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SUSTAINABLE ENERGY

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INTRODUCTION TO SUSTAINABLE ENERGY

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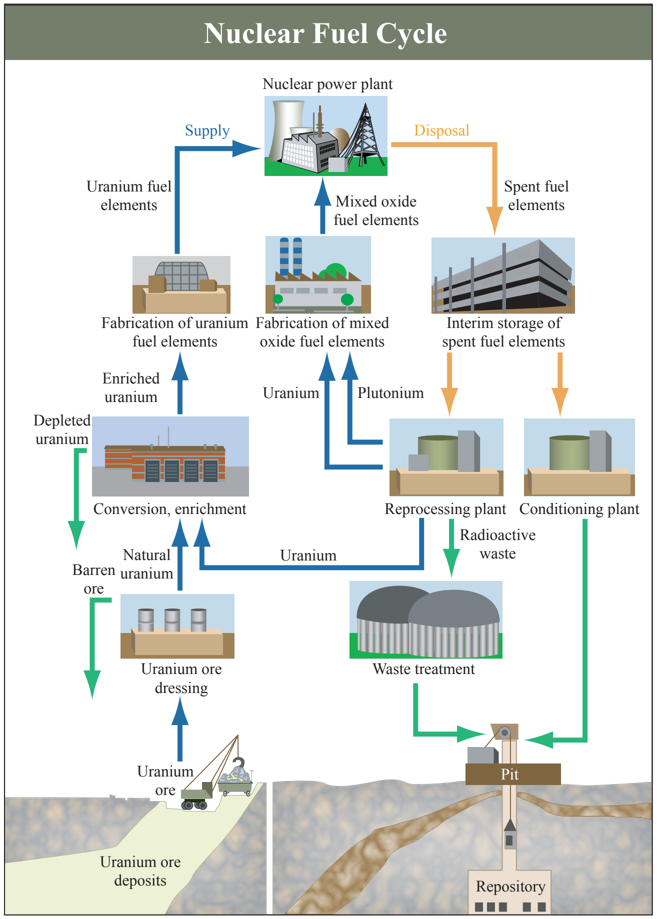

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EXPANSION OF CIVILIAN NUCLEAR POWER AND PROLIFERATION

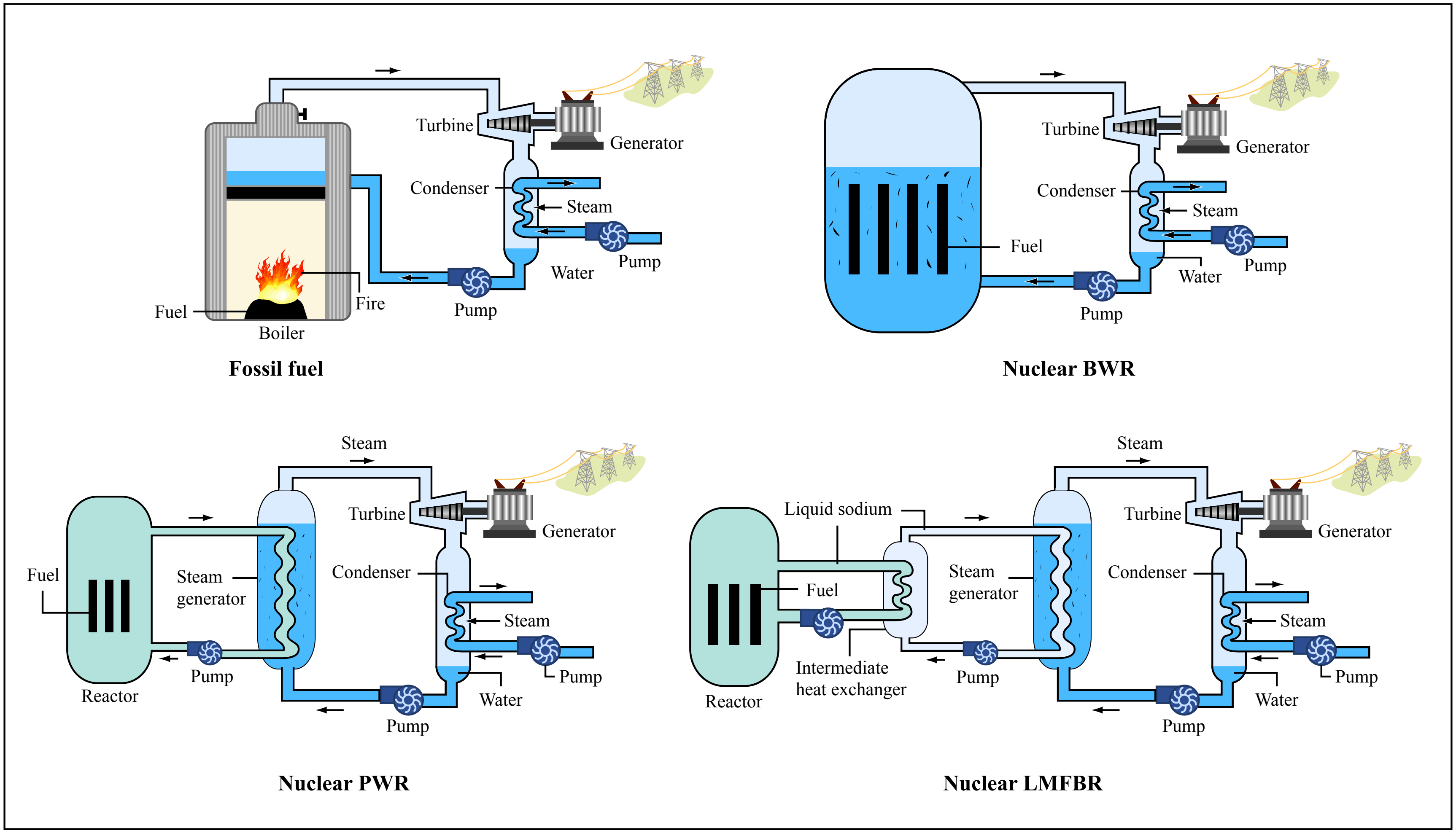
POTENTIAL PRODUCTS FROM FISSION ENERGY

- Electricity (current product)
- Hydrogen
  - High temperature (700C) electrolysis
  - Very high temperature (700-900C) chemical reaction cycle
- Industrial Process Heat (<900C)
- Fertilizer
- Desalinated Water
  - Distillation
  - Reverse osmosis

