Harbin have indigenized F class technology (~80 units)
- Oil
  - ~9 million barrels/day (3.8 indigenous)
- Solar *(Renewable Energy Law)*
  - Largest manufacturer of cells and modules (4 GW/yr, ~40%)
- Wind (onshore and offshore)
  - 2011: Largest installed capacity (62 GW) and manufacturing (15 GW)
  - 70% local content law (04-09) → Chinese domination in manufacturing
- Nuclear (16 reactors with 11.7 GW capacity)
  - ~26 reactors under construction and 51 planned/design
  - Developing standard LWR, HWR, FNR (goal ~\$2.0 per watt)

China: nuclear energy

- 16 operating reactors
- 26 under construction
- Deploying AP1000, M310, Areva EPR, VVER, CANDO units (technology adoption/evaluation)
- Short-term: Opted for standardizing foreign technology
  - AP-1000 Westinghouse (Gen III) Technology Transfer
  - CPR-1000 (upgraded version of the 900 MWe-class French M310 three-loop (Gen II+) technology by Framatome)
- Long-term: HTGCR and Fast Breeder Reactors
  - China Experimental Fast Reactor 65 MWt (2011-07-21)

Plan: Add 400-500 GW capacity by 2050

China: PWR Reactors

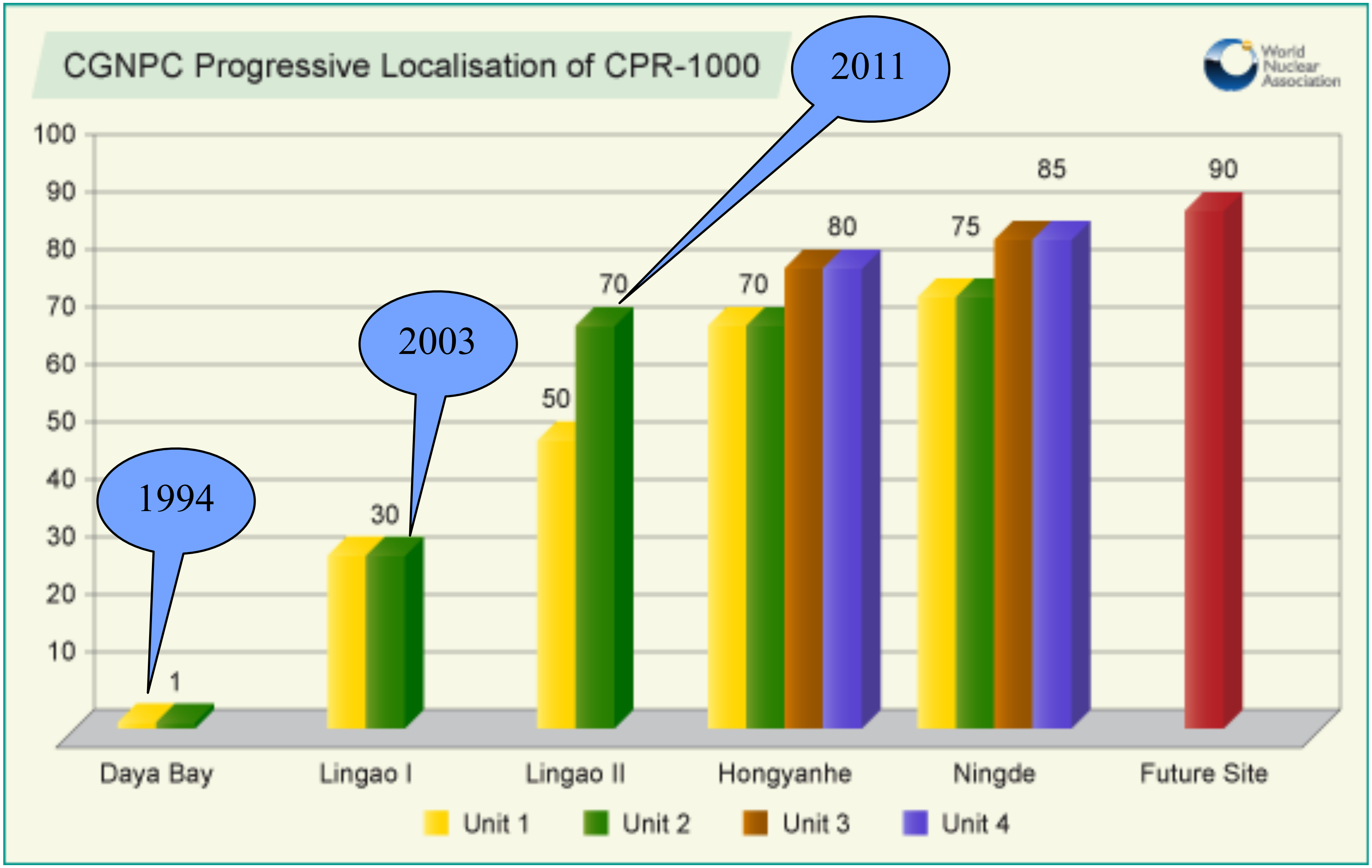
- Westinghouse AP-1000:
  - 1250 MWe gross reactor with two coolant loops
  - Technology transfer agreement with SNPTC & CNNC
  - 4 units being built at Sanmen (2013,14) and Haiyang (2014,15)

- CPR-1000, ACPR-1000 (Framatome 3-loop design M310)
  - China Guangdong Nuclear Power Corporation (CGNPC) led the development
  - Areva retains intellectual property rights on the CPR-1000
  - CGNPC launched ACPR-1000 in Nov. 2011 with full Chinese intellectual property rights after 6 CPR-1000 units at Daya Bay and Ling Ao
  - Oct 2008: Areva(45%) & CGNPC+(55%) form joint venture for CPR-1000 & EPR

- CNP-1000, CNP-600, CNP-300 (ACP1000, ACP600, ACP 300)
  - Working with Westinghouse and Framatome (Areva) at SNERDI since early 1990s
  - Qinshan (7 reactors) Demonstration of 1-loop and 2-loop systems

http://www.world-nuclear.org/info/inf63.html

CPR-1000: process of Indigenization



China: Reactor Development Priorities

- The workhorses for the next 15 years will be AP-1000 and CPR-1000
- Indigenization of Westinghouse AP-1000:
  - Having shared design technology with SNERDI, Westinghouse expects 100% localization by 2015
  - Standardized large pre-assembled modules
  - Special firms – example: Hubei Nuclear Power Equipment Company

