Nuclear Energy

Outline

- Nuclear Reactions: Unstable nucleus → Stable nucleus
- Uranium Mining and Supply Chain
- Nuclear Reactors
- Economics

Based on

- Das, A. and T. Ferbel. 2004. Introduction to Nuclear and Particle Physics. Second edition by World Scientific Publishing. ISBN 981-238-744-7.
- The Future of Nuclear Power. An Interdisciplinary MIT Study, 2003 and its 2009 update.
- The Future of the Nuclear Fuel Cycle. An Interdisciplinary MIT Study, 2010.

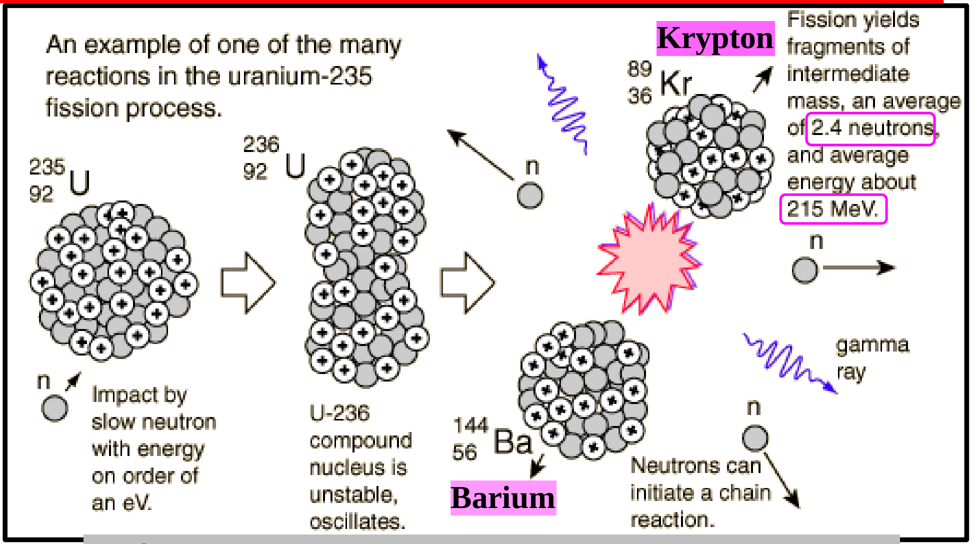
See http://web.mit.edu/nuclearpower/

A U-236 Fission (Splitting) Reaction

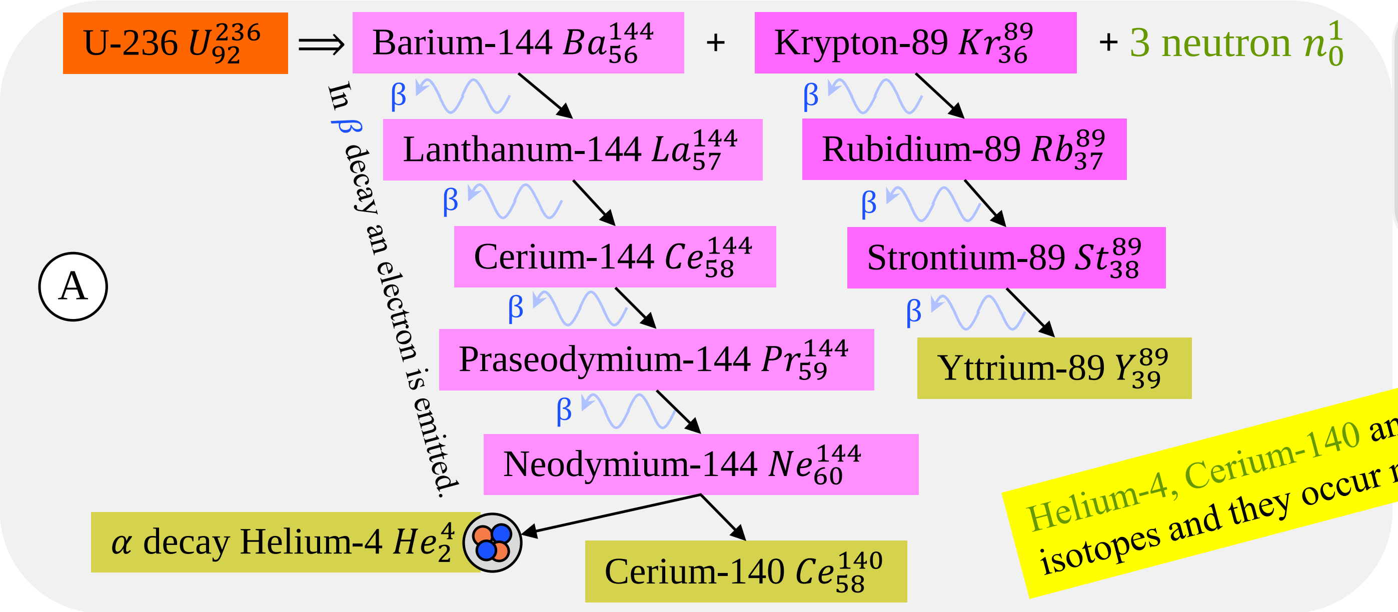
- When a slow-moving neutron is caught by the nucleus of U-235, they result in unstable U-236 (another isotope of Uranium with 144 neutrons).
  - Even when U-238 is in the same environment with U-235, U-238 is more stable and is not often disturbed by slow moving neutrons. Faster neutrons (more kinetic energy) can potentially yield U-239 but they are not used in nuclear reactors.
  - Fast-moving neutrons are not caught by the nucleus of U-236 upon a collusion; they sort of bounce off.
- The nucleus of U-236 has 92 protons and 144 neutrons. It does not split equally by weight.

Following reactions are possible for U-235:

U-235 U_{92}^{235} + neutron n_0^1 $\Longrightarrow$ U-236 U_{92}^{236}



A fission example. Source: http://hyperphysics.phy-astr.gsu.edu



U-236 U_{92}^{236} $\Longrightarrow$ Barium-144 Ba_{56}^{144} + Krypton-89 Kr_{36}^{89} + 3 neutron n_0^1

β Lanthanum-144 La_{57}^{144}

β Cerium-144 Ce_{58}^{144}

β Praseodymium-144 Pr_{59}^{144}

β Neodymium-144 Ne_{60}^{144}

α decay Helium-4 He_2^4

Cerium-140 Ce_{58}^{140}

β Rubidium-89 Rb_{37}^{89}

β Strontium-89 St_{38}^{89}

β Yttrium-89 Y_{39}^{89}

In β decay an electron is emitted.

Nuclear transmutation

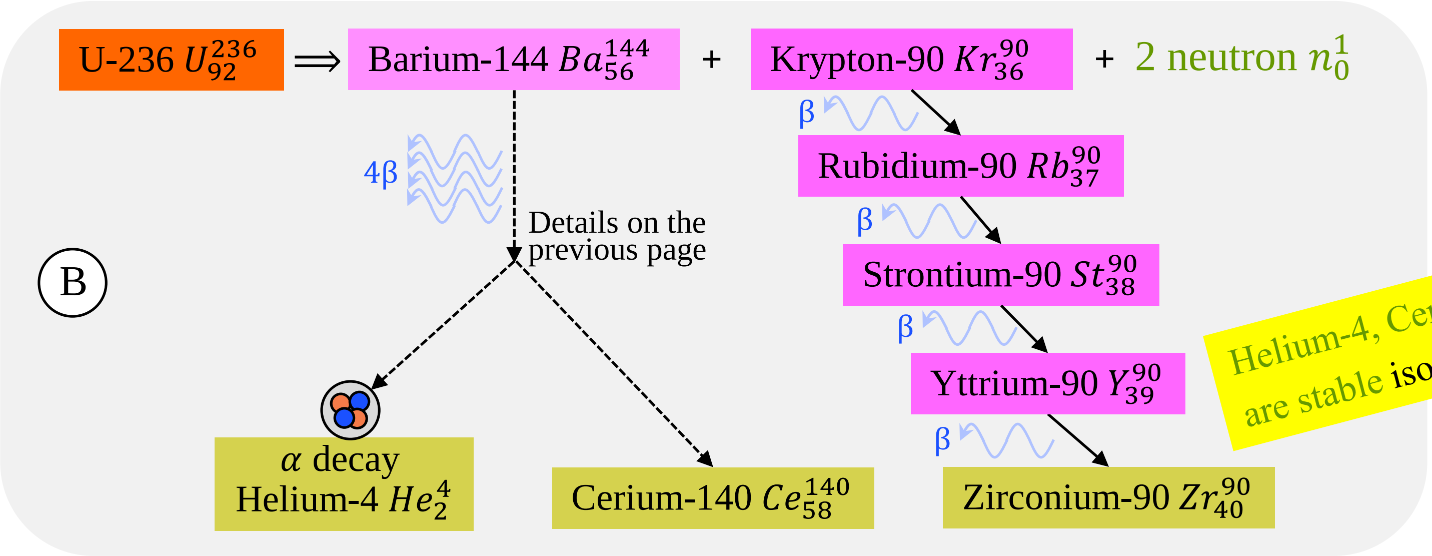
$Kr_{36}^{89} \longrightarrow Rb_{37}^{89} + e_{-1}^{0}$

Neutron ⇒ Proton + electron

Neutron becomes proton by releasing an electron

Helium-4, Cerium-140 and Yttrium-89 are stable isotopes and they occur naturally.

Other U-236 Fission Reactions: B and C



B

U-236 U_{92}^{236} ⟹ Barium-144 Ba_{56}^{144} + Krypton-90 Kr_{36}^{90} + 2 neutron n_0^1

Rubidium-90 Rb_{37}^{90}

Strontium-90 St_{38}^{90}

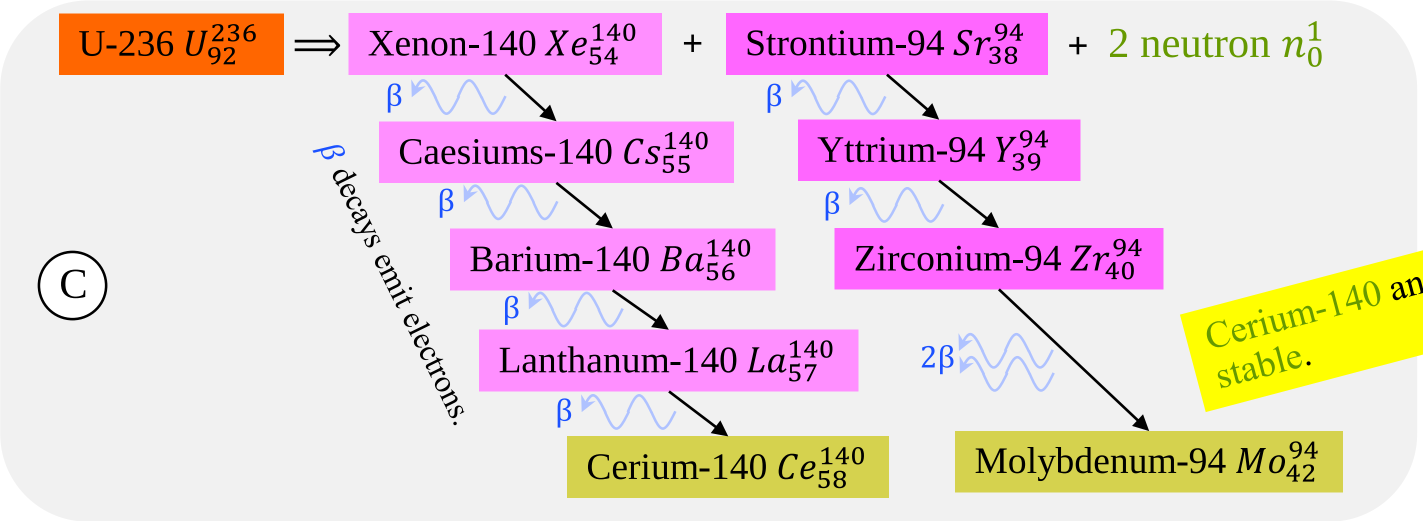
Yttrium-90 Y_{39}^{90}

α decay
Helium-4 He_2^4

Cerium-140 Ce_{58}^{140}

Zirconium-90 Zr_{40}^{90}

Helium-4, Cerium-140 and Zirconium-90 are stable isotopes.



C

U-236 U_{92}^{236} ⟹ Xenon-140 Xe_{54}^{140} + Strontium-94 Sr_{38}^{94} + 2 neutron n_0^1

Caesiums-140 Cs_{55}^{140}

Barium-140 Ba_{56}^{140}

Lanthanum-140 La_{57}^{140}

Cerium-140 Ce_{58}^{140}

Yttrium-94 Y_{39}^{94}

Zirconium-94 Zr_{40}^{94}

Molybdenum-94 Mo_{42}^{94}

β decays emit electrons.

Cerium-140 and Molybdenum-94 are stable.