Surry

Desal

TYPES OF STEAM-ELECTRIC GENERATING PLANTS



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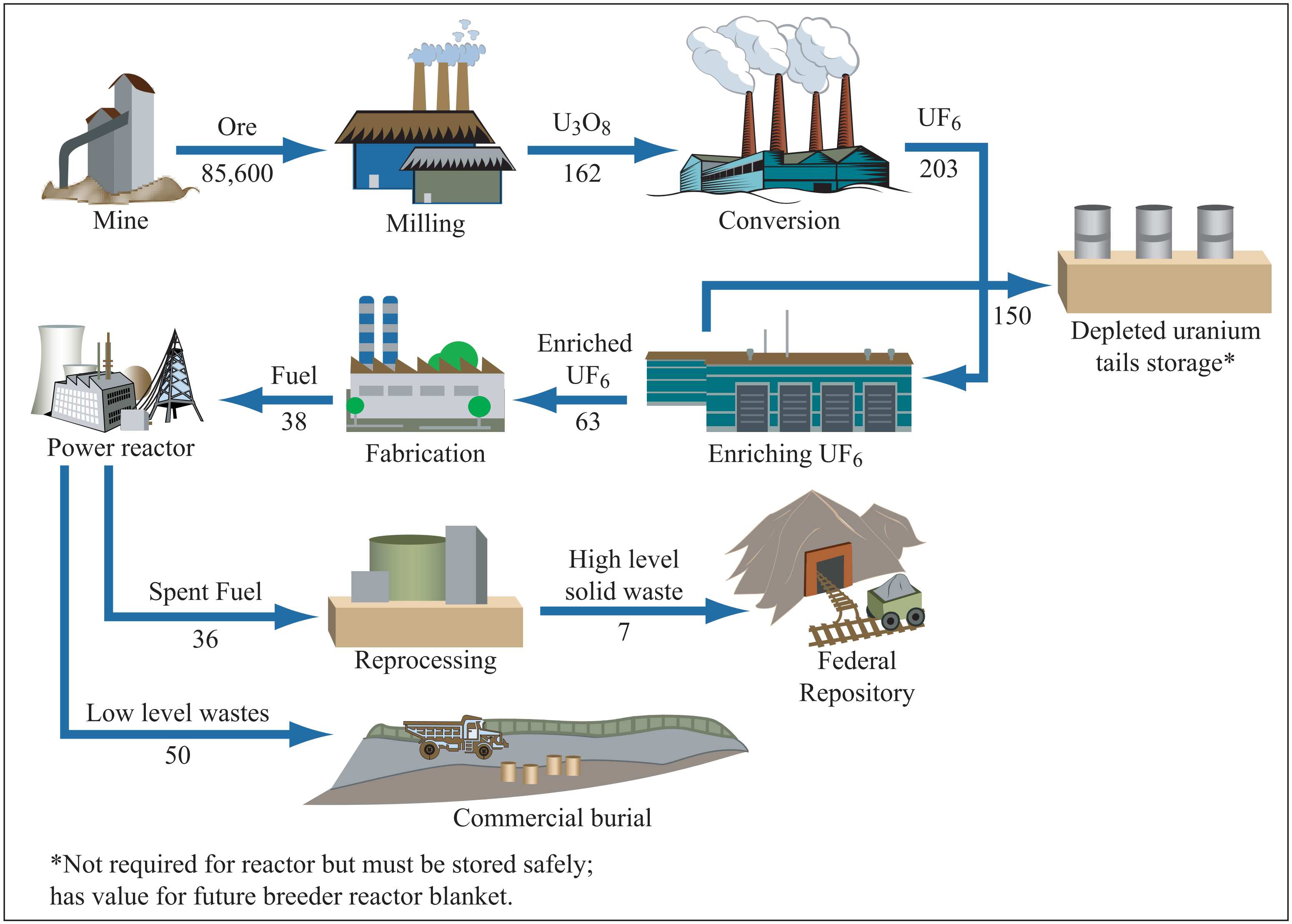
ANNUAL QUANTITIES OF FUEL MATERIALS REQUIRED FOR ROUTINE (EQUILIBRIUM) OPERATIONS OF 1,000 MWe LWR



URANIUM

- Abundance/Supply Duration [see IAEA *Red Book*]
  - Centuries at current usage rates
  - Decades at heavy usage rates
- Composition

Where

Overview

	^{235}U	^{238}U
Natural Uranium	0.007	0.993
LWR Gas-Cooled Reactor Uranium	0.03 - 0.05	0.97 - 0.95
New Research Reactor Uranium	^{2} 0.20	^{3} 0.80
Old Research Reactor Uranium	^{2} 0.93	^{3} 0.07
Breeder Reactor Uranium	0.15 - 0.35	0.65 - 0.85

PLUTONIUM

- Abundance – Potentially Unlimited
- Source: Neutron Absorption Reactions in Reactors

Isotope	Source Reaction	Bare Critical Mass (kg)	Neutron Source Density (n/g·s)	Specific Power (W/kg)
^{238}Pu	$^{237}Np + n \rightarrow {}^{238}Pu + \beta$ $^{242}Cm \rightarrow {}^{238}Pu + \alpha$	10	2600	570
^{239}Pu	$^{238}U + n \rightarrow {}^{239}Pu + 2\beta$	10	---	1.9
^{240}Pu	$^{239}Pu + n \rightarrow {}^{240}Pu$	40	910	7.1
^{241}Pu	$^{240}Pu + n \rightarrow {}^{241}Pu$	12	---	3.2
^{242}Pu	$^{241}Pu + n \rightarrow {}^{242}Pu$	100	1700	0.7

SALIENT PHYSICAL PARAMETERS OF POTENTIAL EXPLOSIVE FISSIONABLE MATERIALS

Isotope	Pa^{231}	Th^{232}	U^{233}	U^{235}	U^{238}*	Np^{237}
Halflife (y)	32.8k	14.1B	159k	700M	4.5B	2.1M
Neutrons /sec-kg	nil	nil	1.23	0.364	0.11	0.139
Watts/kg	1.3	nil	0.281	0.00006	8E-06	0.021
Critical mass** (kg)	162	infinite*	16.4	47.9	infinite*	59

* Not explosive fissionable material
**Bare sphere

SALIENT PHYSICAL PARAMETERS OF POTENTIAL EXPLOSIVE FISSIONABLE MATERIALS (continued)