- High-temperature gas-cooled reactor (HTR)
  - demonstration Shidaowan HTR-PM with twin 105MWe reactors
    (China Nuclear Engineering & Construction Group (CNEC); Tsinghua University's INET)

- Continue to explore VVER-1000, EPR and CANDU technologies

http://www.world-nuclear.org/info/inf63.html

China: Fast Neutron Reactor Research

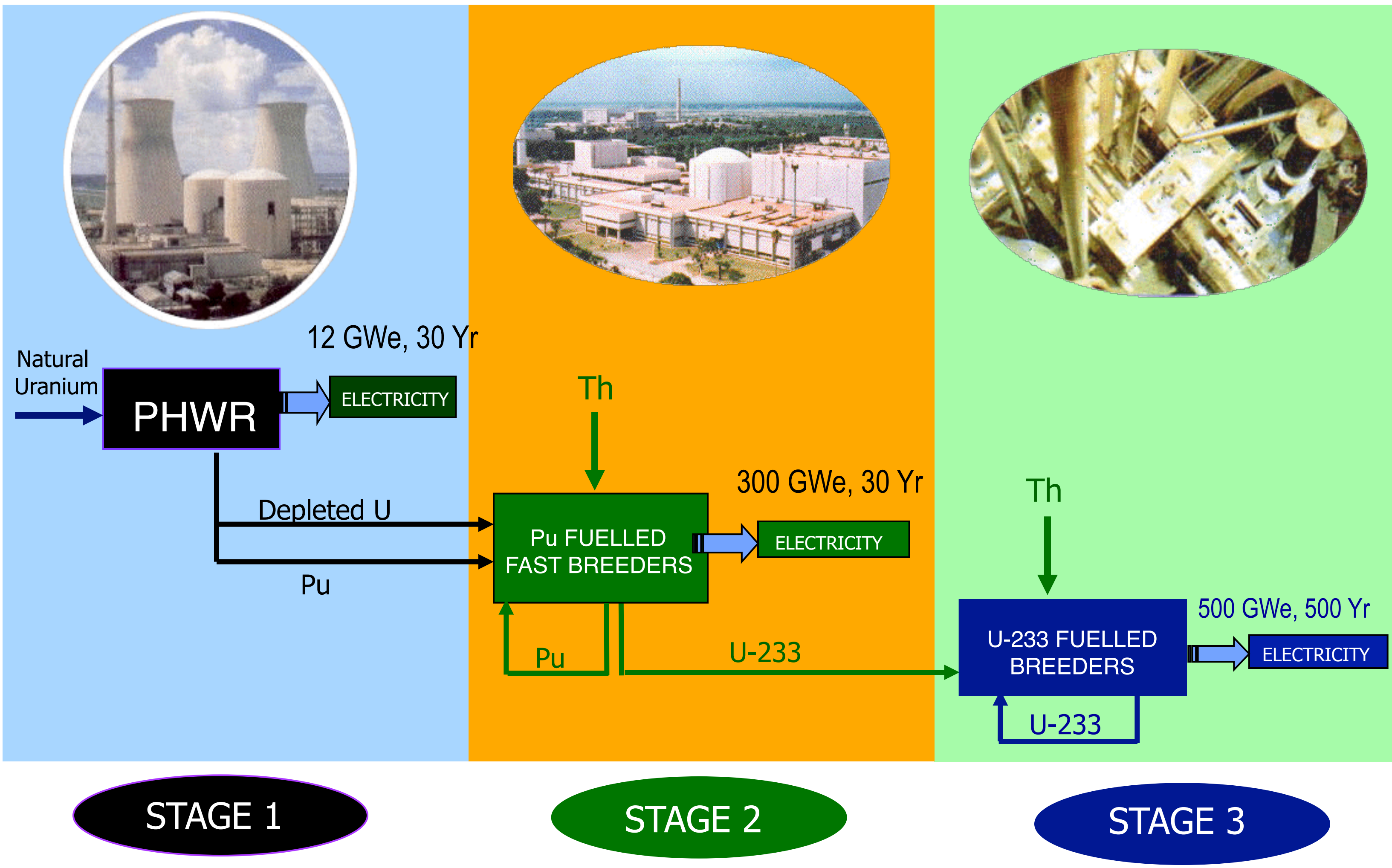
- Chinese Experimental Fast Reactor (CEFR)
  - 65MWt reached criticality on 2010-07-21 (now grid connected)
- Chinese Demonstration Fast Reactor (CDFR)
  - Construction scheduled to start in 2017
- Possible purchase of BN-800 from Russia

http://www.world-nuclear.org/info/inf63.html

India (0.2TW in 2011 → 0.7 TW)

- Coal (120 GW)
  - 0.6 gigatons/year
  - BHEL (5 GW annual production capacity with up to 500 MWe units)
- Natural Gas (16 GW)
  - BHEL manufactures under license from GE/Siemens (~ 2GW/year)
- Oil
  - ~3.1 million barrels/day (0.75 indigenous)
- Solar *(Jawaharlal Nehru Solar Mission)*
  - Manufactures cells and modules (1.5 GW) importing wafers from China
- Wind
  - 2010: Installed capacity (13 GW) and manufacturing (3.5 GW)
  - Suzlon-RWE: 3rd largest company & globally integrated
- Nuclear (4.4 GW from 20 reactors)
  - 2x920 MW (VVER-1000) nearing completion;
  - 4x630 MW (Indian standard PHWR-700) construction start
  - 1x470 MW FBR (Bhavini) under construction (2013)
  - Developing Thorium based AHWR

INDIA'S THREE STAGE NUCLEAR POWER PROGRAMME



India’s 3 Stage Program

- Stage I
  - 630 MW PHWR (construction of 4 reactors started in 2011)
  - Imported PWR