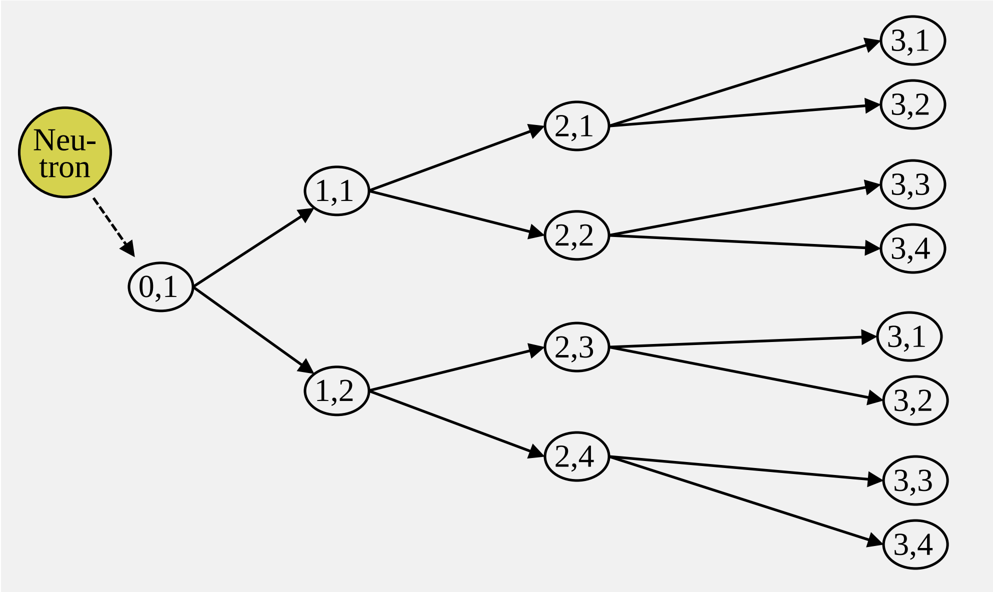
Decay reactions are from http://periodictable.com/isotopes/P.M, P is the number of protons and M is the mass (protons+neutrons) of a nucleus.
E.g., for Kr_{36}^{89} and Kr_{36}^{90} decays go to http://periodictable.com/Isotopes/036.89 and http://periodictable.com/Isotopes/036.90 .
E.g., for Ba_{56}^{144} decay with pictures go to http://periodictable.com/Isotopes/056.144/index.p.full.html .

Observations from 3 Fission Reactions A, B, C

- Except for 1 final product in the 3 fission reactions A, B, C, all final products have even number of protons and even number of neutrons.
  - Only Yttrium Y_{39}^{89} has odd number of protons and yet it has a stable nucleus.

- Reaction A releases 3 neutrons, reaction B releases 2 neutrons and reaction C releases 2 neutrons.
- Ex: If reactions A, B, C are happening with equal probability, how many neutrons are released on average?
  - Average of 2, 2, 3 is 2.33.
- The number of neutrons released in U-236 fission is found experimentally to be about 2.4.

- If the fission reaction releases 2 neutrons always, the number of neutrons grow exponentially over time (chain reaction):



Number of neutrons after the 1st stage reaction is 2, after the 2nd stage reaction is 4, after the third stage reaction is 8, ….,

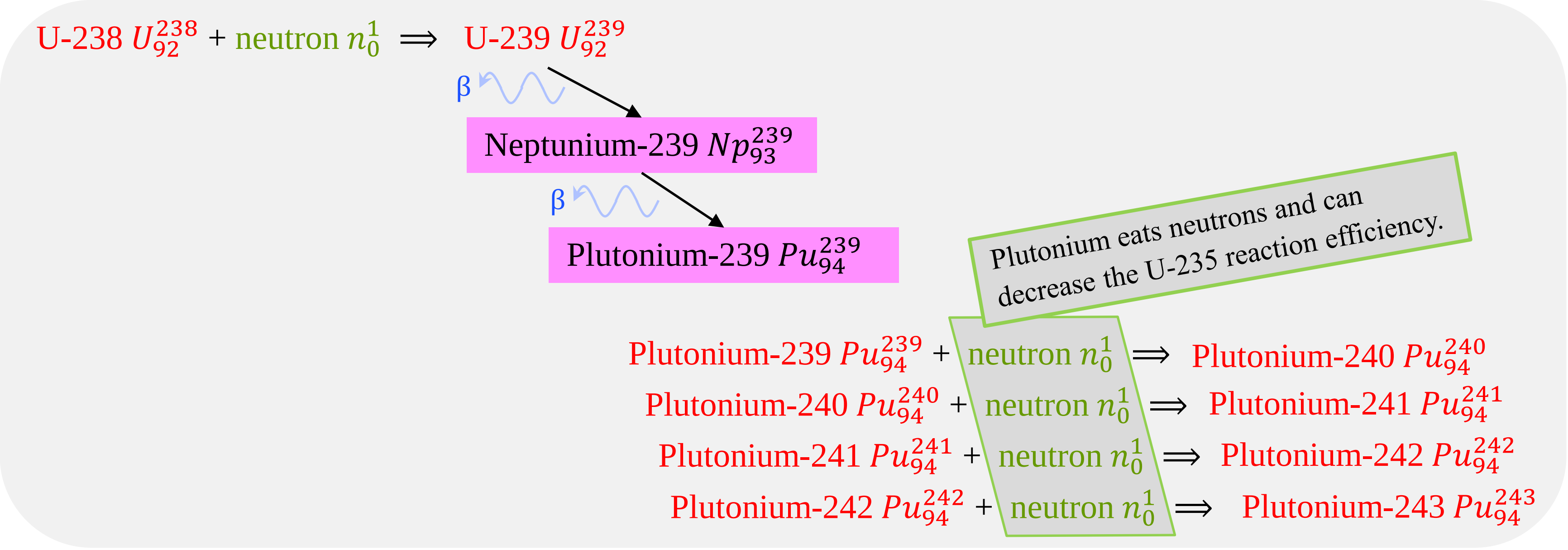
…., after the nth stage reaction is 2^n.

The number of neutrons released by a reaction is in general random. Then the growth of number of neutrons can be studied as a Branching Process, a topic covered in Probability.

- Not all of U 235 is hit by an electron. Spent fuel still has U 235 but at a lower concentration.

Plutonium Breeding Process

- When a neutron hits U-238, it sometimes can be captured by the nucleus of U-238, which then becomes U-239.



U-238 U_{92}^{238} + neutron n_0^1 $\Longrightarrow$ U-239 U_{92}^{239}

β

Neptunium-239 Np_{93}^{239}

β

Plutonium-239 Pu_{94}^{239}

Plutonium eats neutrons and can decrease the U-235 reaction efficiency.

Plutonium-239 Pu_{94}^{239} + neutron n_0^1 $\Longrightarrow$ Plutonium-240 Pu_{94}^{240}

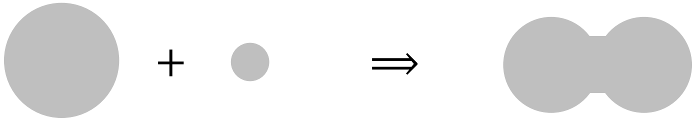
Plutonium-240 Pu_{94}^{240} + neutron n_0^1 $\Longrightarrow$ Plutonium-241 Pu_{94}^{241}

Plutonium-241 Pu_{94}^{241} + neutron n_0^1 $\Longrightarrow$ Plutonium-242 Pu_{94}^{242}

Plutonium-242 Pu_{94}^{242} + neutron n_0^1 $\Longrightarrow$ Plutonium-243 Pu_{94}^{243}

- Nuclear fuel has much more U-238 than U-235.
- U-238 goes through nuclear reactions (Plutonium Breeding) and becomes P-239, Pu-240, Pu-241, Pu-242, Pu-243.
- Pu 240, 241, 242, 243 are unstable isotopes can be used as nuclear fuel.

- What causes a fission can be that nuclear forces in U-236 and U-239 are overwhelmed by electrical forces after the capture of an neutron which disturbs the shape of the nucleus, say from spherical to an ellipsoidal.



Short-ranged nuclear forces are ineffective from one end of the ellipsoidal to the other.

- Stable atoms can be fused to obtain energy, this fusion process is the opposite of fission. Fusion is applicable to small atoms and fission is applicable to large atoms; the size affects the (binding) nuclear energy.

Energy from U-235+n_0^1 Fission

- Fission of a single Uranium-235 atom yields about 215 mega electron volts.
  - 1 electron volt is the energy gained by moving 1 electron from 0 volts (ground) to 1 volt.
  - 1 mega electron volt $1.6*10^{-13}$ joules so it is a very small amount of energy.
- Single U-235 atom yields $3.44*10^{-11}$ joules.
- 235 gram of U-235 has 1 mole of atoms, that is $6.02*10^{23}$ atoms. 235 gram releases $2{,}070*10^{10}$ joules.

U-235 U_{92}^{235} + neutron n_0^1 $\Rightarrow$ U_{92}^{236} $\Rightarrow$ Ba_{56}^{144} + Kr_{36}^{89} + 3 neutrons n_0^1 + $2{,}070*10^{10}$ joules/mole

- 1 gram of Uranium-235 releases ≈ 10^{11} joules (=$2{,}070*10^{10}$/235) or 1 Mega Watt day (MWd).
  - 1 Watt = 1 joules per second
  - 1 MWd = $10^6 * 24 * 60 * 60$ joules = $0.864 * 10^{11}$ joules.

1 gram U-235 …. $\Rightarrow$ …. + 1 MWd

- A typical US household spends ≈ 1000 kilo Watt hour (kWh) per month or 1.375/1000 MWd per day
  - 1000 kWh / month = 33 kWh / day = 1.375 kWd / day = 1.375/1000 MWd / day.
- 1 gram U-235/day suffices for 727 (=1000/1.375) households.

1 gram U-235 $\Rightarrow$ 727 US houses for a day

- Uranium is 5,000,000 times more efficient than coal. 5,000,000= $10^{11}/(20*10^3)$.
  - 1 gram of U-235 gives 10^{11} joules.
  - 1 gram of coal releases $20*10^3$ joules.

1 gram U-235 ≈ 500,000 gram coal

- A nuclear reactor has 1,200 MW power and gives 438,000 (=1200*365) MWd over an entire year.
  - It requires burning 438,000 grams or 0.438 tons of U-235 in a year.
- If U-235 is only 6% of nuclear fuel, the reactor needs 7.3 (=0.438/0.06) tons of fuel (U-235 and U-238) per year
  - It requires 20 (=7,300/365) kilograms of nuclear fuel per day.
- The reactor uses 20 kilograms of enriched fuel to generate 1,200 MWd.

1 kilogram of enriched fuel U-235 and U 238 = 60 MWd

Uranium Mining and Supply Cycle

Uranium Reserves are Plenty

Current usage of Uranium ore is 68,000 ton/year.

Total **known** reserves is 5,400,000 ton.

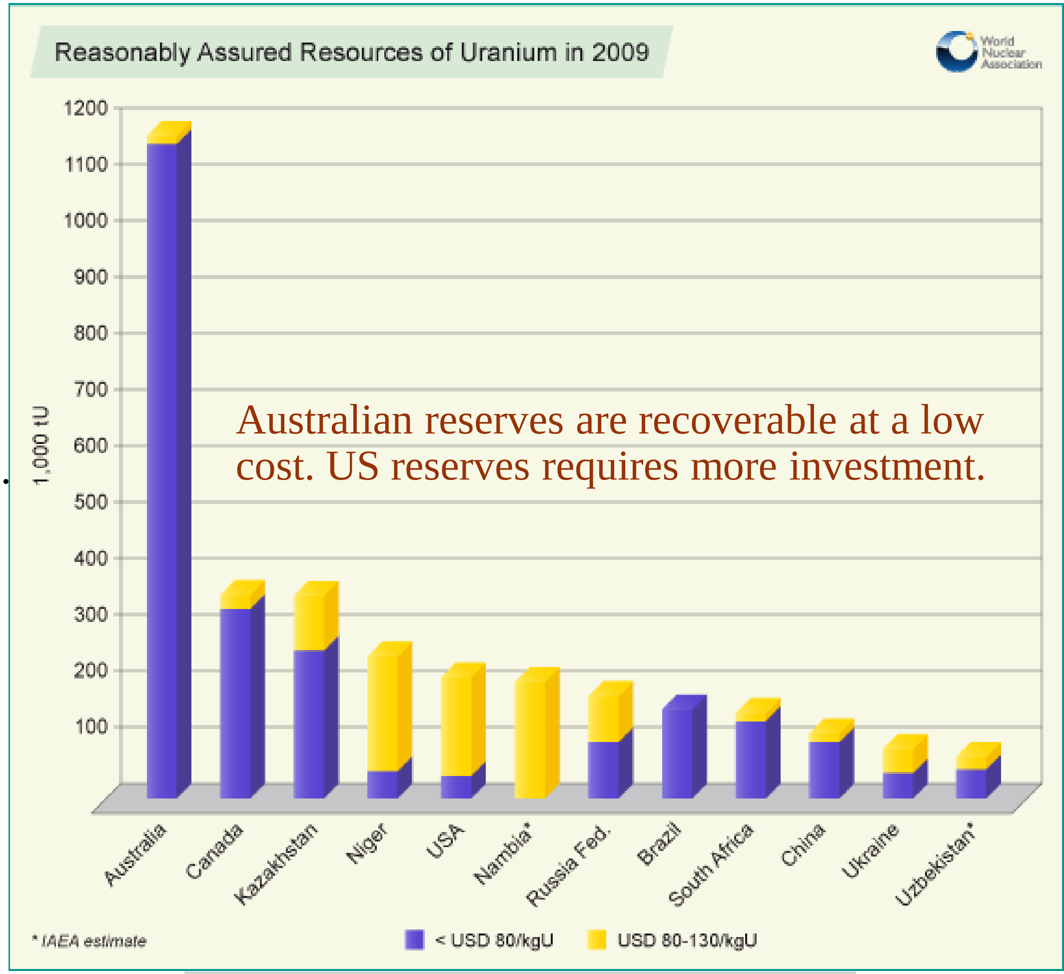
Reserves will last 5,400,000/68,000=80 years.

Total reserves to be discovered is 10,500,000 ton.

According to **How long will the world's uranium supplies last?** by S. Fetter, Scientific American, Jan 26, 2009.

Reserves will last 15,900,000/68,000=233 years.

Australia has 31% of known reserves;
Kazakhstan has 12%; Canada 9%; Russia 9%;
Namibia 5%; Brazil 5%; Niger 5%.