Isotope	Pu^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}	Am^{241}
Halflife (y)	88	24k	6.54k	14.7	376k	433
Neutrons /sec-kg	2.67M	21.8	1.03M	49.3	1.73M	1540
Watts/kg	560	2.0	7.0	6.4	0.12	115
Critical mass** (kg)	10	10.2	36.8	12.9	89	57

**Bare sphere

SALIENT PHYSICAL PARAMETERS OF POTENTIAL EXPLOSIVE FISSIONABLE MATERIALS (continued)

Isotope	Am^{243}	Cm^{244}	Cm^{245}	Cm^{246}	Bk^{247}	Cf^{251}
Halflife (y)	7.38k	18.1	8.5k	4.7k	1.4k	898
Neutrons /sec-kg	900	11B	147k	9B	nil	nil
Watts/kg	6.4	2.8k	5.7	10	36	56
Critical mass** (kg)	155	28	13	84	10	9

**Bare sphere

SIMPLE GUN-ASSEMBLED NUCLEAR WEAPON

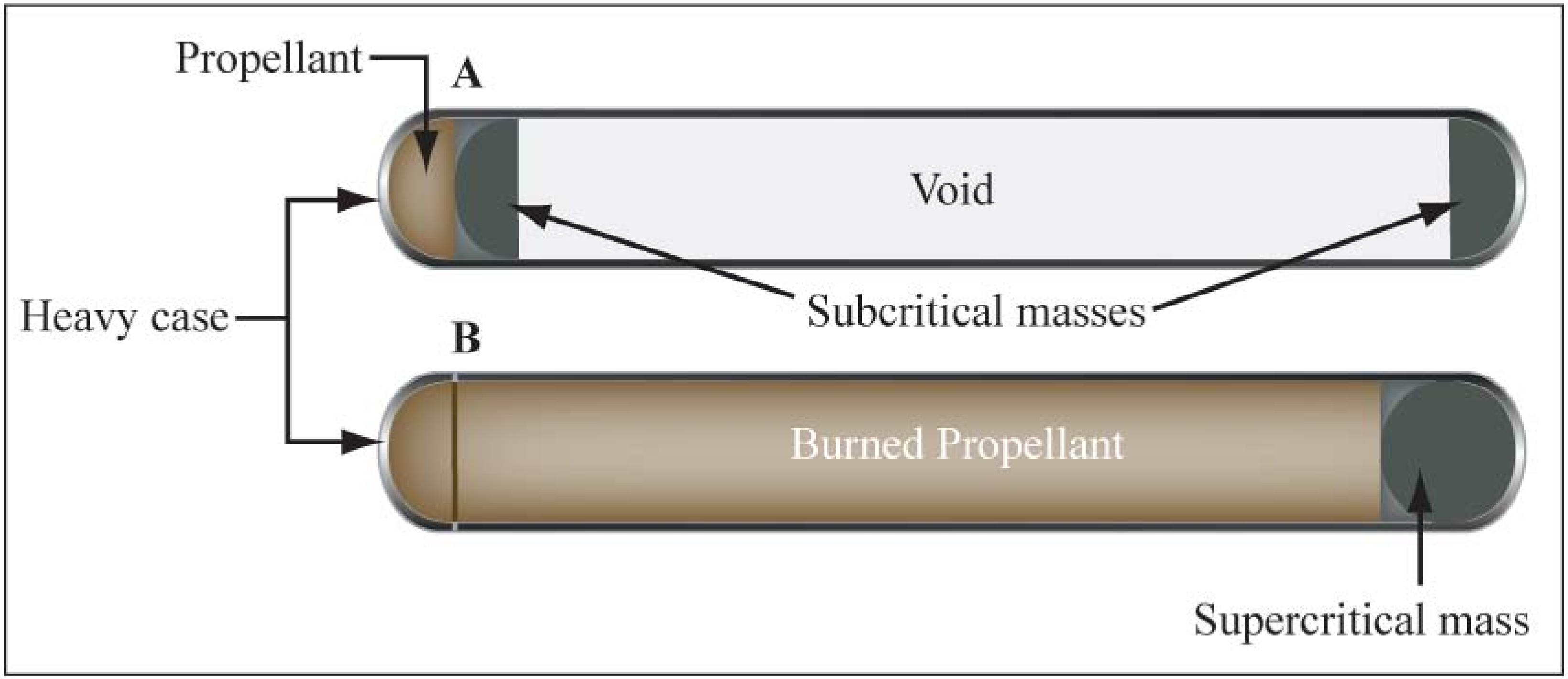


Image by MIT OpenCourseWare.

- Fissile Material is Uncompressed ∴ Large amounts of HEU needed
- Assembly is Slow ∴ Pu explodes prematurely due to spontaneous fission and other neutrons