12 GW by 2020

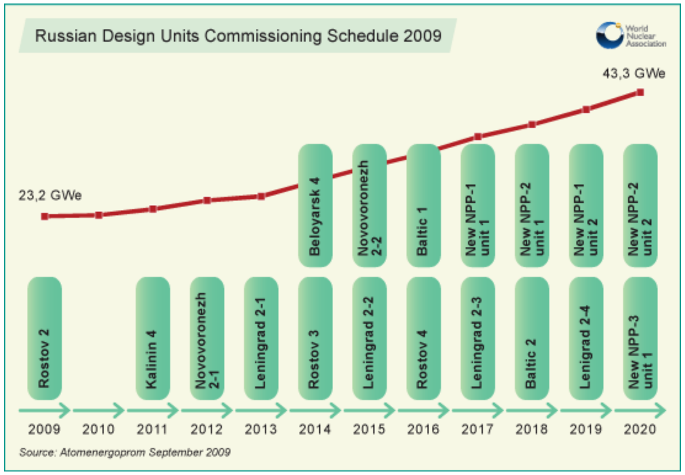
- Stage II
  - Fast Breeder Test Reactor (40 MWt). It has been testing fuel breeding and closed fuel cycle for FBR since 1985
  - Prototype Fast Breeder Reactor 470MW (u.c. scheduled for 2013)
  - Breeding blanket around the core to contain U and Th
- Stage III
  - Kamini (30 MWt): Testing U^{233} breeding & fuel cycle since 1996
  - Advanced Heavy Water Reactor (AHWR): Burn U^{233} from stage 2

Russia

- A Government Priority to revive nuclear industry post Chernobyl
  - Increase share of nuclear power domestically (displace coal & gas)
  - Develop Export Industry
  - Fast neutron reactors with a closed fuel cycle
- Existing reactors are
  - 4 Gen-I VVER-440/230 or similar PWR
  - 2 Gen-II VVER-440/213 PWR
  - 11 Gen-III VVER-1000/320
  - 11 RMBK light water graphite reactors (only in Russia)
  - 1 BN-600 FNBR

Life extension from 30 to 45-55 years

- 10 reactors under construction
- Standardize VVER-1000, -1200, -TOI
- Develop other civilian uses of nuclear power:
  - Aluminum Smelters
  - Desalination
  - Icebreakers
  - Medical Isotopes (Mo-99)



Russia: Export market

(Rosatom through subsidiary Atomstroyexport)

- Standardize Gen-III+ VVER-1000, VVER-1200, VVER-TOI
- Exported Reactors: Gen-III VVER-1000
  - India (2 at Kudankulam – 2004--2012)
  - Turkey, Jordan, Bangladesh, Vietnam under planning
- Exported Operating Reactors in
  - Armenia (1× VVER-440)
  - Bulgaria (2× VVER-1000)
  - China (Tianwan – 2 operating (2007), 6 under development)
  - Czech Republic (4× VVER-440, and 2× VVER-1000)
  - Finland (2× VVER-440)
  - Hungary (4× VVER-440)
  - Iran (1× VVER-1000)
  - Slovakia (4× VVER-440)
  - Ukraine (2× VVER-440, and 13× VVER-1000)

Why standardization helps [me]

IAEA, emergency operators, …

Russian PWR nuclear power reactors*

Generic reactor type	Reactor plant model	Whole power plant
VVER-300	V-478	(under development, based on VVER-640), Gen III+
VVER-440	V-230 V-213	
VVER-640	V-407	(under development), Gen III+
VVER-600	V-498	(under development, based on V-491), Gen III+
VVER-1000	V-320	most Russian & Ukraine plants
	V-338	Kalinin 1-3, Temelin 1&2, S. Ukraine 2
	V-446	based on V-392, adapted to previous Siemens work, Bushehr
	V-413	AES-91
	V-428	AES-91 Tianwan, based on V-392, Gen III
	V-412	AES-92 Kudankulam, based on V-392, Gen III
	V-392	AES-92 - meets EUR standards, Gen III, Belene contract?, Armenia, Khmelnitsky 3-4, Gen III
	V-466	AES-91/99 Olkiluoto bid, Belene proposal, Gen III+
VVER-1200	V-392M	AES-2006 Novovoronezh, Seversk, Central, S.Urals, Gen III+
	V-491	AES-2006 Leningrad, Belarus, Akkuyu?, Gen III+
VVER-1200A	V-501	AES-2006, Gen III+
VVER-1300	V-488	AES-2006M, Gen III+
VVER-TOI	V-510	AES-2010, Gen III+
VVER-1500	V-448	(under development), Gen III+

France

- 2 Gen III+ standardized reactors
  - EPR 1600–1700 MWe
  - Atema 1 (with MHI) 1000 MWe
- Focus on export
  - Completion will drive down price of EPR reactors
  - Completion of Olkiluoto-3 and Flamanville-3 reactors
- Compete in the market for operation, maintenance and repair of reactors

Canada AECL PHWR (CANDU)

Last unit commissioned in 1993: 881MW Darlington-4

200 MWe Reactor at Douglas Point, Ontario (1967-84)

↓

Design basis of the first Indian PHWR Rawatbhata 1 & 2

↓

INDIAN PHWR:
16 Reactors 202 Mwe
2 Reactors 490 MWe
Standardized 670 MWe

Canada: 22 CANDU Reactors commissioned between 1971-1993

↓

Candu 6 (EC6)
(2 x Qinshan, China)
(4 x Wolsong, S. Korea)

The next-generation Advanced CANDU Reactor (ACR-1000)

Future?

South Korea

- 2012: 21 reactors (20.8 GWe) provide ~35% of electricity
  - nuclear power cost is $30/MWh and to KEPCO ~$50/MWh
  - Coal cost is ~$40, LNG is ~$110, Hydro is ~$125/MWH
- 1×OPR-1000 and 2×APR-1400 under construction
  - Technology transfer with Combustion Engineering (now Westinghouse) incorporating CE System 80+
- Standardize APR-1400
- Goals by 2030:
  - Achieve 59% of electricity from 40 reactors (43 GWe)
  - Export 80 reactors worth $400 billion
    - 2008 contract with UAE: 4 APR-1400 reactors + 20 year O&M ($40B)
  - Compete in the operation, maintenance and repair of reactors market

Growing International Partnerships

- Westinghouse
  - Toshiba–Westinghouse (87% – 13%): Advanced Pressurized Water Reactor (APWR)
  - Westinghouse–KHNP: System 80+ is basis of Korean standard (KSNP)
- GE Hitachi Nuclear Energy Ltd
  - Hitachi (80.01%) GE (19.99%)
  - 92 BWR: directly from GEH designs or based on GEH licensed designs.
  - Market ABWR and ESBWR nuclear plants
- Areva, EdF in Japan: Developed Atema 1 in collaboration with MHI
- Areva in China: CGNPC, AREVA Dongfang JV
- Areva with Kazatomprom to develop the largest fuel fabrication facility
- Russia-Siemens (Siemens pulled out after Germany abandoned nuclear energy)
- India seeking collaboration with AECL to market PHWR to developing countries