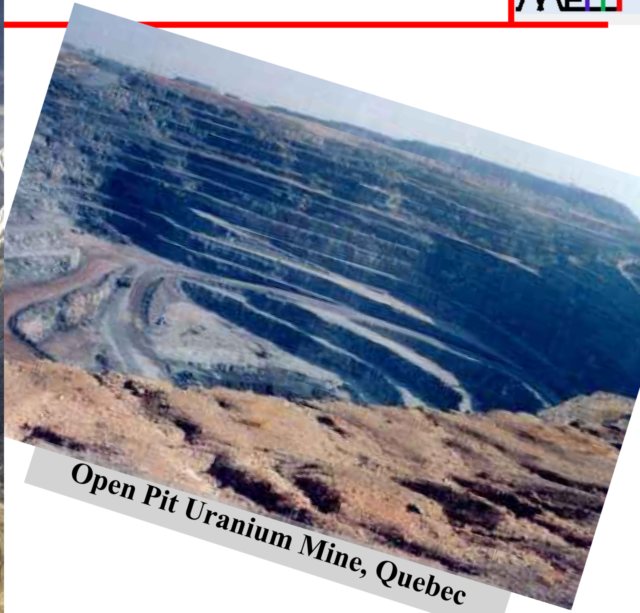
Australian reserves are recoverable at a low cost. US reserves requires more investment.

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

Uranium Mines


Open Pit Uranium Mine, New Mexico

Open Pit Uranium Mine, Namibia

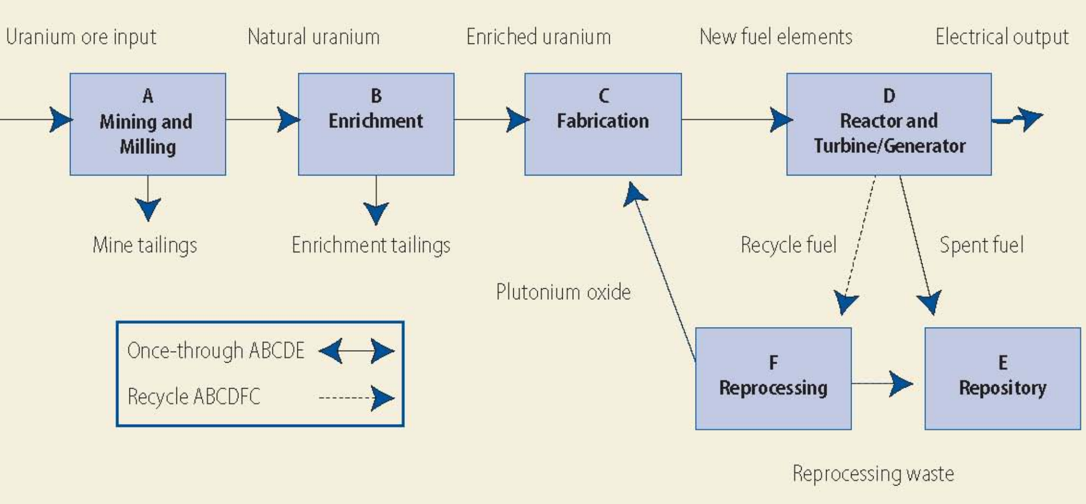


Open Pit Uranium Mine, Quebec


Underground Uranium Mine, Australia

Uranium Ore
Uranium Oxides: UO_2 or UO_3


Uranium Yellowcake (powder)

Uranium Supply Chain and Cycle



Uranium ore input
Natural uranium
Enriched uranium
New fuel elements
Electrical output

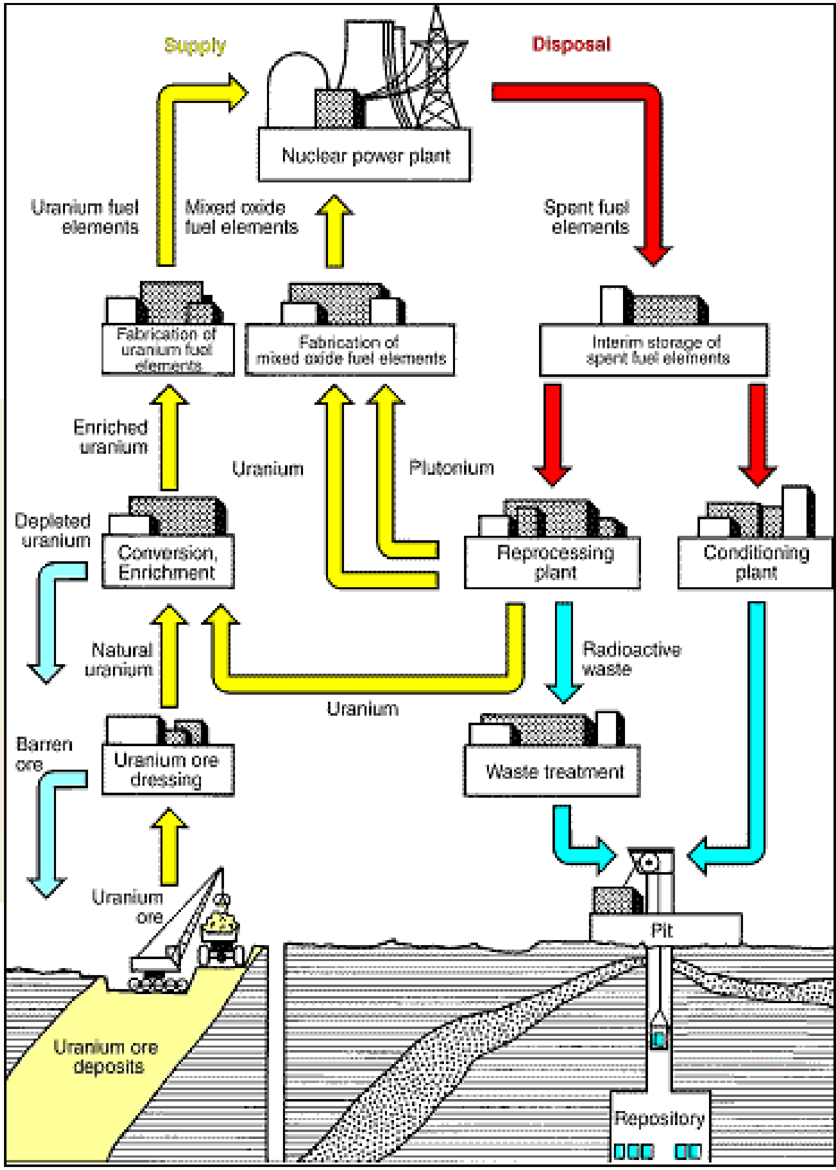
A Mining and Milling
B Enrichment
C Fabrication
D Reactor and Turbine/Generator

Mine tailings
Enrichment tailings
Plutonium oxide
Recycle fuel
Spent fuel

F Reprocessing
E Repository

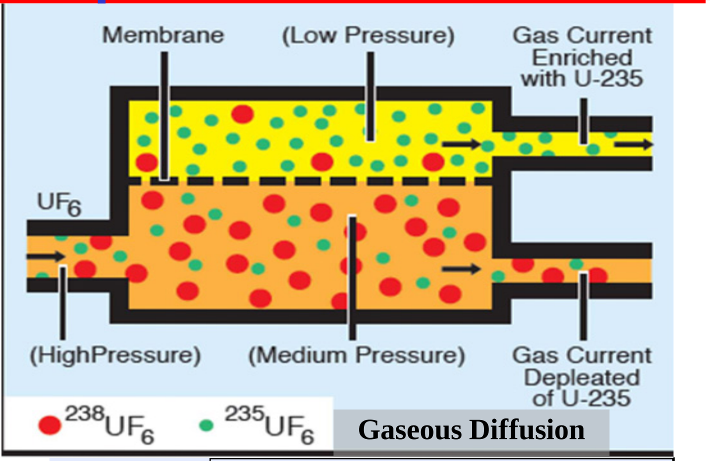
Reprocessing waste

Once-through ABCDE ⟷
Recycle ABCDFC - - - - ->

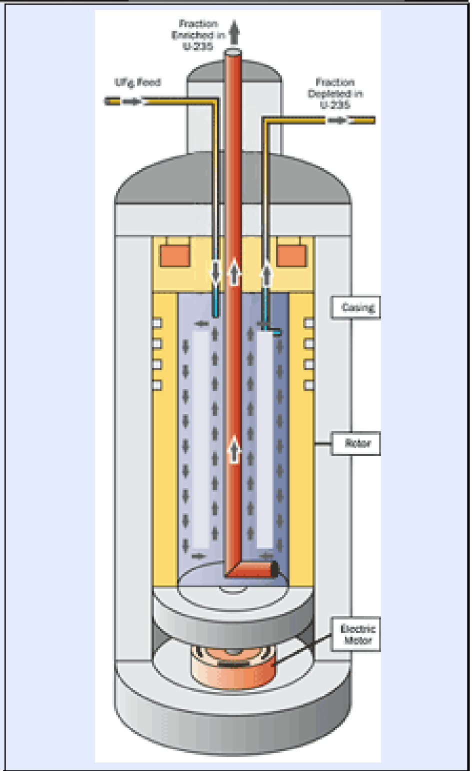


Enriching: Increasing the Concentration of Uranium 235 Isotope

- Uranium ore contains 0.7205% U-235 isotope and the rest is stable U-238. U-235 concentration needs to be increased to 7-8% to use in a nuclear reactor.
- Isotopes have the same chemical properties so they cannot be separated by chemical reactions.
- U-235 is lighter and smaller than U-238; U-235 goes through an appropriate membrane, moves faster and is affected less by centrifugal forces in a centrifuge.
  - Gaseous Diffusion, e.g., US Enrichment Cooperation plant in Paducah, Kentucky.
  - Centrifugal Separation, e.g., Louisiana Energy Services plant in Eunice, New Mexico.

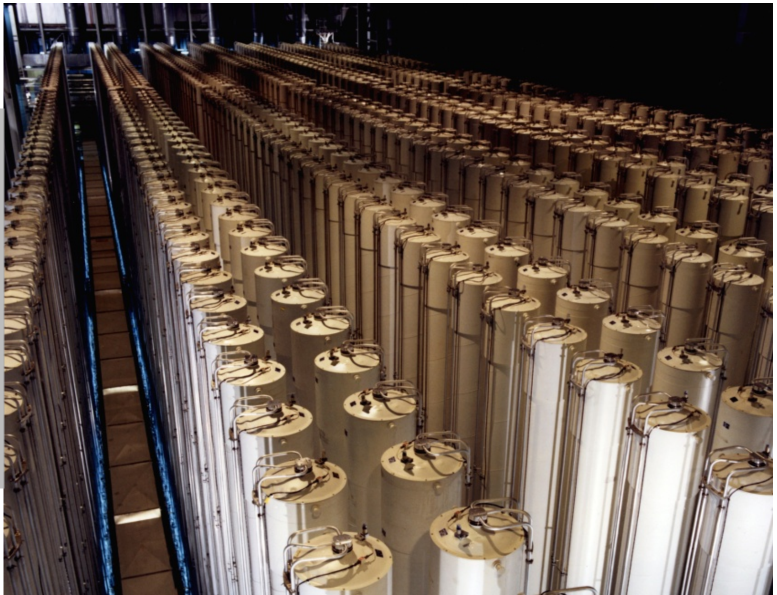


Gaseous Diffusion



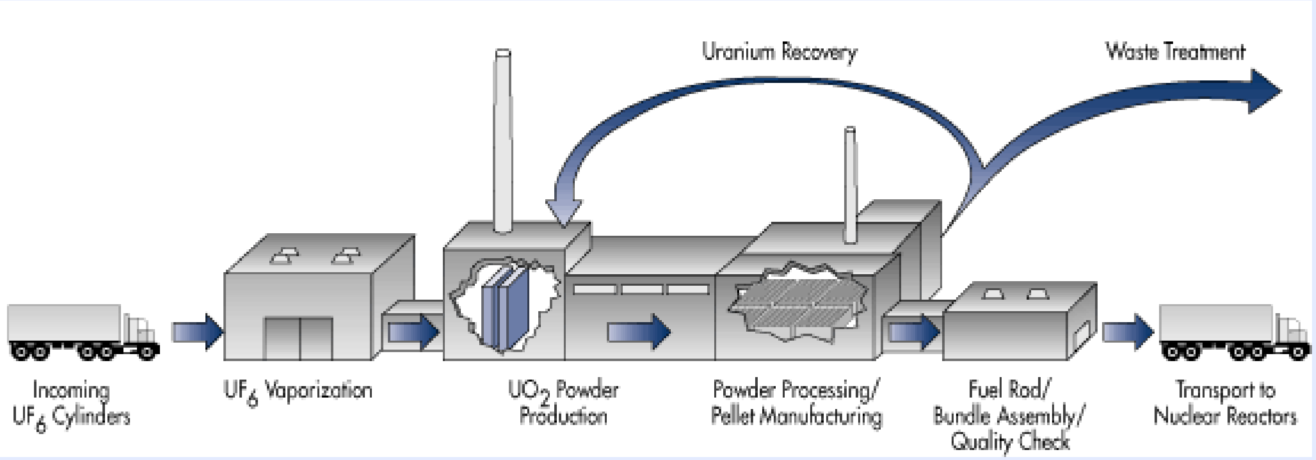
Centrifugal Separation

U-235 is collected from the center; U-238 from periphery of the centrifuge. Centrifugal separation consumes less energy.



Caskets used in centrifugal separation

Fabrication: From Enriched Gas to Fuel Rods



Enriched UF_6 gas
in solid form

Enriched Uranium
as packaged rods.
Each rod12 feet long
5-9 inch square.
Up to 64-264 rods
in a rod assembly.