SIMPLE IMPLOSION NUCLEAR WEAPON

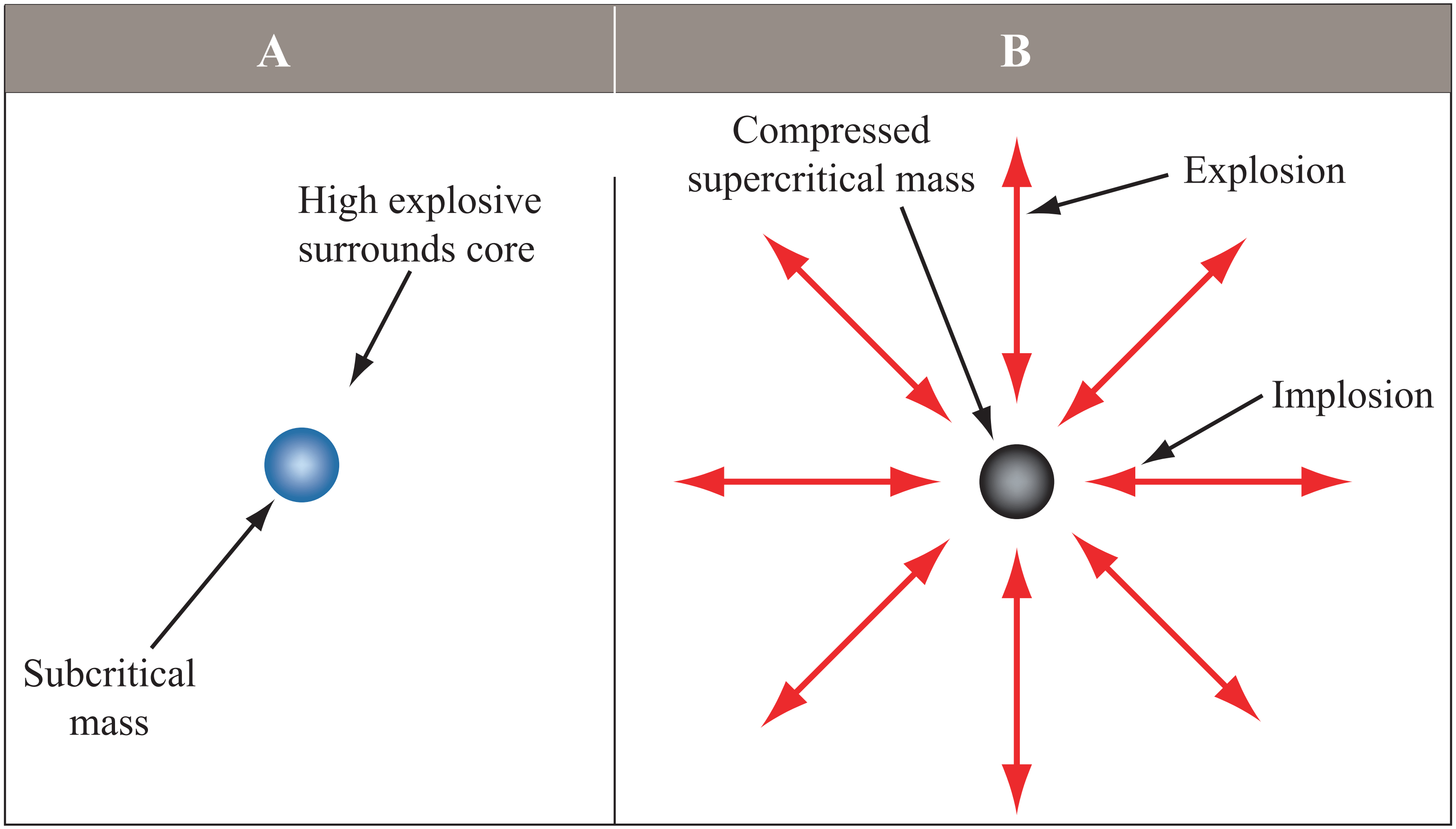


Image by MIT OpenCourseWare.

- Implosion Velocity >> Gun Velocity ∴ No premature explosion
- Explosive compresses Fissile Core ∴ Less than a M_c required

NEUTRONIC PROPERTIES OF NUCLEAR FUELS

	NEUTRON ENERGIES					
	THERMAL			MeV		
Parameter	U^{233}	U^{235}	Pu^{239}	U^{233}	U^{235}	Pu^{239}
α	0.123	0.2509	0.38	0.1	0.15	0.1
η	2.226	1.943	2.085	2.45	2.3	2.7
ν	2.50	2.43	2.91	2.7	2.65	3.0

$$\eta = \frac{\nu}{1+\alpha}, \frac{\text{n's produced}}{\text{absorption}}; \quad \alpha = \frac{\text{n's captured}}{\text{fission}}; \quad \nu = \frac{\text{n's produced}}{\text{fission}}$$

<u>Conversion Reactions</u>:

$$U^{238} + n \rightarrow U^{239} + \gamma \rightarrow Np^{239} + \beta^- \rightarrow Pu^{239} + \beta^-$$

$$Th^{232} + n \rightarrow Th^{233} + \gamma \rightarrow Pa^{233} + \beta^- \rightarrow U^{233} + \beta^-$$

SELF-SUSTAINED CHAIN REACTION

$$1 \text{ neutron } + U^{235} \rightarrow \eta \text{ neutrons} \Rightarrow \begin{cases} \text{1 neutron for subsequent fission, and} \\ (\eta - 1) \text{ neutrons for leakage, parasitic absorption, and conversion} \end{cases}$$

Necessary Condition for Breeding: for each fissile nucleus consumed another is produced via conversion of fertile material, e.g., a U^{235} nuclear is consumed and replaced by production of a new Pu^{239} nucleus, via the reaction –

$$n + U^{238} \rightarrow U^{239} + \gamma$$
$$U^{239} \rightarrow Np^{239} + \beta^- + \gamma$$
$$Np^{239} \rightarrow Pu^{239} + \beta^- + \gamma$$

Conversion Ratio ≡ Number of new fissile nuclei produced as a result of fission of a single nucleus

$$\text{Conversion Ratio}: \begin{cases} \geq 1 \text{ for breeding} \\ < \text{ for burning} \end{cases}$$

ROUTES TO WEAPONHOOD

ROUTE	PROSPECTS
Dedicated fuel cycle (U, Pu)	Preferred method to-date
Reactor fuel diversion (U, Pu)	India, N. Korea using research reactor fuel: Attractive
Enrichment-related misuse or diversion (U)	Unattractive
Fuel-fabrication related misuse or diversion (U, Pu)	Unattractive
Reprocessing-related misuse or diversion (Pu)	Unattractive
Breakout or abrogation (U, Pu) Enrichment with U feedstock Reprocessing reactor fresh*/spent fuel	Iran, N. Korea, Israel, Pakistan: Very Attractive

Facility

Canisters

*HEU or MOX

NUCLEAR SAFEGUARDS

- Non-Proliferation Treaty (NPT)
  - Promise to use facilities in prescribed fashion
  - Subject to seals, surveillance monitoring, inspections
  - Subject to security for weapons-usable materials
- Guard Force

PROLIFERATION RESISTANCE

- Use of Materials Unattractive in Weapons
  - High fizzle probability
  - Radioactive
  - Massive
  - Self-heating
- Long Diversion Time Durations
- Easy Detection
- Cumbersome Access

FISSILE MATERIAL CONTROLS

- Discouraging Diversion
  - Safeguards (active means)
    - Remote monitoring (cameras, detectors, portal monitors, data transmission in real time)
    - Seals and containers
    - Guards, gates and locks
    - Inspections
    - Material “inventories”
  - Proliferation resistance features (passive means), addition to fissile materials other materials for
    - Degradation of fission properties (i.e., reactor grade vs. weapons grade Pu)
    - Neutron production
    - Heating
    - Increase of handling difficulty
      - Mass increase via shielding or extra material
      - Radiation sources

FISSILE MATERIAL CONTROLS, cont'

- Incentives
  - Threats
  - Protection
  - Support and cooperation
- Securing – Reactor Fuel Supply and Takeback
  - International fuel market competition and diversity within NPT
  - Controlled international fuel supply and takeback (including wastes?)
  - Dispersed network of nationally controlled fuel cycle facilities

ENRICHMENT-BASED FISSILE MATERIAL (U) ACQUISITION

- Wish Enrichment > 20% ^{235}U
- Technologies (all use UF_6)

Image of yellowcake uranium removed due to copyright restrictions.