Generation IV Reactors: Goals

- More efficient use of U and/or Th
- Higher burn up
- More economical
- Less waste
- Less long-lived waste
- Greater safety
- More proliferation resistant

Generation IV Reactors under R&D

- Fast neutron breeder reactors
  - Gas cooled
  - Sodium cooled
  - Lead cooled
- Very High Temperature Reactors (VHTR)
- Supercritical-Water Cooled Reactor (SCWR)
- Molten Salt reactors

- Modular reactors
- Wakefield reactors
- Novel concepts

Source: https://inlportal.inl.gov/portal/server.pt/community/research_programs/260

Fast Neutron Breeder Reactors

(A less than encouraging history starting with US and UK programs)

	Years	Capacity	Type (Sodium cooled)	Issues
Rapsodie (Fr)	1967–1983	40 MWt	breeder (no power gen)	
Phenix (Fr)	1973–2009	233 MWe	Pool type	(ASTRID ?)
Superphenix (Fr)	1984–1998	1200 MWe		corrosion, leaks
FBTR (India)	1985–	40 MWth	Breeds U^{233} from ThO_2 (used in 30 MWt Kamini)	leaks, fire
PFBR (India)	2013–	470 MWe		
Joyo (Japan)	1977–	140 MWt		
Monju (Japan)	1994–??	280 MWe	MOX-fueled loop type	Fire, crane accident
BN-600 (Russia)	1980–2020	600MWe		leaks, fire
BN-800 (Russia)	2013–	800 MWe		Beloyarsk NPP (export to China)

No compelling motivation as long as U is inexpensive and LWR work

Source:http://fissilematerials.org/library/rr08.pdf

Issues with FNBR

- Water cannot be used as heat transfer fluid as it degrades the neutron spectrum. Water provides passive safety in LWR
- Reliability
  - Frequent shutdowns
  - Maintenance and Repairs of Na cooled reactors is complicated. It can take months as (radioactive) Na has to be carefully drained
- Safety
  - Fires with sodium cooled systems (Leaks, hotspots)
- Proliferation
  - Separation/breeding/recycling of Pu is an integral part of program
- Costly to build and operate compared to LWR
  - No clear estimate of cost as all current reactors are experimental, demonstration, or part of weapons programs

Uranium Resources

Typical Concentrations	Parts Per Million (ppm) U
Very high-grade ore (Canada) - 20% U	200,000
High-grade ore - 2% U,	20,000
Low-grade ore - 0.1% U	1000
Very low-grade ore (Namibia) - 0.01% U	100
Granite	3-5
Sedimentary rock	2-3
Earth's continental crust (av)	2.8
Seawater	0.003

Source: http://www.world-nuclear.org/info/inf75.html

2009: Recoverable Resource at $130/kg U

	tonnes U	percentage of world
Australia	1,673,000	31%
Kazakhstan	651,000	12%
Canada	485,000	9%
Russia	480,000	9%
South Africa	295,000	5%
Namibia	284,000	5%
Brazil	279,000	5%
Niger	272,000	5%
USA	207,000	4%
China	171,000	3%
Jordan	112,000	2%
Uzbekistan	111,000	2%
Ukraine	105,000	2%
India	80,000	1.5%
Mongolia	49,000	1%
other	150,000	3%
World total	5,404,000	

Source: OECD NEA & IAEA, *Uranium 2009: Resources, Production and Demand* ("Red Book")

Uranium Usage in LWR

- Reserves: 5.4 million tonnes of U
- Current global usage 68,000T/year
- Typical Requirements (once through)
  - 180 T of U per GW capacity per year
  - 5.4 million T of U = 500 GW capacity for 60 years