Chemical:
UF_6 to UO_2

Physical:
powder to
pellets to rods

Package:
Rods in
zircaloy tubes

- Fabrication facilities in Lynchburg, Virginia; Erwin, Tennessee; Columbia, S. Carolina; Wilmington, N. Carolina.
  - In the supply chain, enriched Uranium is shipped from enrichment facilities to fabrication facilities; Packaged uranium rods are shipped to nuclear reactors; spent fuel is stored at reactor sites in USA.
  - Shipping in zircaloy (95% Zirconium+other metals) is relatively safe; it stops radioactive particles from escaping into the environment.
    - If temperature rises too much (beyond 100 ^{o}C), zircaloy can react with water and degrade. Such degradation is suspected at Fukushima and silicon carbide is considered as an alternative packaging material.
- Example: Assume that a single pass of the centrifuge doubles the U-235 concentration, how many passes required to turn 0.007205 U-235 into U-235 enriched by 0.08 or more?

In 4 passes: 0.007205 – 0.01441 – 0.02882 – 0.05764 – 0.11528.

- Example: Weapon grade uranium must have 90% U-235, how many passes?

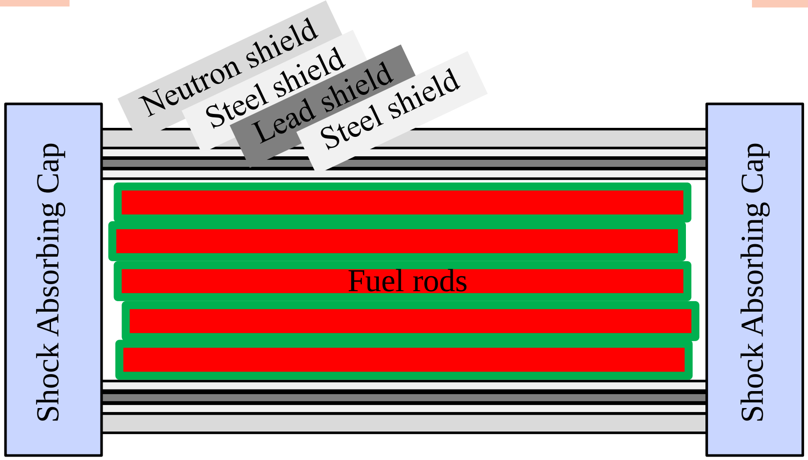
In 3 more passes: 0.11528 – 023056 – 0.46112 – 0.92224.

Caution: Every pass may not double the concentration.

Fresh and Used Fuel Transport

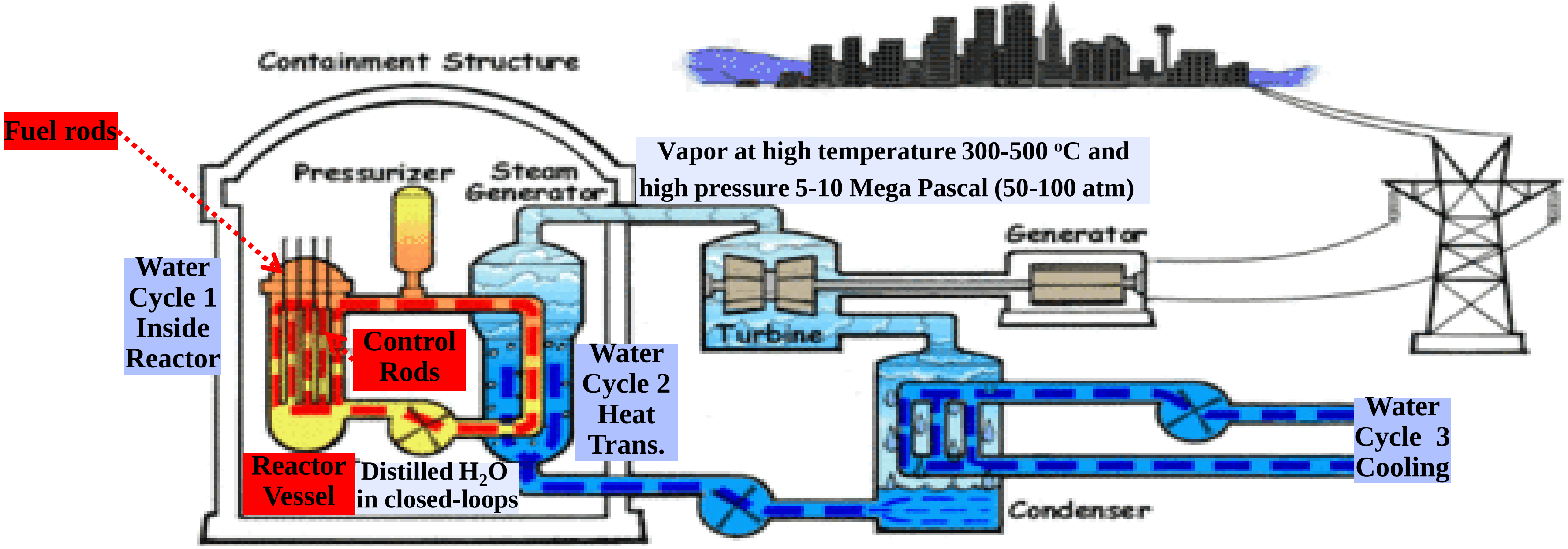
Fresh Fuel Transport

Used Fuel Transport



Nuclear Reactors

Pressurized Water Reactor (PWR) vs Boiling Water Reactor (BWR)



Fuel rods

Vapor at high temperature 300-500 °C and high pressure 5-10 Mega Pascal (50-100 atm)

Water Cycle 1 Inside Reactor

Control Rods

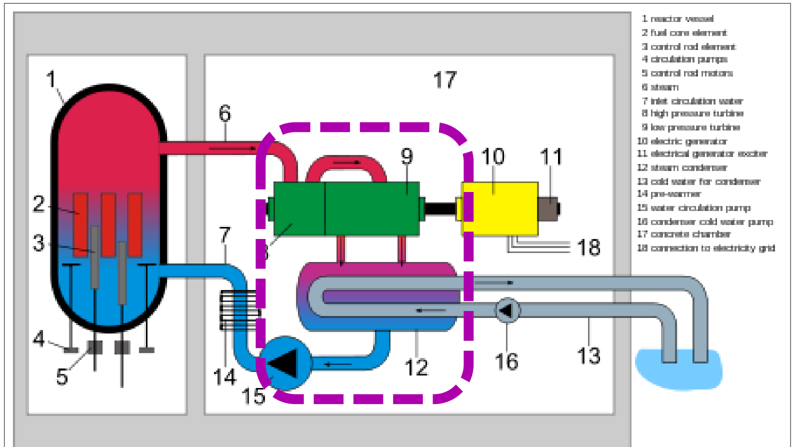
Water Cycle 2 Heat Trans.

Water Cycle 3 Cooling

Reactor Vessel

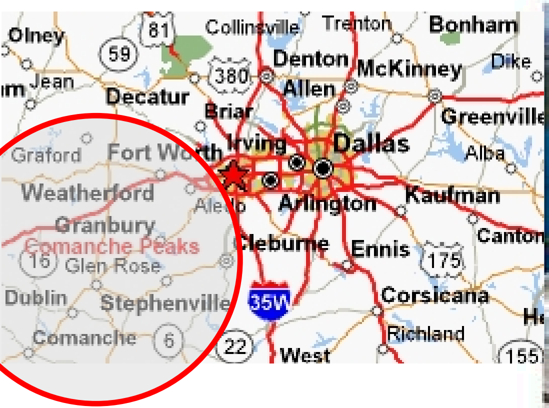
Distilled H_2O in closed-loops

All of operational US reactors are either PWR or BWR. They are both light water reactors (LWR) using regular water as neutron moderator (speed brake) and are cooled by water. BWR is older technology. Built in 1960s and 1970s.



Contamination is more likely with 2 cycles

Reactors Close to Dallas are in Glen Rose Comanche Peak 1 and Comanche Peak 2



Comanche Peaks are 100 miles south west of UT Dallas campus.

Take I-35 E south and US 67 to south west to go to Glen Rose.

In case of a contamination:

10 miles radius around a reactor is plume (smoke) exposure zone. Do not breath in plume exposure zone.

50 miles radius is ingestion pathway zone. Do not eat/drink in ingestion pathway zone.

Comanche Peaks are owned by Luminant, Energy Future Holdings.

They are both pressurized water reactors.

Peak 1 commissioned in 1990 generates 1209 mega watt (MW) of power.

Peak 2 commissioned in 1993 generates 1158 MW.

Burn up rate and Enrichment factor

Recall the previous examples: 1 kilogram of enriched fuel U-235 and U 238 = 60 MWd

Burn up rate is the amount of energy obtained from 1 ton of enriched fuel.

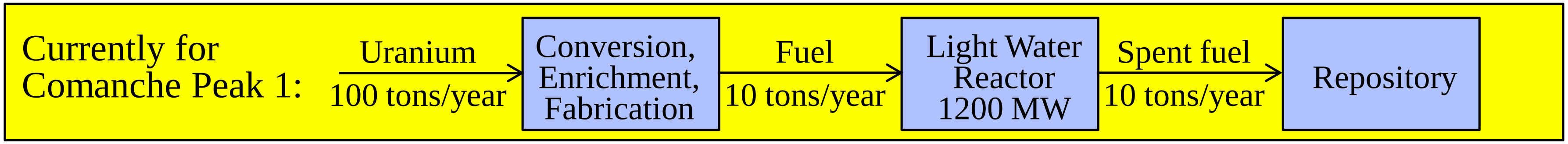
- Theoretically related to the percentage of atoms having the nuclear reaction. But, hard to measure in a reactor.
- In practice, it is measured in terms of MWd/kg (=GWd/ton). Previous example had 1,200 MW reactor consuming 20 kilograms per day of enriched fuel ⇒ Burn up rate of 60 MWd/kg.
  - For example, Burn up rate is about 50 MWd/kg for once-through fuel cycle.
      - See Table 7A.2 on p.176 of "*The Future of the Nuclear Fuel Cycle*".
    - Operating a 1,200 MW (=power) plant for a day generates 1,200 MWd (=energy).
      1,200=1,200*1
    - To obtain 1,200 MWd with a 40 MWd/kg reactor, we burn 30 kg of enriched fuel in a day.
      30=1,200/40
    - In a year of 360 days, we burn 10,800 kg of enriched fuel.
      10,800=30*360
  - More advanced reactors can achieve 60 MWd/kg.
    - Operating a 1200 MW plant with burn up rate of 60 MWd/kg.
      - Burn 20 kg of enriched fuel in a day.
      - Burn 7,200 kg of enriched fuel in a year
- Comanche Peak 1 has 1200 MW and 40 MWd/kg, it requires about 10 tons (=365*30 kg) of enriched fuel (Uranium) per year. Uranium has density of 19 tons per cubicmetre, so 10 tons of Uranium fits into half of a cubicmeter=500 litre =113 (dry) gallons=17.6 cubicfeet.
  - 2014 Ford Taurus has 20.1 cubicfeet of trunk volume. You cannot ship rods in a Sedan's trunk but perhaps 1-truck delivery of enriched fuel per year suffice.

Enrichment factor is the unit of natural ore needed to manufacture 1 unit of enriched fuel.

- For example, enrichment factor can be 10 for converting ore containing 0.7% radioactive Uranium to Uranium fuel containing 5% radioactive Uranium. That is, 10 kg of ore is needed to obtain 1 kg of fuel.

Fuel Cycles: Once-through and Plutonium Recycle

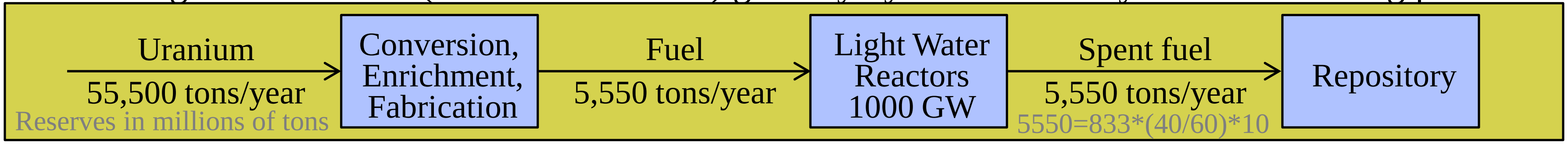
Assuming burn up rate of 40 MWd/kg and enrichment factor of 10, in view of computations on previous page



Currently for Comanche Peak 1:

Uranium → 100 tons/year → Conversion, Enrichment, Fabrication → Fuel 10 tons/year → Light Water Reactor 1200 MW → Spent fuel 10 tons/year → Repository

With a target of 1000 GW (= 833 * 1200 MW) globally by the midcentury with 60 MWd/kg plants.



Uranium 55,500 tons/year → Conversion, Enrichment, Fabrication → Fuel 5,550 tons/year → Light Water Reactors 1000 GW → Spent fuel 5,550 tons/year → Repository

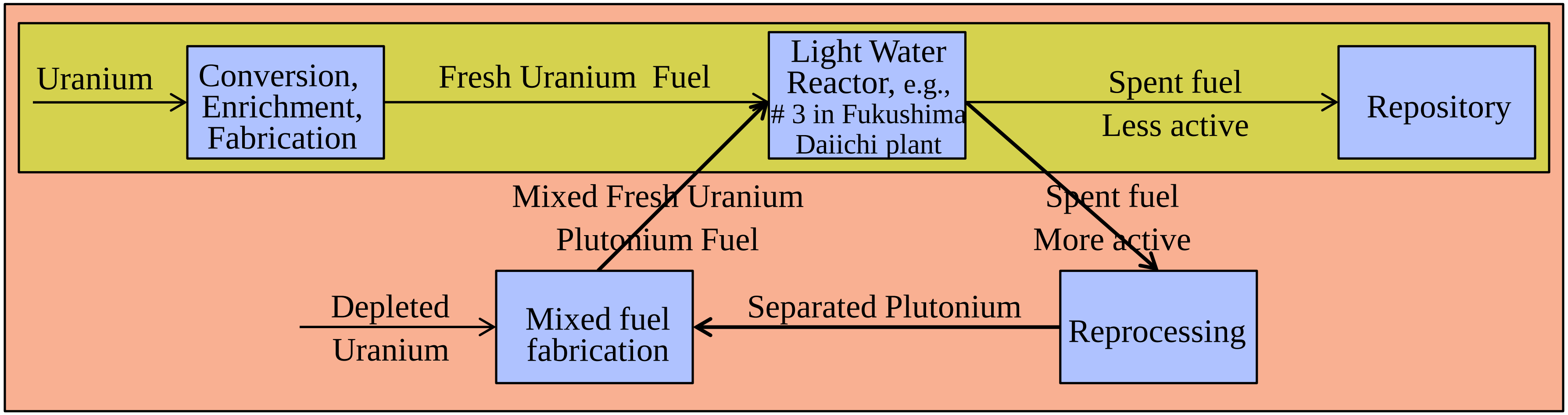
Reserves in millions of tons

5550=833*(40/60)*10

Above are once-through cycles common in the USA. Plutonium can also be used as fuel.