	Footprint	Energy Use	Emissions
Gaseous diffusion (past)	Large	High	Largest
Centrifuge (current)	Smaller	Lower	Small
Laser (MLIS) (future?)	Smallest	Lowest	Small

Enrichment Plants Centrifuge

Molecular Laser Isotope Separation

ENRICHMENT-RELATED U ACQUISITION SCENARIOS

- Diversion
  - Removal and dummy replacement of enriched-U canister, with
  - Evasion of safeguards
- Misuse
  - Evasion of safeguards, falsification of operational records
  - Increased mass throughput
  - Increased operational duration
  - Plant reconfiguration (quickly following inspection)
- Breakout/Abrogation of NPT
  - Previously accumulated inventory of natural or low-enriched Uranium is feedstock
  - Enrich feedstock to high concentration (93-97% ^{235}U)
    - Use previously declared facility, or
    - Use previously constructed undeclared and unoperated facility (Qom)

FUEL FABRICATION FACILITY-BASED FISSILE MATERIAL (U, Pu) ACQUISITION

- Inputs: LEU (UO_2), Pu (PuO_2)
- Outputs: Reactor Fuel Bundles
- Other Potential Fuel Forms: Metal, Carbide, Nitrate, Molten Salt

Fuel

SCENARIOS

- Diversion
  - Removal and dummy replacement of fuel material or rod bundles, with
  - Evasion of safeguards
- Breakout/Abrogation of NPT
  - Capture of fuel material or rod bundles

UO_2

SPENT FUEL REPROCESSING-BASED FISSILE MATERIAL (Pu) ACQUISITION

LaHague

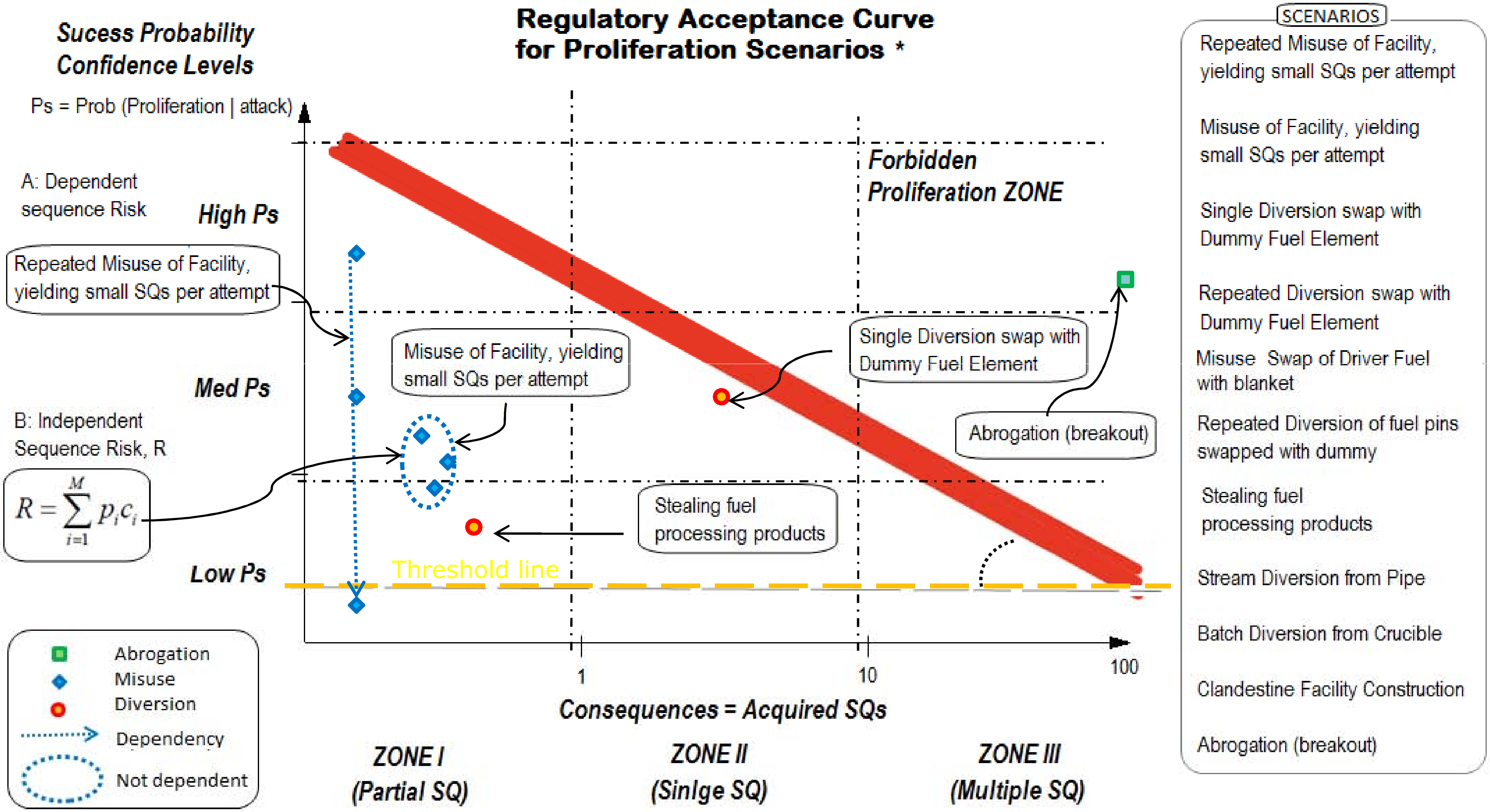
- Facility Separates Spent Fuel into Streams of
  - Plutonium
  - Uranium
  - Fission products and actinides
  - Metallic wastes
- Technologies
  - Aqueous (UO_2, MOX and HNO_3 and TBP-based)
    - PUREX (provides pure Pu, U streams)
    - UREX, etc. (provides mixed fission product and Pu, U streams)*
  - Pyrochemical
    - Metalic fuel, eletrolytic salt or metal, anode and cathode-based (provides stream of mixed* Pu and fission products)