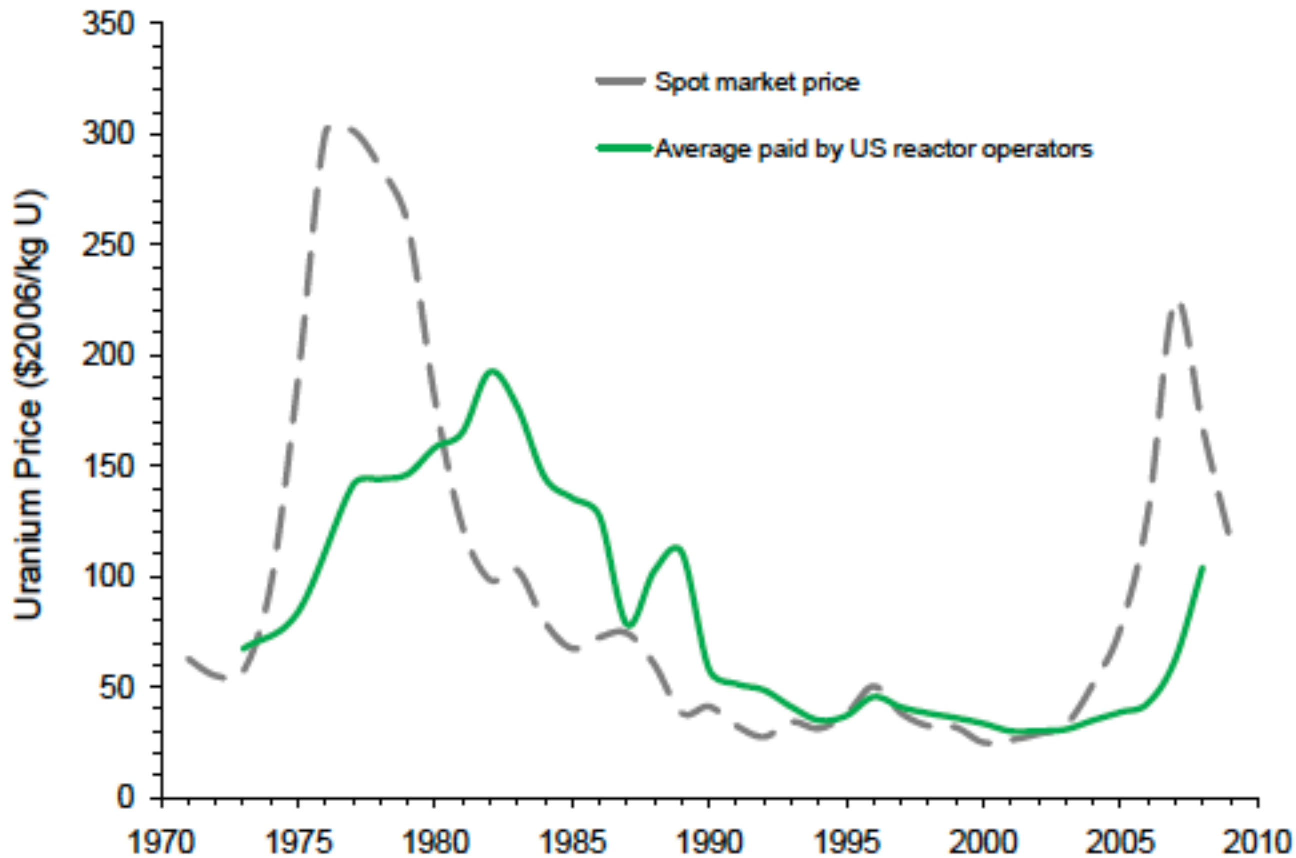
Emerging Fuel Banks

- Russian LEU Reserve: 120 T
- IAEA LEU Bank:
- American Assured Fuel Supply (AFS): 230+60T

The US (Westinghouse and GE) is a major fuel fabricator. Since US reactors provide ~35% of nuclear power generated, there is a large market at home