Plutonium is more dangerous than Uranium. The latter is found in nature but the former is produced artificially in the lab and has not been found on earth yet. Unlike Uranium, Plutonium emits rays/particles that cannot go through the skin but are much more harmful within the body. Its higher energy can cause mutations and more choromosom anomalies.

Below are Plutonium recycles. Cost of producing electricity with Plutonium recycle is 4 times of the once-through cycle. Storage/repository cost can be less in Plutonium cycle, but how much less is hard to quantify.



Uranium → Conversion, Enrichment, Fabrication → Fresh Uranium Fuel → Light Water Reactor, e.g., # 3 in Fukushima Daiichi plant → Spent fuel Less active → Repository

Light Water Reactor → Spent fuel More active → Reprocessing → Separated Plutonium → Mixed fuel fabrication

Depleted Uranium → Mixed fuel fabrication → Mixed Fresh Uranium Plutonium Fuel → Light Water Reactor

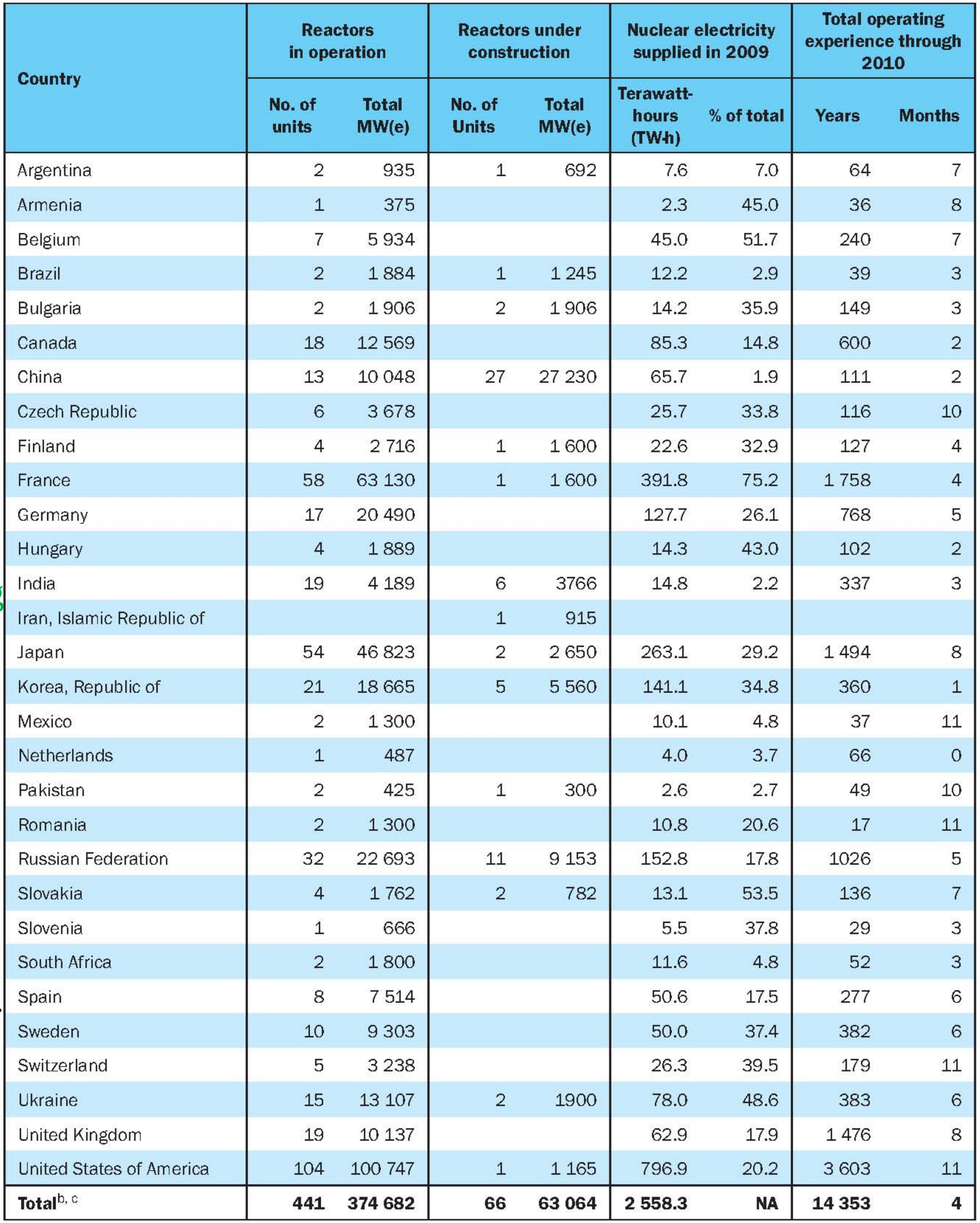
Nuclear Reactors

US, France and Japan have the most number of reactors. These three countries also generate the most nuclear power.

China, Russia and India are building the most number of reactors. These three countries also building the most nuclear power.

On Dec 31, 2010, the global nuclear capacity was about 375 GW = 375*10^9 Watt.

An incandescent lamp consumes 50 Watt. 375 GW powers 7.5 billion such lamps.



Country	Reactors in operation		Reactors under construction		Nuclear electricity supplied in 2009		Total operating experience through 2010	
	No. of units	Total MW(e)	No. of Units	Total MW(e)	Terawatt-hours (TW·h)	% of total	Years	Months
Argentina	2	935	1	692	7.6	7.0	64	7
Armenia	1	375			2.3	45.0	36	8
Belgium	7	5 934			45.0	51.7	240	7
Brazil	2	1 884	1	1 245	12.2	2.9	39	3
Bulgaria	2	1 906	2	1 906	14.2	35.9	149	3
Canada	18	12 569			85.3	14.8	600	2
China	13	10 048	27	27 230	65.7	1.9	111	2
Czech Republic	6	3 678			25.7	33.8	116	10
Finland	4	2 716	1	1 600	22.6	32.9	127	4
France	58	63 130	1	1 600	391.8	75.2	1 758	4
Germany	17	20 490			127.7	26.1	768	5
Hungary	4	1 889			14.3	43.0	102	2
India	19	4 189	6	3766	14.8	2.2	337	3
Iran, Islamic Republic of			1	915				
Japan	54	46 823	2	2 650	263.1	29.2	1 494	8
Korea, Republic of	21	18 665	5	5 560	141.1	34.8	360	1
Mexico	2	1 300			10.1	4.8	37	11
Netherlands	1	487			4.0	3.7	66	0
Pakistan	2	425	1	300	2.6	2.7	49	10
Romania	2	1 300			10.8	20.6	17	11
Russian Federation	32	22 693	11	9 153	152.8	17.8	1026	5
Slovakia	4	1 762	2	782	13.1	53.5	136	7
Slovenia	1	666			5.5	37.8	29	3
South Africa	2	1 800			11.6	4.8	52	3
Spain	8	7 514			50.6	17.5	277	6
Sweden	10	9 303			50.0	37.4	382	6
Switzerland	5	3 238			26.3	39.5	179	11
Ukraine	15	13 107	2	1900	78.0	48.6	383	6
United Kingdom	19	10 137			62.9	17.9	1 476	8
United States of America	104	100 747	1	1 165	796.9	20.2	3 603	11
Total[b, c]	**441**	**374 682**	**66**	**63 064**	**2 558.3**	**NA**	**14 353**	**4**

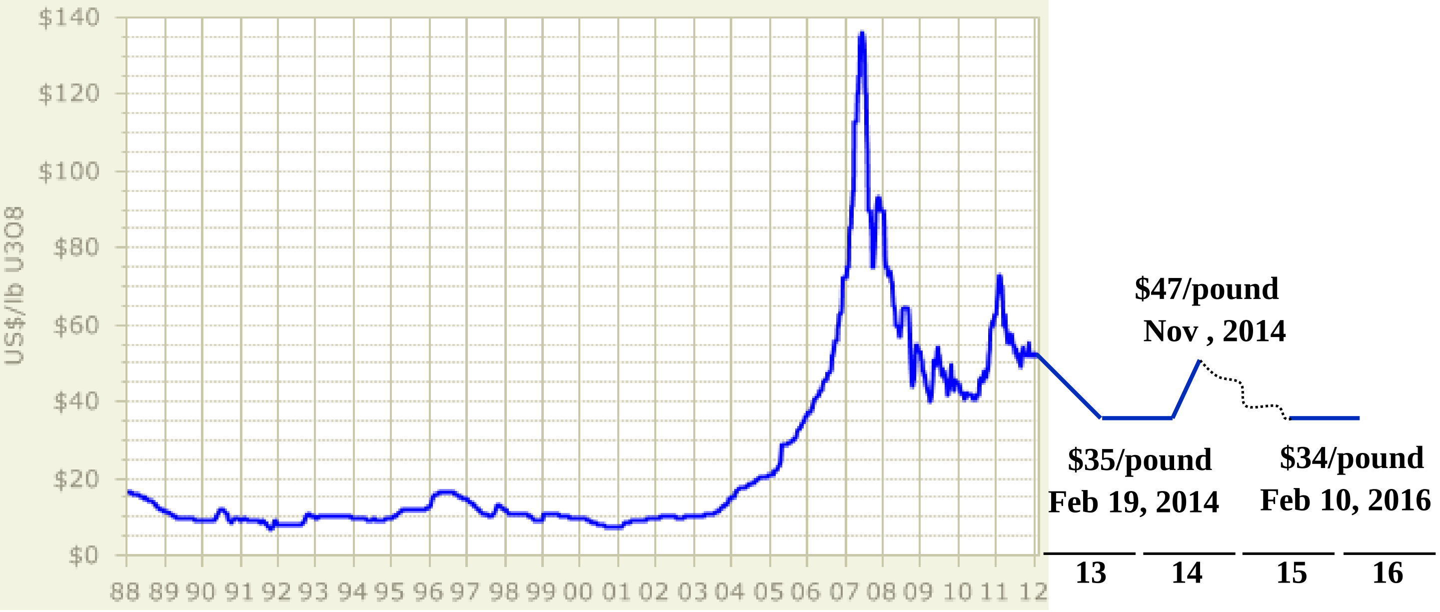
IAEA is International Atomic Energy Agency
Source: IAEA Annual Report 2010.

Economics of Nuclear Power

Economics: Cost of Uranium Ore

- There is plenty of Uranium in the earth.
- The price of Uranium Oxide (U_3O_8) is $52.15 per pound in Mar 2012;

see www.cmegroup.com/trading/metals/other/uranium_quotes_globex.html



Source: www.uxc.com

$47/pound Nov , 2014

$35/pound Feb 19, 2014

$34/pound Feb 10, 2016

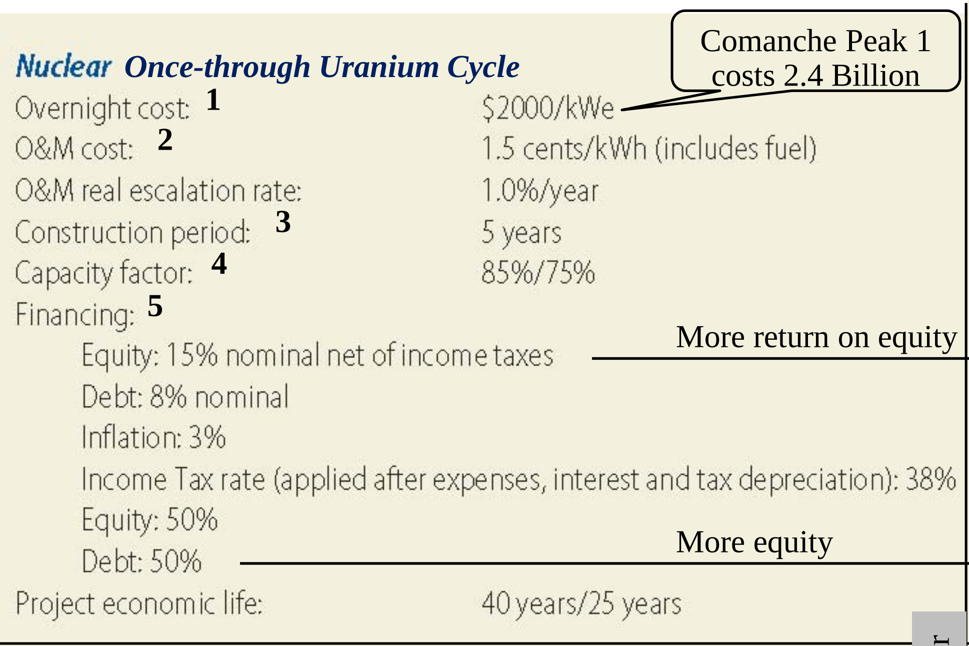
$52.15 per pound is close to $130 per kg.