*Note: streams of mixed species can be separated chemically

REPROCESSING FACILITY Pu ACQUISITION SCENARIOS

- Diversion
  - Removal and dummy replacement of Pu product, and
  - Evasion of safeguards
- Misuse
  - Alteration of separation processes, and
  - Evasion of safeguards, falsification of operational records
  - Concentrated Pu removed via process streams
  - Concentrated Pu left in process vessels for subsequent harvesting
- Breakout/Abrogation of NPT
  - Uses previously accumulated feedstock inventory of spent reactor fuel
  - Remove Pu
    - Using previously declared facility
    - Using previously constructed, undeclared facility

REGULATORY ACCEPTANCE CRITERIA
Probability-Consequence Curve



* P-C curve proposed is parallel to Level 2 PRA Risk Assessment

PROSPECTS FOR GETTING WEAPON

- Dedicated Fuel Cycle
- Reactor Fuel Diversion
- Enrichment-Related Misuse or Diversion of U
- Fuel-Related Misuse or Diversion of U, Pu
- Reprocessing-Related Misuse or Diversion of Pu
- Abrogation
  - Reactor spent fuel
  - Enrichment
  - Reprocessing

SUMMARY

- Large Scale Use of Nuclear Power is Inevitable Should Global Warming Prove to be as Serious as it Appears
- Risks of Nuclear Weapons Proliferation Will Grow with the Scale of the Nuclear Enterprise
- Proliferation Risks are Not Strongly Sensitive to Technological Choices
- Proliferation (i.e., Diversion and Misuse) Controlled Relying Heavily upon Safeguards
- Current International Safeguards Arrangements Could be Improved Substantially via Greater Funding
- Breakout (NPT Abrogation) Scenarios Dominate Proliferation Risks, are Not Currently Well Protected Against
- Management of Breakout Risks Demands New International Arrangements for
  - Regulation of proliferation risks
  - Reactor fuel supply and take-back

NUCLEAR POWER ENVIRONMENT COLLAGE

Photo of a tour group entering the north portal of Yucca Mountain removed due to copyright restrictions.

Photos by Stephen Codrington on Wikimedia Commons, U.S. Department of Energy Digital Photo Archive, and Charles Tilford on Flickr.

Pressurized Water Reactor (PWR)

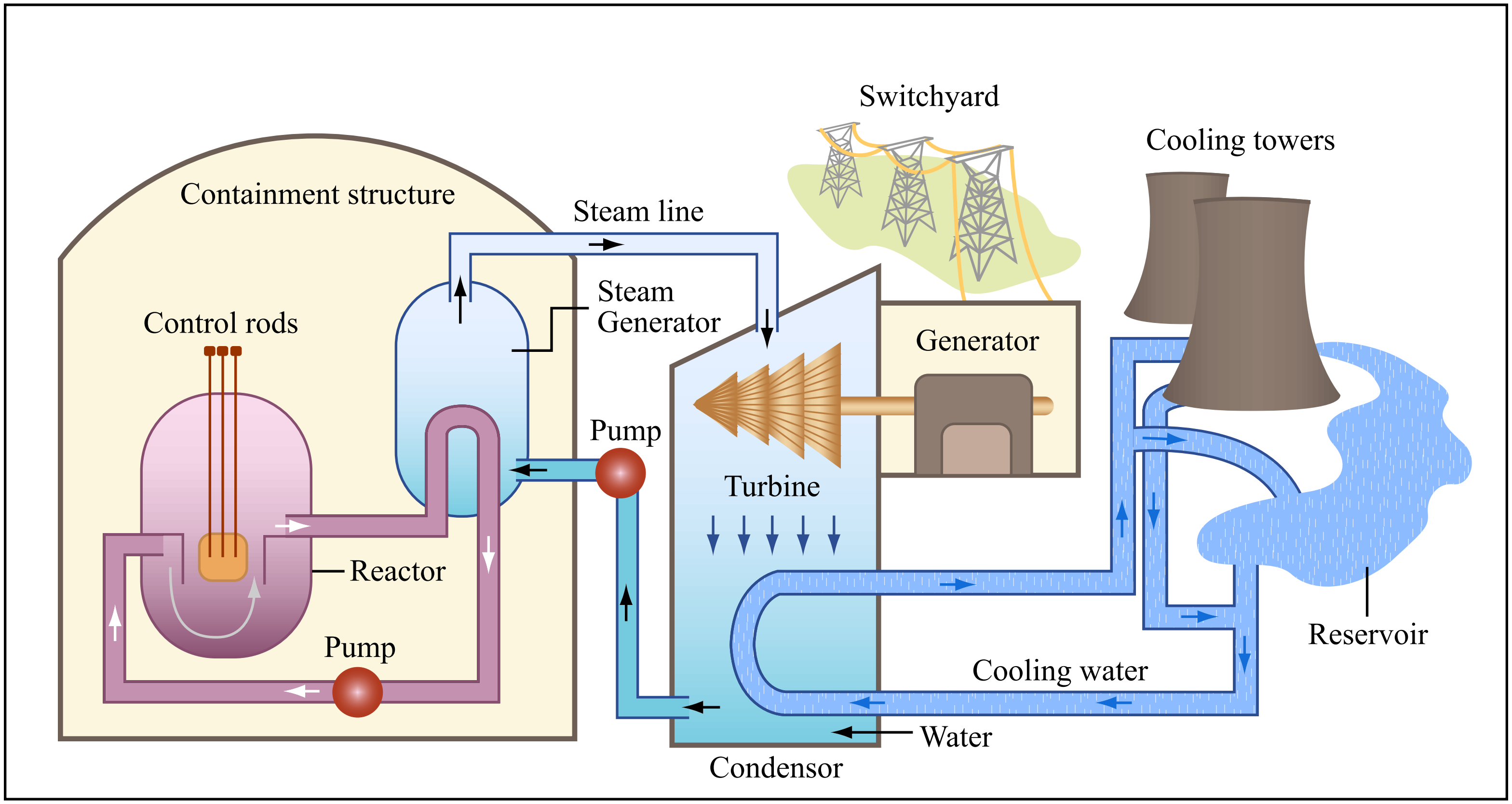


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Photo of Surry nuclear power plant has been removed due to copyright restrictions.