Source: http://www.world-nuclear.org/info/inf75.html

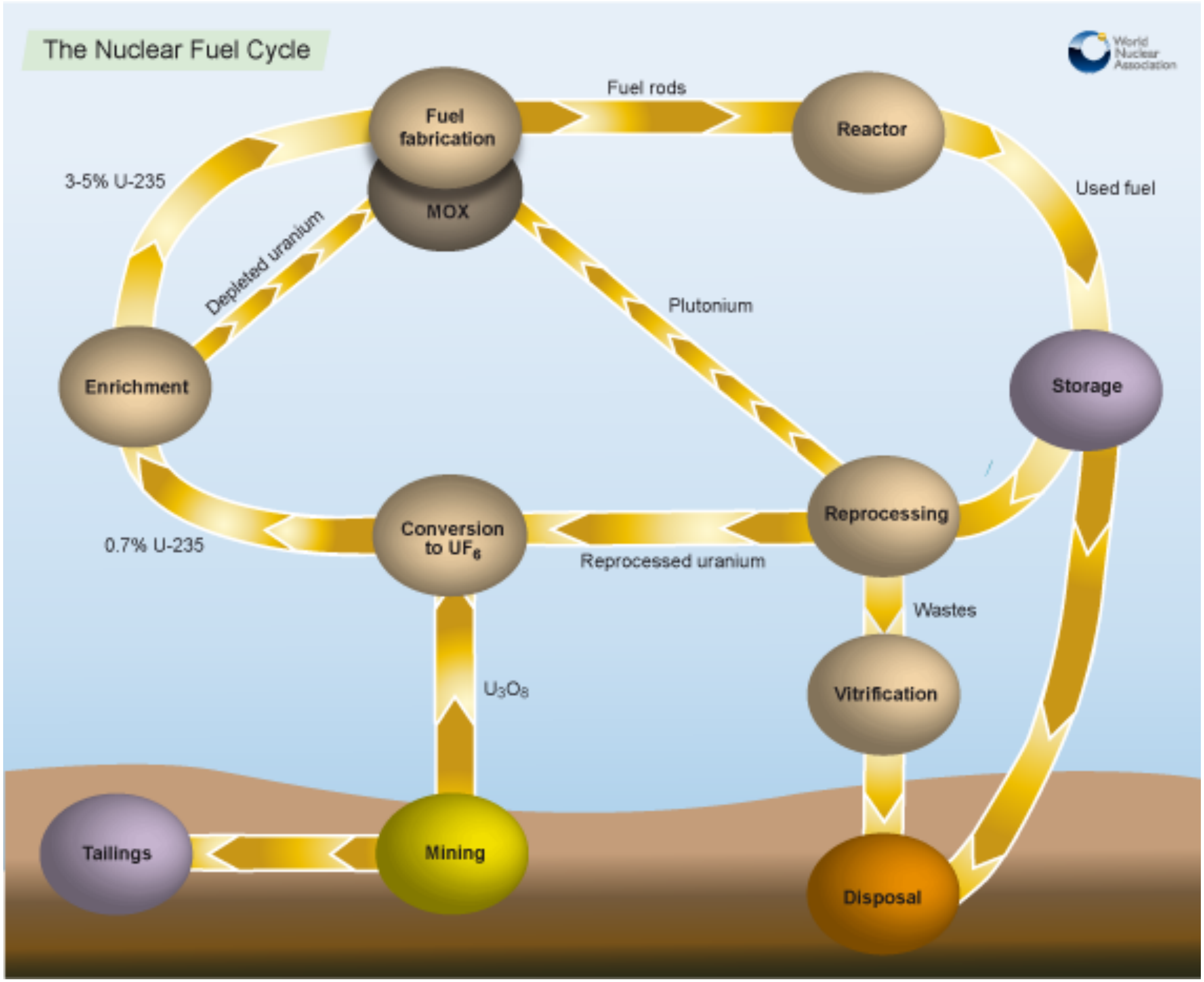
History of Uranium prices since 1970



At $130/kg, U fuel costs at 45 GWd/T add $3/MWh

Source:http://fissilematerials.org/library/rr08.pdf

Nuclear Fuel Cycle



Source: http://www.world-nuclear.org/info/nuclear_fuel_fabrication-inf127.html

Fuel Type and Assemblies Vary

Type of Reactors **(%fraction)**

- PWR (66%)
- BWR (22%)
- Candu (6%)
- RBMK (3%)
- AGR (2.7%)
- FNR

Type of Fuel

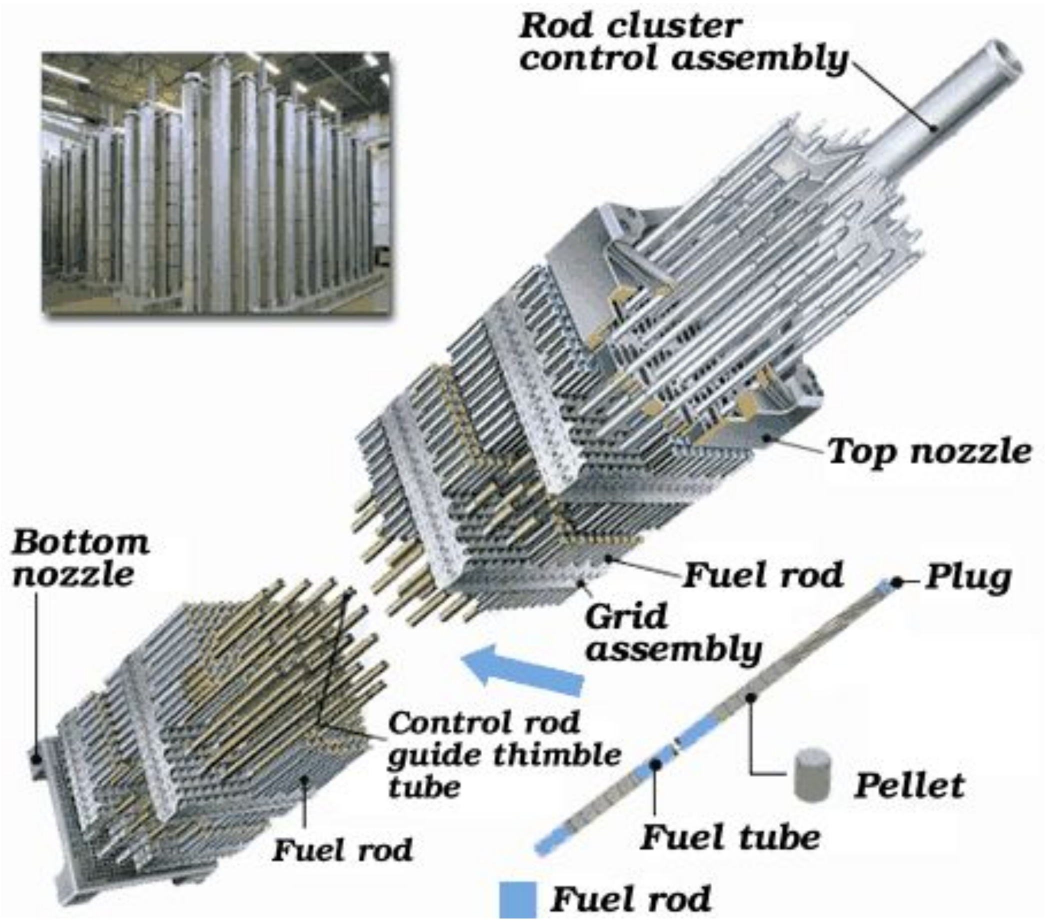
- UO_2
- MOX
- Metal
- Thorium/Uranium
- Enrichment levels

Desired Fissioning Components: U^{235}, [Pu^{239}, U^{233}]

0.7% in Natural U

Require breeding from U^{238}, Th^{232}

Schematic view of LWR fuel assembly by Mitsubishi Nuclear Fuel



Source: http://www.world-nuclear.org/info/nuclear_fuel_fabrication-inf127.html

Table 1: World LWR fuel fabrication capacity, tonnes/yr

	Fabricator	Location	Conversion	Pelletizing	Rod/assembly
Belgium	AREVA NP-FBFC	Dessel	0	700	700
Brazil	INB	Resende	160	160	280
China	CNNC	Yibin Batou	400	400	450
France	AREVA NP-FBFC	Romans	1800	1400	1400
Germany	AREVA NP-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (PWR)	Kumatori	0	360	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	475	440	440
	GNF-J	Kurihama	0	750	750
Kazakhstan	Ulba	Ust Kamenogorsk	2000	2000	0
Korea	KNFC	Daejeon	600	600	600
Russia	TVEL-MSZ*	Elektrostal	1450	1200	120
	TVEL-NCCP	Novosibirsk	250	200	400
Spain	ENUSA	Juzbado	0	300	300
Sweden	Westinghouse AB	Västeras	600	600	600
UK	Westinghouse**	Springfields	950	600	860
USA	AREVA Inc	Richland	1200	1200	1200
	Global NF	Wilmington	1200	1200	750
	Westinghouse	Columbia	1500	1500	1500
Total			**13433**	**14558**	**12662**

** Includes approx. 220 tHM for RBMK reactors*
*** Includes approx. 200 tHM for AGR reactors*

Table 2: World PHWR fuel fabrication capacity, tonnes/yr

	Fabricator	Location	Rod/Assembly
Argentina	DIOXITEK SA & ENACE	Cordoba & Eizeiza	160
Canada	Cameco		1500
	GE		1200
China	CNNC	Baotou	200
India	DAE Nuclear Fuel Complex	Hyderabad	435
Pakistan	PAEC	Chasma	20
Korea	KEPCO	Taejon	400
Romania	SNN	Pitesti	240
Total			**4155**

Source: http://www.world-nuclear.org/info/nuclear_fuel_fabrication-inf127.html

Spent Nuclear Fuel (SNF)

	At Charge (%)	At Discharge (%)
Uranium	100	93.4
Enrichment (U^{235})	4.2	0.71
Plutonium	0	1.27
Minor Actinides	0	0.14
Fission Products	0	5.15

Typical for a LWR

- Pu – Useful for both fuel and nuclear weapons
- Fission Products → hot and need storage
- Minor Actinides
  - Many are poisons (n absorbers) – buildup on reprocessing limits number of fuel reprocessing cycles for LWR
  - Long-lived and hot – thus a concern for geological storage
  - *Can be burned as fuel in fast reactors ((n,γ)/fission small)*

Spent Nuclear Fuel (SNF)

Actinides				Half-life	Fission products			
^{244}Cm	^{241}Pu f	^{250}Cf	^{243}Cm f	10–30 y	^{137}Cs	^{90}Sr	^{85}Kr	
^{232}U f		^{238}Pu	f is for	69–90 y			^{151}Sm nc→	
4n	^{249}Cf f	^{242}Am f	fissile	141–351	No fission product has half-life 10^2 to 2×10^5 years			
	^{241}Am		^{251}Cf f	431–898				
^{240}Pu	^{229}Th	^{246}Cm	^{243}Am	5–7 ky				
4n	^{245}Cm f	^{250}Cm	^{239}Pu f	8–24 ky				
	^{233}U f	^{230}Th	^{231}Pa	32–160				
	4n+1	^{234}U	4n+3	211–290	^{99}Tc		^{126}Sn	^{79}Se
^{248}Cm		^{242}Pu		340–373	Long-lived fission products			
	^{237}Np	4n+2		1–2 My	^{93}Zr	^{135}Cs nc→		
^{236}U			^{247}Cm f	6–23 My		^{107}Pd	^{129}I	
^{244}Pu	4n+1			80 My	>7%	>5%	>1%	>.1%
^{232}Th		^{238}U	^{235}U f	0.7–12 Gy	fission product yield			