Table A-5.E.2
Source: The Future of nuclear Power

Ore price in $/kg	Cost of Uranium in Electricity in cents/kWh
60	0.221
130	**0.479**
200	0.737

Cost of Uranium ore is not too critical; less than 1 cent/kWh in all scenarios.

Cost Comparison Context

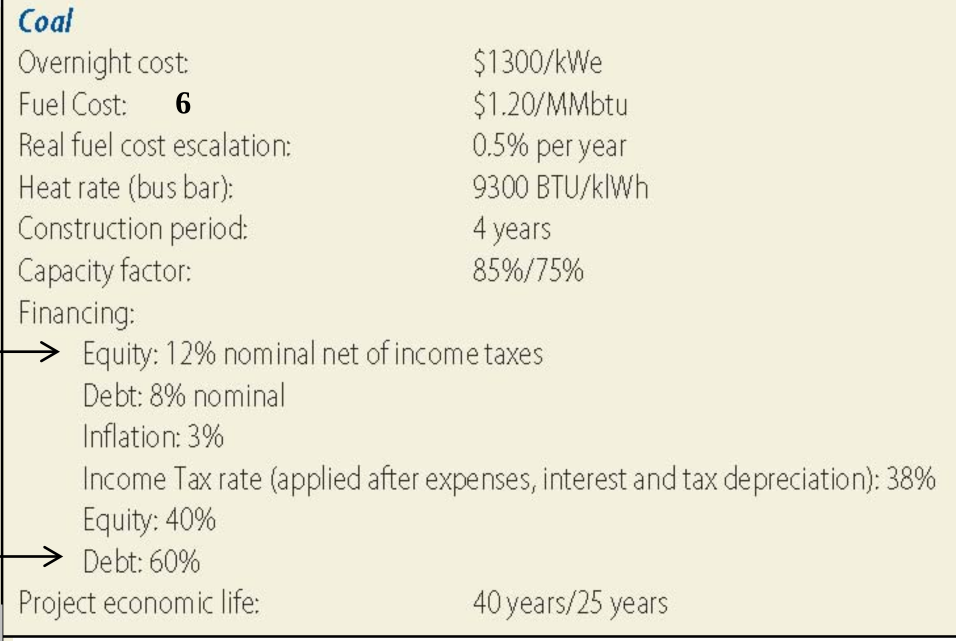


Comanche Peak 1 costs 2.4 Billion

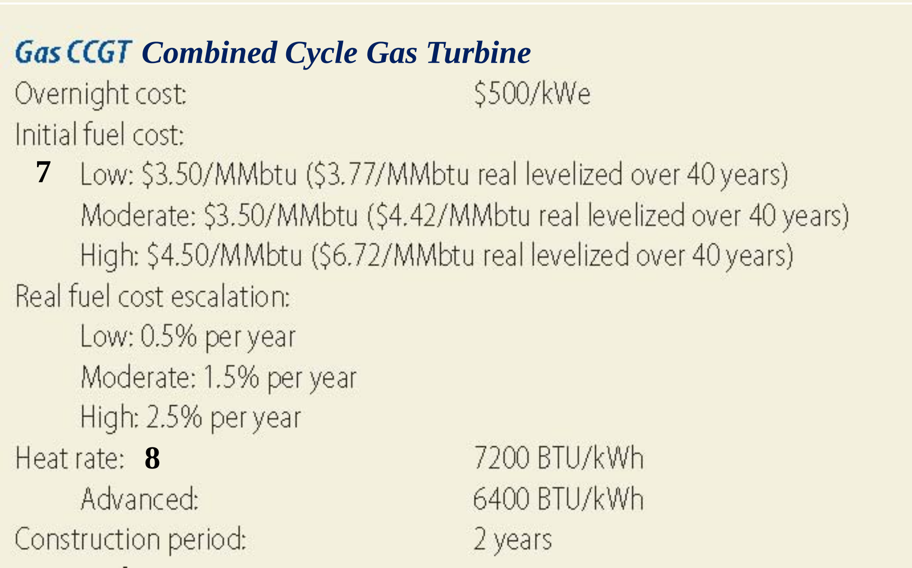
***Nuclear* Once-through Uranium Cycle**	
Overnight cost: **1**	$2000/kWe
O&M cost: **2**	1.5 cents/kWh (includes fuel)
O&M real escalation rate:	1.0%/year
Construction period: **3**	5 years
Capacity factor: **4**	85%/75%
Financing: **5**	
Equity: 15% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income Tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 50%	
Debt: 50%	
Project economic life:	40 years/25 years

More return on equity

More equity



Coal	
Overnight cost:	$1300/kWe
Fuel Cost: **6**	$1.20/MMbtu
Real fuel cost escalation:	0.5% per year
Heat rate (bus bar):	9300 BTU/klWh
Construction period:	4 years
Capacity factor:	85%/75%
Financing:	
Equity: 12% nominal net of income taxes	
Debt: 8% nominal	
Inflation: 3%	
Income Tax rate (applied after expenses, interest and tax depreciation): 38%	
Equity: 40%	
Debt: 60%	
Project economic life:	40 years/25 years



***Gas CCGT* Combined Cycle Gas Turbine**	
Overnight cost:	$500/kWe
Initial fuel cost:	
7 Low: $3.50/MMbtu ($3.77/MMbtu real levelized over 40 years)	
Moderate: $3.50/MMbtu ($4.42/MMbtu real levelized over 40 years)	
High: $4.50/MMbtu ($6.72/MMbtu real levelized over 40 years)	
Real fuel cost escalation:	
Low: 0.5% per year	
Moderate: 1.5% per year	
High: 2.5% per year	
Heat rate: **8**	7200 BTU/kWh
Advanced:	6400 BTU/kWh
Construction period:	2 years

Source: The Future of Nuclear Power

1. Overnight cost is cost of building/equipment.
2. O&M cost is for operating and maintaining.
3. Nuclear plants take longer to construct.
4. Capacity factor is utilization.
5. Nuclear plants need more equity financing and higher rate of return on equity.
6. Coal is more expensive now; see coal slides for more details.
7. Gas is less expensive than low fuel cost scenario in 2012.
8. Heat rates: Input (BTU)/Output (kWh). This is the reciprocal of efficiency=output/input. 6400-7200 BTU/kWh assumed here is slightly better than ~ 9000 Btu/kWh we shall study later in transformation module.

Discussion of the Context

1. Cost of building a nuclear power plant with 1700 MW capacity is $3.4 Billion. The same capacity coal plant costs $2.21 Billion while gas plant is only $0.85 Billion.

- 1700 MW is not extraordinarily high capacity for nuclear power plants.
- NGCC power plants can be built in smaller sizes such as 500 MW.
- 500 MW NGCC costs around $0.25 Billion. This is 1/13 of the cost of nuclear plant. Smaller the initial investment ⇒ the smaller the risk & larger the set of investors.
- The uncertainty surrounding the licensing/regulations of nuclear plants inflate the costs.

2. O&M cost for nuclear plants is 1.5 cents per kWh including the fuel cost. Although Uranium prices go up and down, the effect on O&M is little, say 0.2 cents/kWh.

3. Nuclear plants construction time is longer but can perhaps be reduced by 1 year.

4. Utilization of nuclear power plants are generally high, except for France where nuclear energy is used a lot and may have to be shut down when consumption drops.

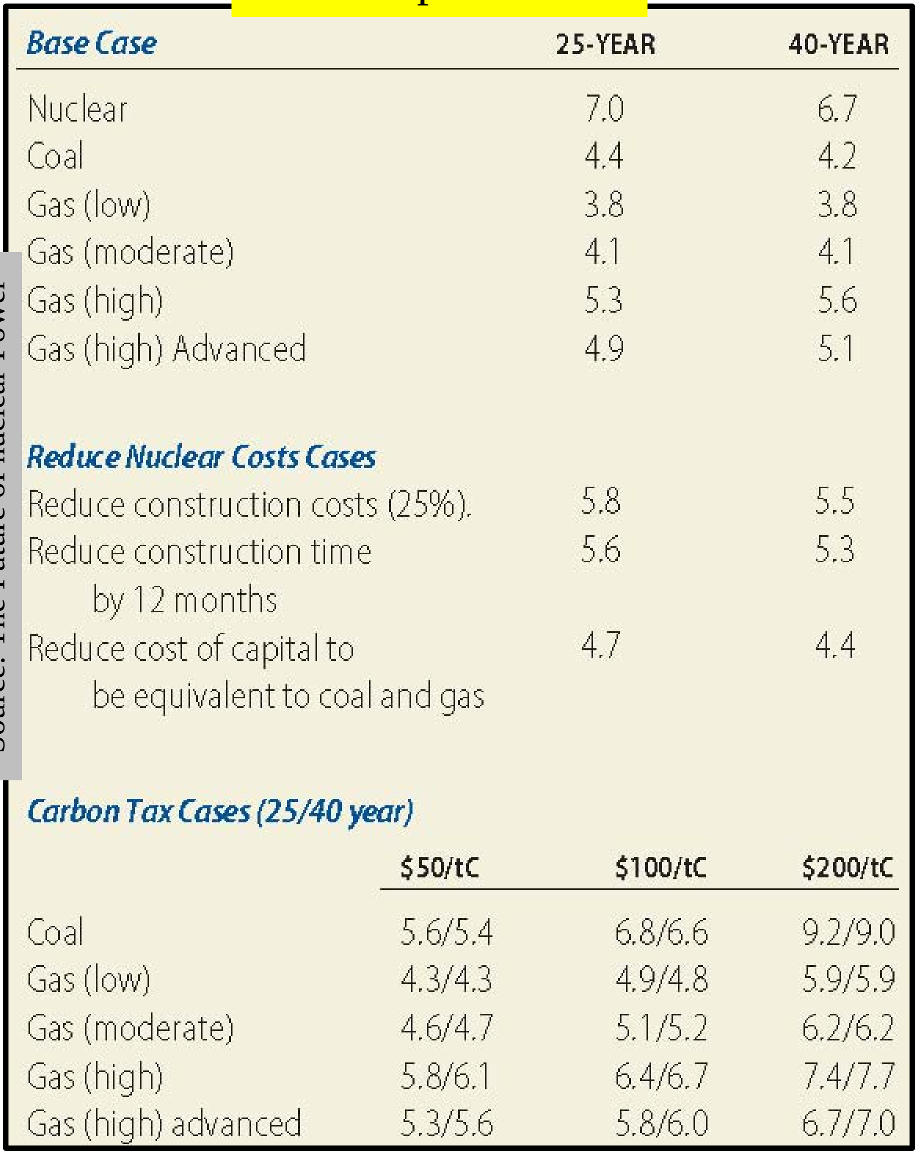
5. Due to higher risks and uncertainties, nuclear reactor financing cannot be done by relying too much on debt.

- Governments having access to more capital and having the regulatory authority have an advantage over companies for building nuclear reactors. Governments may want to help companies to reduce the cost of capital for investing into nuclear power plants.
- This explains the international growth of nuclear energy.

6-7-8. Price and heat rates for the analysis come from early 2000s. Markets and technology have evolved.

Levelized Cost of Electricity: Nuclear, Coal or Gas

Cents per kWh



Base Case	25-YEAR	40-YEAR
Nuclear	7.0	6.7
Coal	4.4	4.2
Gas (low)	3.8	3.8
Gas (moderate)	4.1	4.1
Gas (high)	5.3	5.6
Gas (high) Advanced	4.9	5.1
Reduce Nuclear Costs Cases		
Reduce construction costs (25%).	5.8	5.5
Reduce construction time by 12 months	5.6	5.3
Reduce cost of capital to be equivalent to coal and gas	4.7	4.4

Carbon Tax Cases (25/40 year)

	$50/tC	$100/tC	$200/tC
Coal	5.6/5.4	6.8/6.6	9.2/9.0
Gas (low)	4.3/4.3	4.9/4.8	5.9/5.9
Gas (moderate)	4.6/4.7	5.1/5.2	6.2/6.2
Gas (high)	5.8/6.1	6.4/6.7	7.4/7.7
Gas (high) advanced	5.3/5.6	5.8/6.0	6.7/7.0

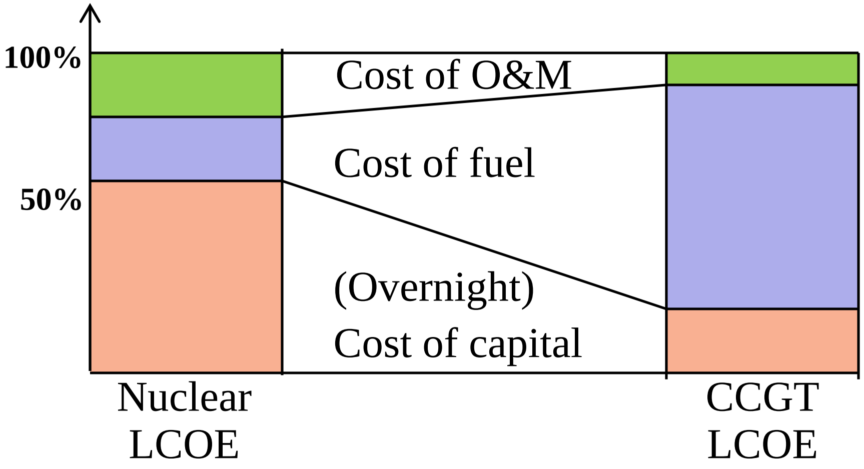
Source: The Future of nuclear Power

- For 25 and 40 years, nuclear is the most expensive.
  - Nuclear closes the gap slightly when 40 years of lifetime is considered; but not enough.
- Natural gas seems to be the cheapest and the least risky way to generate electricity. This has been reinforced by cheaper gas prices in the recent years.
- If construction costs or time can be reduced, nuclear competes with a gas in the expensive gas scenario which is unlikely to happen.
- If cost of capital for nuclear is reduced and equalized to the others, nuclear competes with coal and gas, except for the cheap gas scenario, which is happening now.
- If there is a carbon tax of $50 per ton of carbon dioxide, nuclear beats every other options and is head-to-head with gas in the cheap gas scenario.