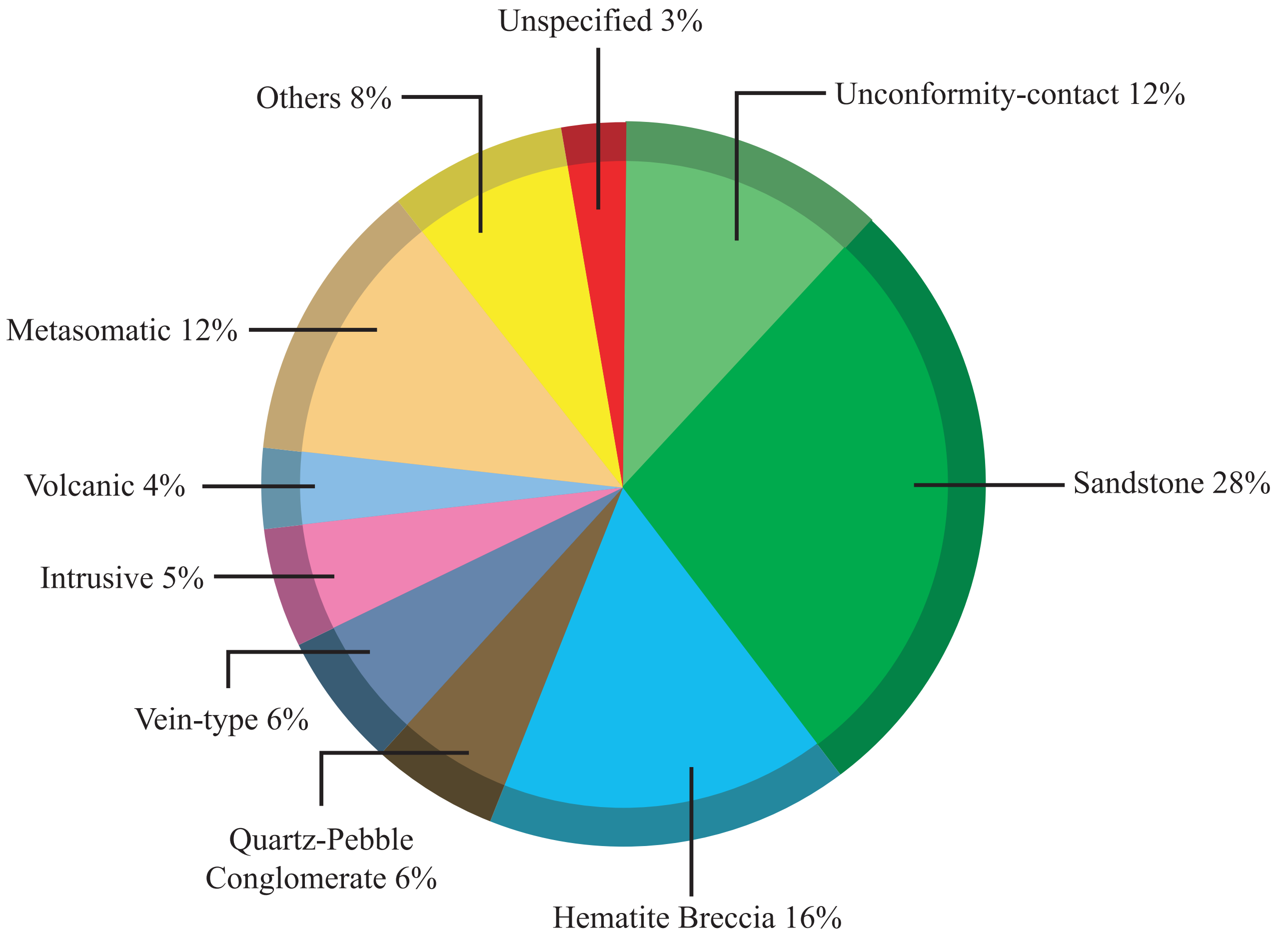
Adelaide Desalination Plant

Photo of Adelaide desalination plant removed due to copyright restrictions.

Photo by jonrawlinson on Flickr.

Jubail Desalination Plant

Types of Uranium Deposits (tonnes)



Total Discovered Resources: 5.46 million

Undiscovered Resources: 7.77 million

Unconventional Resources: ~7.3-22 million

Seawater: 4 billion

Image by MIT OpenCourseWare. Source: IAEA.

World Distribution of Uranium Resources

Australia	1,243,000 tU	22.7%
Kazakhstan	817,000	14.9%
Russia	546,000	10.0%
South Africa	435,000	8.0%
Canada	423,000	7.7%
United States	342,000	6.3%
Brazil	278,000	5.1%
Namibia	275,000	5.0%
Niger	274,000	5.0%
Others	941,000	17%
Total	**5,469,000 tU**	**100%**

Undiscovered resources: 7,771,100 tU

Image by MIT OpenCourseWare. Source: NEA/IAEA Group on Uranium, *Uranium 2007: Resources, Production and Demand*. See http://infcis.iaea.org/ for data on 1176 uranium deposits from 71 countries, total 19,193,456 tU.

Uranium Reserves vs. Grade

Original Grade	Original Reserves					
	<500	500 - 1,000	1,000 - 10,000	10,000 - 100,000	>100,000	Total
< 0.03	3	9	65	32	6	115
0.03 - 0.10	13	26	96	31	6	172
0.10 - 1.00	33	106	282	89	7	517
1.00 - 5.00	5	3	13	10	0	31
> 500	0	0	1	0	2	3
Grand Total	54	144	457	162	21	838

Image by MIT OpenCourseWare. Source: UDEPO.

MARCOULE FRANCE ENRICHMENT FACILITY

Photos of the nuclear energy production and research site in Marcoule, France removed due to copyright restrictions.