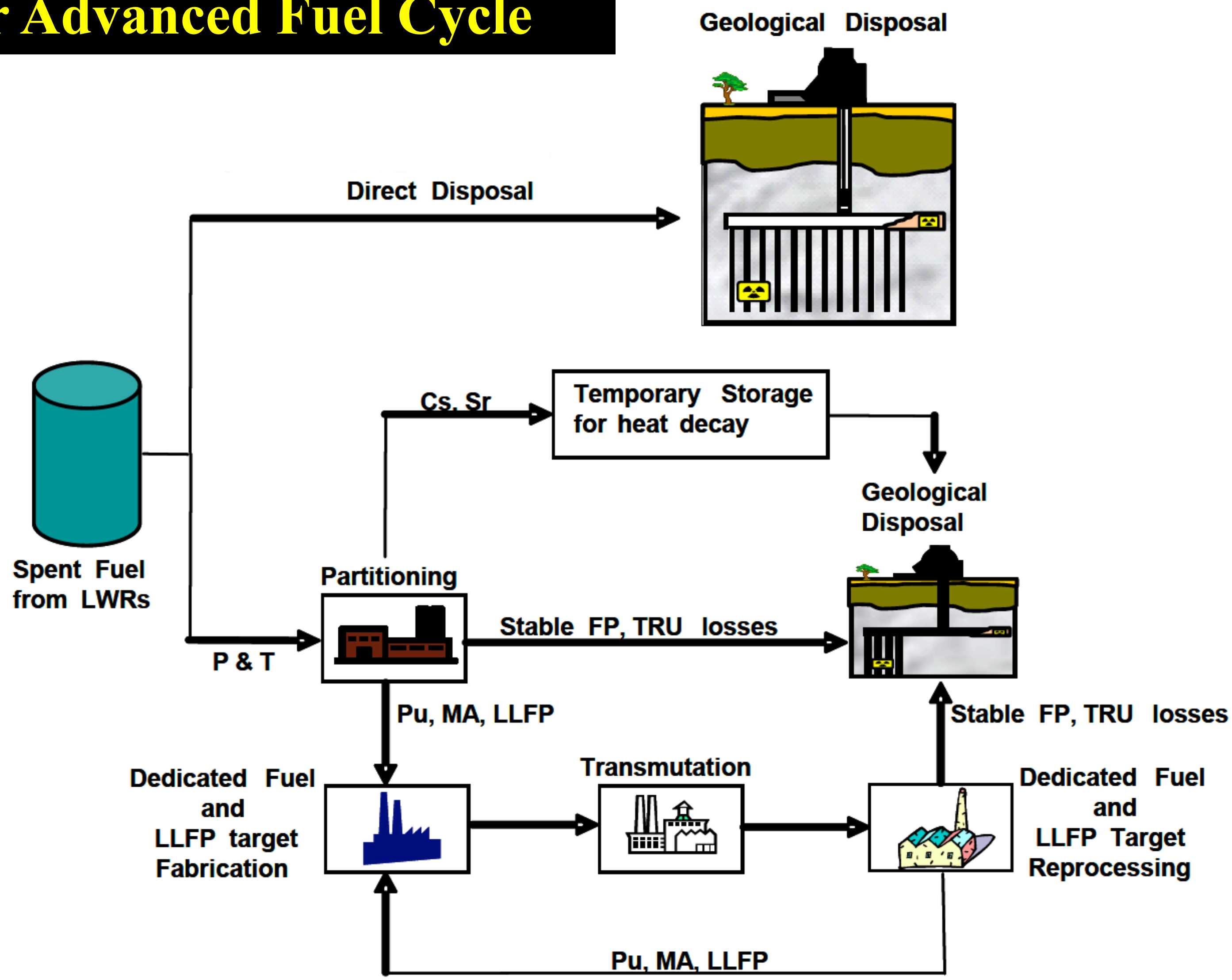
Short lived

Medium-life

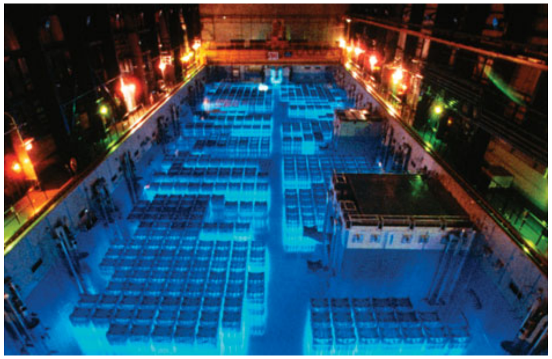
Long-lived

Half-life, type of radiation, spectrum drive storage strategy

Partitioning and Transmutation (P/T) schematic for Advanced Fuel Cycle



LLFP: Long lived fission products (Tc-99, I-129, Se-79, ...); MA: Minor Actinides (Am, Np, Cm)



SNF Management

- Cooling water tanks
- Dry cask storage
  - Inert gas bath inside steel tube, and concrete casing
- Vitrification / Geological Storage
- Transmutation
- Fast breeder reactors
- Reprocessing
  - France, Japan, Russia, the U.K [future → China, India]

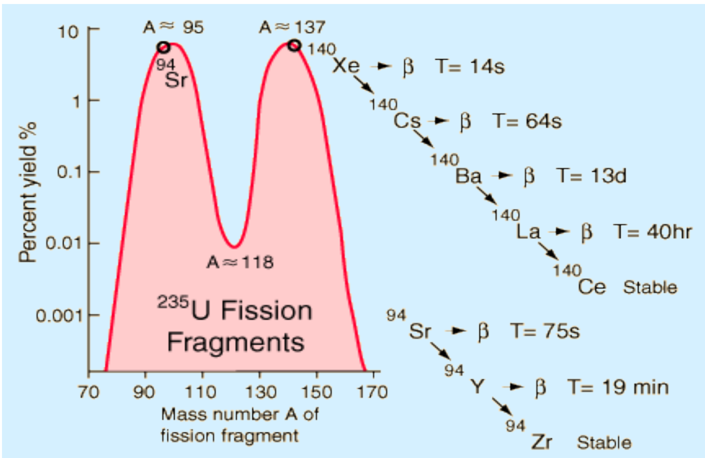
SNF Management

- US: Cooling tanks
- Russia: Dry storage
- Ukraine: Dry storage
- China: At-reactor storage; away-from-reactor storage; reprocessing; vitrification; geological storage
- …

Reprocessing being done by

Belgium, China, Germany, France, India, Japan, Pakistan, Russia, UK, USA, ?