Further Discussion on Nuclear Reactor Costs

From WNA (World Nuclear Association) report titled The New Economics of Nuclear Power (2005):

- Cost of capital (including accrued interest) accounts for around 60% of the levelized cost of electricity (LCOE) of a new nuclear plant. The corresponding percentage is 20% for CCGTs.
- Fuel cost accounts for a smaller portion of the cost of electricity produced through nuclear than that of the electricity produced through burning coal or gas as fuel.
  - » "Fuel costs for new nuclear plants (including spent fuel management) account for only around 20% of the LCOE whereas for CCGTs, it is typically 75%."
- Nuclear power plant O & M costs account for 20% of LCOE.



If loan interest rates drop, cost of capital drops and Nuclear plants are cheaper than Gas plants.
If gas (fuel) prices drop, Gas plants are cheaper.
Both of these are happening now!!

Further Discussion on Overnight Costs

Source: Reduction of Capital Costs of Nuclear Plants by OECD Nuclear Energy Agency (2000)

	Cz	Mex	UK	Fr	USA	Ge
Direct costs						
Land and land rights	0.3	0.1	0.2		0.2	1.8
Reactor plant equipment	21.9	27.6	23.2	29.0	18.6	32.0
Turbine plant equipment	7.2	14.7	5.9	16.0	16.5	22.8
Electrical plant equipment	20.0	13.2	13.5	10.0	5.1	5.9
Heat rejection equipment	2.0	2.2	2.5	7.0	3.8	3.1
Miscellaneous equipment	6.3	15.2	7.1	8.0	3.3	
Construction	19.4	10.1	23.4	10.0	13.4	17.8
Direct costs total	**77.1**	**83.1**	**75.8**	**80.0**	**60.9**	**83.4**
Indirect costs						
Design and engineering	6.7	3.7	11.7		3.5	12.9
Project management	4.0	5.9	0.9		5.8	0.9
Commissioning	0.9	1.7	3.8		18.4	
Indirect costs total	**11.6**	**11.3**	**16.4**		**27.7**	**13.8**
Other costs						
Training	0.3	0.9	2.9	6.0		0.4
Taxes and insurance		0.5	0.4			
Transportation		0.1	0.1			0.6
Owner's costs	10.4	1.6	2.4	14.0	2.4	1.8
Spare parts	0.3	2.5			2.4	
Contingencies	0.3		2.0		6.6	
Other costs total	**11.3**	**5.6**	**7.8**	**20.0**	**11.4**	**2.8**
Total	**100**	**100**	**100**	**100**	**100**	**100**

Cz: Czech Temelin
VVER 1000 MW

Mex: Mexico Laguna Verde
BWR 650 MW

UK: United Kingdom Sizewell-B
PWR 1200 MW

Fr: French N4
PWR 1450 MW

USA: American ALWR
PWR 1300 MW

Ge: Germany KONVOI
PWR 1380 MW

Cost breakdown depends on accounting and contracting.

Why no indirect costs or cost of spare parts / repairing / taxes / insurance in France?

Commissioning and contingency costs are high in USA. This includes cost of commissioning labor, materials, tools and equipment (not covered by direct costs), cost of electrical energy, fuel, gas and other utilities until the commercial operation. Contingency cost includes cost of repair, reassembling, reinstallation, and other reworks.

Reducing Capital Cost & Construction Time

MIT study has $2000 per kWh of overnight (capital) cost and 60 months construction time. To reduce these:

- Build multiple reactors in a single site
- Build larger reactors (technical limitations on the core, size of the fuel rods)
- Standardization/Modularization of parts/equipment
- Prefabrication (reactor liner and shield walls)
- Open-top (roof) construction coupled with heavy-lift cranes
- Improved project management
  - Work in parallel and 3 shifts per day
  - Computerized project management / scheduling: Reduction in paperwork/documentation

Overnight Cost	Cost $/kWh
CANDU 6 (Qinshan Phase III)	1,640
Elimination of Heavy Water (D in CANDU)	-120
Reactor Size Reduction	-90
Turbine Generator and Balance Optimization	-50
Component Simplification, Elimination, Standardization	-190
Modularization; Schedule Reduction	-190
ACR-700	**1000**

Construction Time	Months
CANDU 6	47
Civil construction of reactor building	-5
Open-top installation	-2
Modularization	-3
Advanced technology tools	-1
ACR-700	**36**

Source: The Advanced CANDU Reactor (ACR)
Presented at http://www.anes2002.org/

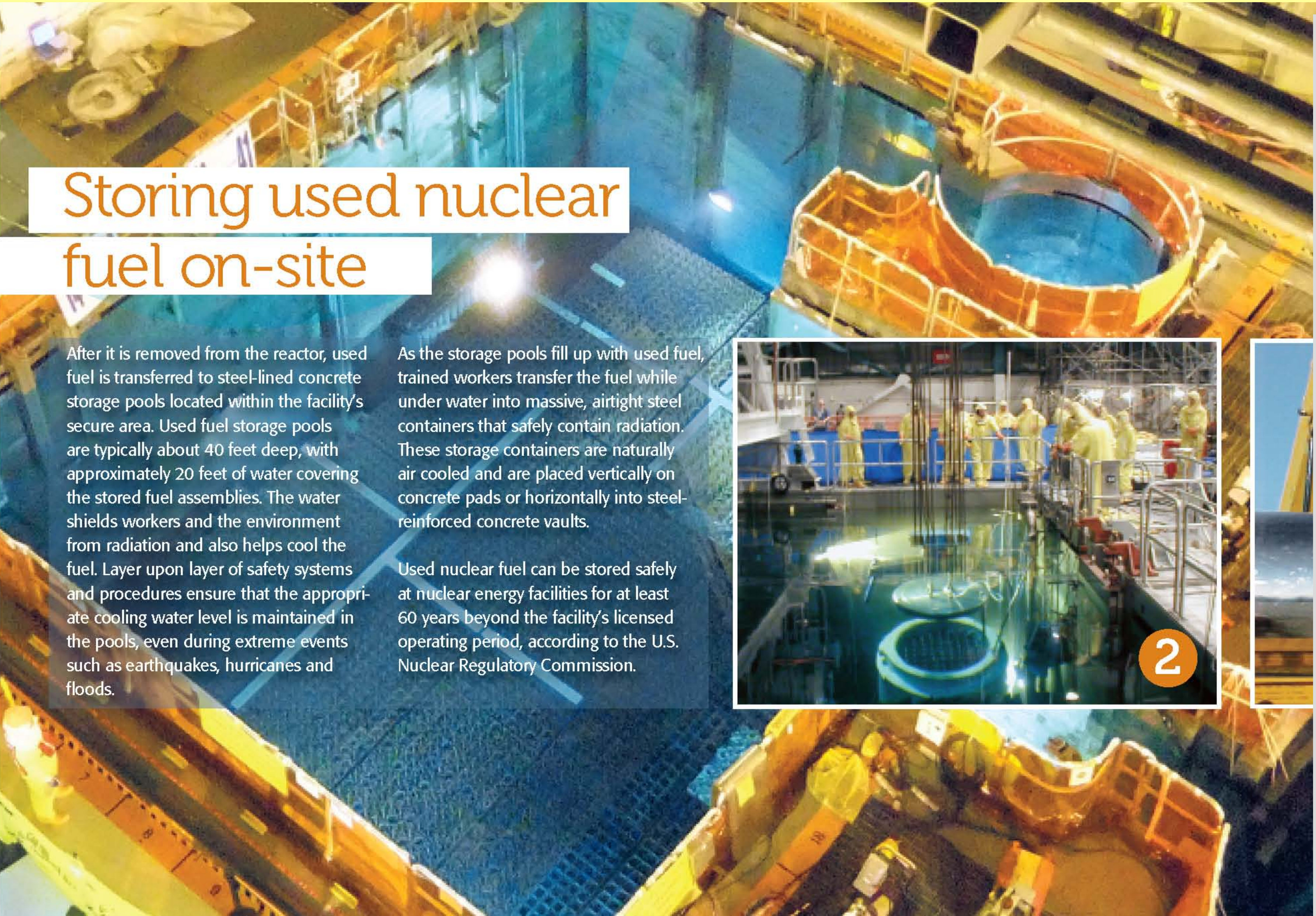
Recommendations for Fuel Cycle

- Incentive program for new nuclear plant construction.
  - High perceived risk of building new nuclear plants.
    - High fixed cost of investment.
      - Loan guarantees from governments?
    - Long term power purchase contracts to ensure stable and sizable demand.
  - Insurance in the case of operational failure (melt-down).
    - Fukushima Daiichi nuclear plant and melt-down in March 2011 and afterwards.
    - German government decides to decommission nuclear plants by 2022.
    - French president de Gaulle was an enthusiast who allegedly tagged government services in some towns to the acceptance of nuclear power plants in those towns.
- Increasing efficiency of burning the fuel at the first pass is more beneficial than passing (recycling) the semi-spent fuel multiple times in the light water reactors.
- Safety: Avoid recycling fuel for now.
- Proliferation: Better distinction between reactor-grade and weapon-grade fuels.
- Storage: Somebody/somewhere must accept storage facility.
  - 1983 Congress’s Nuclear Waste Policy: DOE handles waste, Generators pay for this service.
  - DOE charged generators $1/MWh since the 1980s. For Comanche Peak 1, that is, $1,200 per hour and about $10 Million per year. Nuclear Waste Fund accumulated $24 Billion by 2014; but partially spent on other projects.
  - DOE promised to take waste from generators starting 1999 but could not.
  - Yucca Mountain, Nevada was identified in 2008 as a potential waste storage area. DOE submitted a license application to Nuclear Regulatory Commission but Nevada vetoed this; Congress overwrote the veto.
  - Yucca project is shelved in 2009 and DOE started another initiative to identify a storage site of consensus.

Based on UBS Electric Utilities Conference Call titled “Funding for Nuclear Waste without a plan” hosting Jay Silberg, from the law firm Pillsbury, Winthrop, Shaw and Pittman, Feb 10, 2014.

Every 1-2 years, used fuel rods (the oldest, ~1/3 in the reactor) are cooled & transferred while in the assembly. New rods are inserted into the reactor. Used rods are still solid & compact but decayed in terms of weight.

- Wet storage: A water pool is maintained above the stored used fuels; see below.
- Dry storage: Used fuel is stored in a steel cylindrical container housed in thick concrete; see next page.



Storing used nuclear fuel on-site

After it is removed from the reactor, used fuel is transferred to steel-lined concrete storage pools located within the facility's secure area. Used fuel storage pools are typically about 40 feet deep, with approximately 20 feet of water covering the stored fuel assemblies. The water shields workers and the environment from radiation and also helps cool the fuel. Layer upon layer of safety systems and procedures ensure that the appropriate cooling water level is maintained in the pools, even during extreme events such as earthquakes, hurricanes and floods.

As the storage pools fill up with used fuel, trained workers transfer the fuel while under water into massive, airtight steel containers that safely contain radiation. These storage containers are naturally air cooled and are placed vertically on concrete pads or horizontally into steel-reinforced concrete vaults.

Used nuclear fuel can be stored safely at nuclear energy facilities for at least 60 years beyond the facility's licensed operating period, according to the U.S. Nuclear Regulatory Commission.

Source: Safe and Secure: Managing Used Nuclear Fuel. Published by NEI (Nuclear Energy Institute).

Dry Radioactive Waste Storage

Urenco Enrchmnt Plant in NM

WSC (Waste Control Specialists) in TX

WSC's Dry Storage facility is 360 miles west of UTD campus. Next to New Mexico border & Urenco Enrichment Plant in NM

- Low level radioactive waste is created by hospitals, laboratories and universities
- Two companies currently storing low level radioactive waste
  - Waste Control Specialists http://www.wcstexas.com, Three Lincoln Centre, 5430 LBJ Freeway, Ste. 1700 Dallas, TX 75240
  - EnergySolutions http://www.energysolutions.com
  - EnergySolutions wanted to acquire WCS for $367 million in 2016 but sued by Justice Department
    - Justice Department points to lack of post-acquisition competition
  - WSC applied to Nuclear Regulatory Commission in 2016 to build a 40,000 ton spent fuel storage facility
    - For details watch https://www.youtube.com/watch?v=WxK7BIhbZpI

NIMBY problem for Nuclear Facilities

"Nuclear-less Türkiye" banner hung by protesters from the roof of a stadium during a game

- NIMBY: Not In My BackYard.
- Residents oppose projects such as nuclear power plant, nuclear fuel storage, landfills
  - Yucca Mountain highly radioactive waste storage
  - West Texas lowly radioactive waste storage
  - Sinop, northern Turkey, nuclear power plant
  - Swiss nuclear waste storage https://www.nagra.ch/en
- Residents perceive high risk associated with these projects
- The projects can benefit the society despite exposing the residents to some risks
  - Proposer: Builder/owner of the project
    - Attempting convince the residents that the project is desirable, safe, beneficial, job-creator
  - Host: Residents at the project location
    - Is the project really beneficial for the society at large?
    - Is the project beneficial to my community in particular? I do not want to bear the risks and drawbacks.
  - Non-host: State, federal government

Uncertainty about the project

- Proposer does not have exact design, type of facilities before permitting
- Host does not observe the project details, or does not trust the details or cannot evaluate them
- Non-host
  - struggles to develop mechanisms to overcome the trust issue between the proposer and the host by removing uncertainty and forcing commitments through contracts
  - resorts to monetary incentives given to host by proposer, such as tax rebates, direct payments to residents

Host Surveys

- 1993 Swiss survey questions in verbatim for a nuclear waste repository project
  - 1: Suppose that the National Cooperative for the Storage of Nuclear Waste (NAGRA), after completing exploratory drilling, proposes to build the repository for low- and mid-level radioactive waste in your hometown. Federal experts examine this proposition, and the federal parliament decides to build the repository in your community. In a townhall meeting, do you accept this proposition or do you reject this proposition?
  - 2: Suppose that the National Cooperative for the Storage of Nuclear Waste (NAGRA), after completing the exploratory drilling, proposes to build the repository for low- and mid-level radioactive waste in your hometown. Federal experts examine this proposition, and the federal parliament decides to build the repository in your community. Moreover, the parliament decides to compensate all residents of the host community with 5,000 francs per year and per person. Your family will thus receive xxx francs per year. The compensation is financed by all taxpayers in Switzerland. In a townhall meeting, do you accept this proposition or do you reject this proposition?
  - 3: There are many reasons why one does not support the construction of a repository in one's own community even though compensation is offered. Please indicate if the following reasons were important for your decision:
    - (a) I demand a higher compensation.
    - (b) If so much money is offered, the repository must be very dangerous.

Statistical Analysis of Survey Results

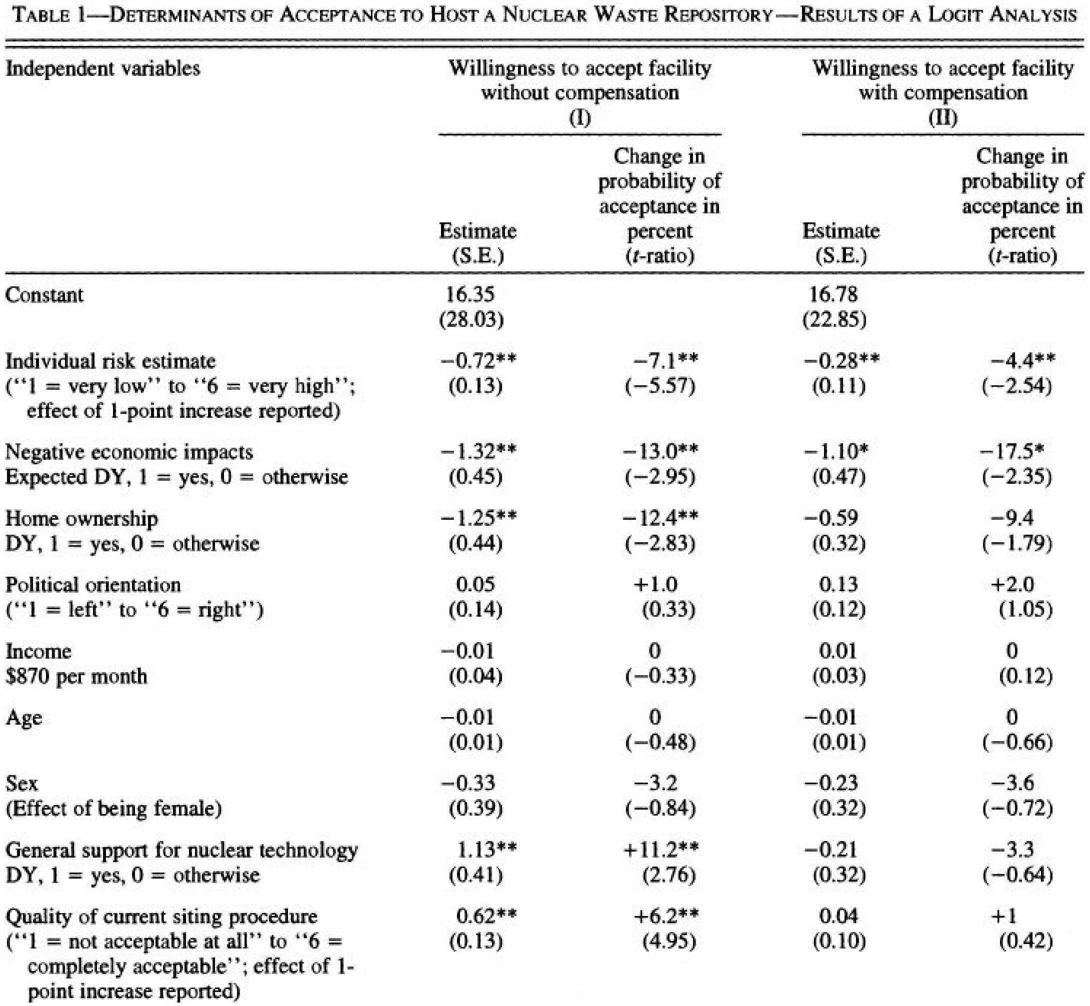


TABLE 1—DETERMINANTS OF ACCEPTANCE TO HOST A NUCLEAR WASTE REPOSITORY—RESULTS OF A LOGIT ANALYSIS

Independent variables	Willingness to accept facility without compensation (I)		Willingness to accept facility with compensation (II)	
	Estimate (S.E.)	Change in probability of acceptance in percent (*t*-ratio)	Estimate (S.E.)	Change in probability of acceptance in percent (*t*-ratio)
Constant	16.35 (28.03)		16.78 (22.85)	
Individual risk estimate (“1 = very low” to “6 = very high”; effect of 1-point increase reported)	−0.72** (0.13)	−7.1** (−5.57)	−0.28** (0.11)	−4.4** (−2.54)
Negative economic impacts Expected DY, 1 = yes, 0 = otherwise	−1.32** (0.45)	−13.0** (−2.95)	−1.10* (0.47)	−17.5* (−2.35)
Home ownership DY, 1 = yes, 0 = otherwise	−1.25** (0.44)	−12.4** (−2.83)	−0.59 (0.32)	−9.4 (−1.79)
Political orientation (“1 = left” to “6 = right”)	0.05 (0.14)	+1.0 (0.33)	0.13 (0.12)	+2.0 (1.05)
Income $870 per month	−0.01 (0.04)	0 (−0.33)	0.01 (0.03)	0 (0.12)
Age	−0.01 (0.01)	0 (−0.48)	−0.01 (0.01)	0 (−0.66)
Sex (Effect of being female)	−0.33 (0.39)	−3.2 (−0.84)	−0.23 (0.32)	−3.6 (−0.72)
General support for nuclear technology DY, 1 = yes, 0 = otherwise	1.13** (0.41)	+11.2** (2.76)	−0.21 (0.32)	−3.3 (−0.64)
Quality of current siting procedure (“1 = not acceptable at all” to “6 = completely acceptable”; effect of 1-point increase reported)	0.62** (0.13)	+6.2** (4.95)	0.04 (0.10)	+1 (0.42)

Source: Frey, B. S. and F. Oberholzer-Gee (1997). The cost of price incentives: An empirical analysis of motivation crowding-out. Amer. Econ. Rev. 87 (4), 746 - 755.

- Significant factors:
  - individual risk estimate
  - economic impact,
  - home ownership,
  - support for nuclear technology,
  - quality of citing procedure.
- Non-significant factors:
  - Age, sex, income, political orientation
- Offering monetary compensation does not turn opponents of the project to proponents. Increasing the compensation does not help either.
  - Compensation is ineffective, income level is insignificant, too.
  - (High) Compensation signals (high) risk
- What other levers do proposers have?
  - Project uncertainty
  - Risk evaluation and reduction
  - ….?

Summary

- Nuclear Reactions: Unstable nucleus → Stable nucleus
- Uranium Mining and Supply Chain
- Nuclear Reactors
- Economics

Nuclear Power Expansion/Contraction in USA as of 2014-15

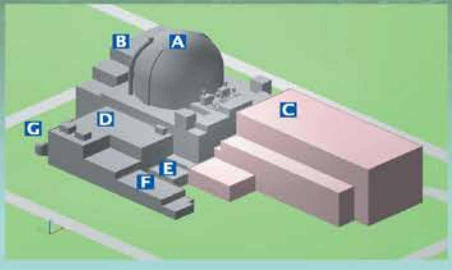
- Nuclear Regulatory Commission (NRC) issued an expansion license to Vogtle Plant on Feb 9, 2012. The first such permit in the last 35 years.
  - Vogtle Plant on the border of Georgia & South Carolina; 30 miles Southeast of Augusta, Georgia.
  - Plant is owned by Southern Company.
  - The expansion project (Vogtle 3 and 4) could begin in 2016 and is estimated
    - To cost $14 billion. But increased by $730 million in Jan, 2014.
    - Both reactors are Westinghouse AP 1000 designs.
    - These numbers are much higher than CANDU ACR numbers.
  - After the permit asked for $8.33 B loan guarantee from the Department of Energy but got $6.5 B.
- Scana is to build 2 more AP 1000 reactors in its Summer Plant, South Carolina.

- Luminant and Mitsubishi applied (in 2007) for a permit for two more reactors in Glen Rose.
  - Each reactor is to have 1700 MW capacity.
  - Reactors will have advanced PWR designed by Mitsubishi. More on the US APWR (US version of Advanced Pressurized Water Reactor) is on the next page.
  - The permit is still being considered by NRC; check www.expandcomanchepeak.com.

- The shale gas boom makes it hard for new reactors to compete. In 2015, some existing reactors are falling behind as well:
    - www.expandcomanchepeak.com is removed by the end of 2015
    - Shut down: Duke Energy's Crystal River in Florida; Edison International's San Onofre in California.
    - Considering shut down: Dominion Resources' Kewaunee in Wisconsin; Entergy's Vermont Yankee

MITSUBISHI US-APWR

Source: http://www.mnes-us.com/htm/usapwrdesign.htm



A Containment Vessel

1. Reactor Vessel
2. Steam Generators
3. Reactor Coolant Pumps
4. Pressurizer
5. Reactor Coolant Piping
6. Advanced Accumulators
7. Refueling Water Storage Pit
8. Main Steam Lines
9. Main Feedwater Lines
10. Pre-stressed Concrete Containment Vessel
11. Polar Crane
12. Containment Spray Ring Headers
13. Equipment Hatch
14. Refueling Machine

B Reactor Building

15. Containment Spray / Residual Heat Removal Heat Exchangers
16. Containment Spray / Residual Heat Removal Pumps
17. Safety Injection Pumps
18. Main Steam Isolation Valves
19. Main Feedwater Isolation Valves
20. Main Control Room
21. Safety Metal Clad Switch Gear & Power Center
22. Component Cooling Water Heat Exchanger
23. Fuel Handling Machine
24. Spent Fuel Storage Pit
25. Spent Fuel Pit Heat Exchanger

C Turbine Building

26. High-Pressure Turbine
27. Low-Pressure Turbines
28. Generator
29. Moisture Separator and Reheaters
30. Turbine Building Crane
31. Main Condensers
32. Low-Pressure Heaters
33. Metal Clad Switch Gear & Power Center

D Auxiliary Building

34. Holdup Tanks
35. Boric Acid Tanks
36. Waste Holdup Tanks
37. Spent Resin Storage Tanks

E Gas Turbine Buildings

38. Safety-Related Chiller Unit & Pump

F Access Control Building

39. Non Safety-Related Chiller Unit & Pump

G Yard

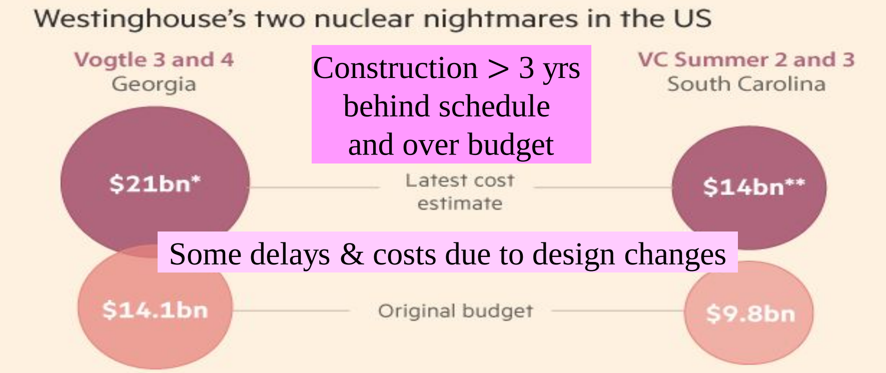
40. Auxiliary Refueling Water Storage Tank
41. Primary Make up Water Tank

2017 Update on Southern and Scana Reactors

- Southern Company's Vogtle Plant expansion reactors 3 & 4 are built by Westinghouse
  - Westinghouse is owned by Toshiba
  - Reactors are AP1000 designs
  - AP1000 is prefab submodule-module system
    - Modular manufacturing saves cost
    - Modules must fit tightly
    - Modules do not fit tightly at Vogtle & other reactors currently built in China & UK.

Installation of reactor vessel cavity (CA04 Module) for Vogtle Reactor 4. The module is 27 ft tall, 21 ft wide and weighs 64,000 pounds.

Installation of structural support (CA05 Module) for Vogtle Reactor The module is has reinforced steel and weighs 180,000 pounds.



Construction > 3 yrs behind schedule and over budget

Some delays & costs due to design changes

Source: Crooks, E., K. Inagaki. 2017. Toshiba brought to its knees by two US nuclear plants. FT Feb 16 issue.

3: Toshiba needs to control & expedite construction
Buys constructor Stone & Webster

Jan 2006: Agrees to buy US nuclear company Westinghouse

Apr/May 2008: Westinghouse signs deals on Vogtle and VC Summer plants

Oct 2015: Westinghouse agrees to buy construction group Stone & Webster

Apr 2016: Records $2.3bn writedown on Westinghouse

Feb 2017: Reveals $6.3bn writedown on its US nuclear business

There are rumors of Toshiba shutting down Southern and Scana expansions by declaring bankruptcy in USA.

Modular construction to save costs, unfitting parts, buying suppliers to exert control on quality and delivery time is a familiar story from Boeing 787 Dreamliner manufacturing.