Fission products need storage

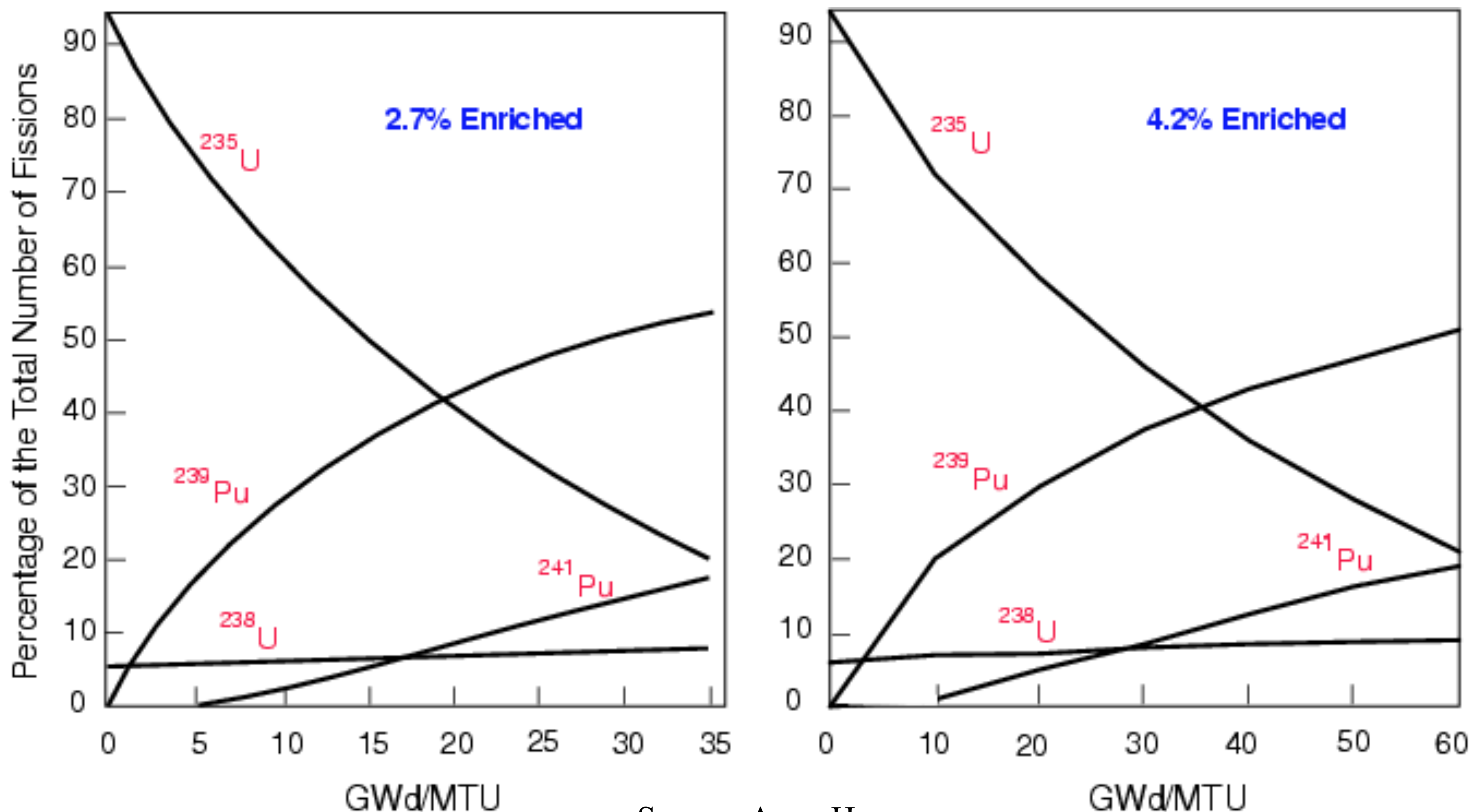


Nuclear Safety & Safeguards

- Safety
  - Preventing nuclear and radiation accidents
  - Limiting impacts and consequences
- Safeguards
  - implementing international initiatives designed to limit the proliferation of nuclear weapons
  - preventing the diversion of fissile materials

In addition to best designs & construction, must have
- Independent regulation [trained inspectors]
- A meticulous, self-critical safety culture

Plutonium builds up in reactors with U^{238} in the fuel



Source: Anna Hayes

Countries with intent and reactors have a source of Pu

Nuclear Threat – Proliferation

The U.S. is unlikely to make much progress on reducing nuclear threat unless Russia and China also view proliferation in North Korea, Burma, Pakistan, Iran, Syria, Libya, …
as a global threat

including a threat to them

Research & Development

- Research on Gen IV concepts being carried out in many organizations in many countries
  - Reactor design
  - Fuel
  - Moderator
  - Coolant
- Safety of Gen III reactors and control systems is high, and increasing steadily. Still need highly trained staff
- Reprocessing of SNF

Source: https://inlportal.inl.gov/portal/server.pt/community/research_programs/260

Summary

- US Gen III reactor systems dominate IP
- Future capacity addition will be dominated by China, India, Russia, South Korea
- Manufacturing of LWR has moved to Asia
- Increasing internationalization of nuclear power: Need for more effective monitoring of safety and safeguards
- Unclear what new market modular reactors will open since urbanization trend is towards mega-cities and large industrial zones
  - Are there enough islands/regions not yet connected & needing ~100MW?
  - Mining activities?
- Most fossil-fuel poor regions (Eastern Europe, India, Asian Tigers, …) will want 30% or more of electric power from nuclear
- Reprocessing of SNF and actinides burn-up in FNR facilities will grow

Conclusions

- Need to develop & standardize at least one FNBR technology
  - Facilitate use of Thorium
  - Facilitate burn up of minor actinides
  - Facilitate reprocessing
- Enhance and strengthen the culture of safety and safeguards
  - Will need increased cooperation between China, France, India, Japan, Russia, South Korea, US
- **My guesstimate: ~850 GW nuclear capacity by 2050 based on reviewing trends, social and political challenges, and anticipating growth in combined exploitation of U and Th**