SPENT FUEL STORAGE CANISTERS

Photos of various methods of spent fuel storage removed due to copyright restrictions. Please see, for example:

http://www.nucleartourist.com/systems/spfuel1.htm

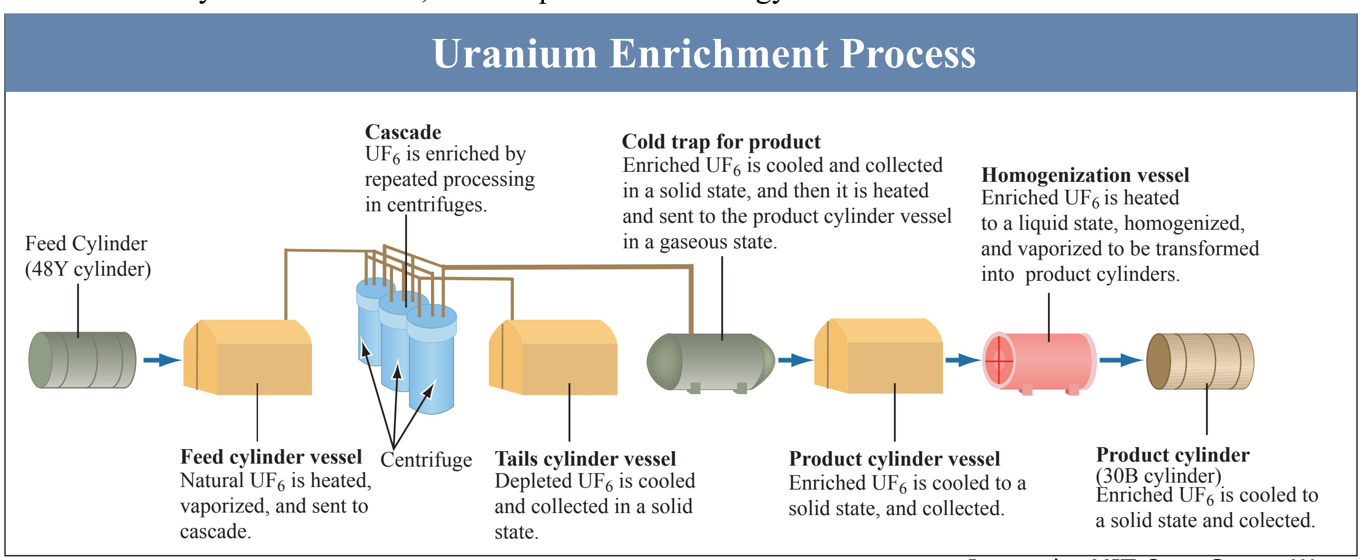
http://environmentalheadlines.com/ct/2010/08/29/ct-paying-price-in-fight-over-nuclear-waste-storage/

ENRICHMENT PLANTS

K-25 Uranium enrichment plant, 1986, Knoxville, TN

Photo by Frank Hoffman, U.S. Department of Energy.

Photo of K-27 uranium enrichment plant in Oak Ridge, TN removed due to copyright restrictions.



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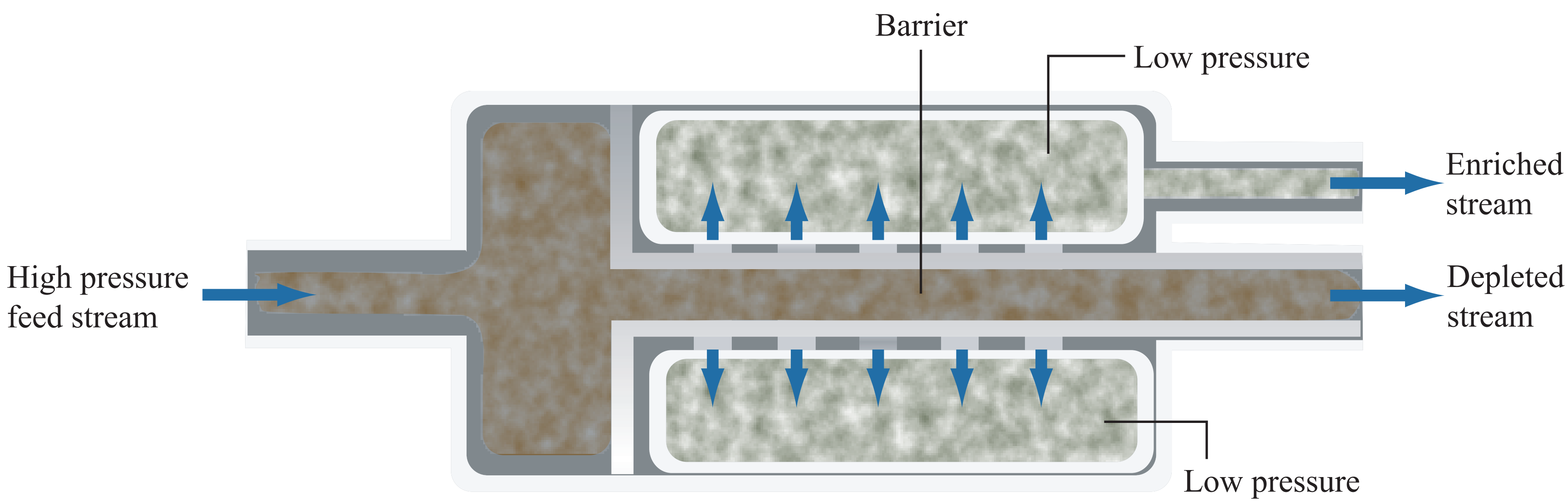
GASEOUS DIFFUSION CASCADES

Gaseous Diffusion Stage



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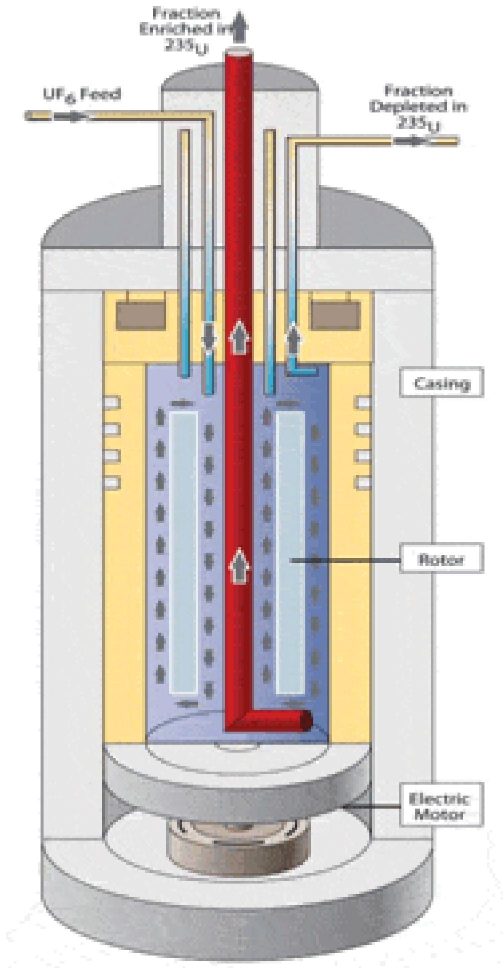
URENCO'S ALMELO CENTRIFUGE ENRICHMENT PLANT

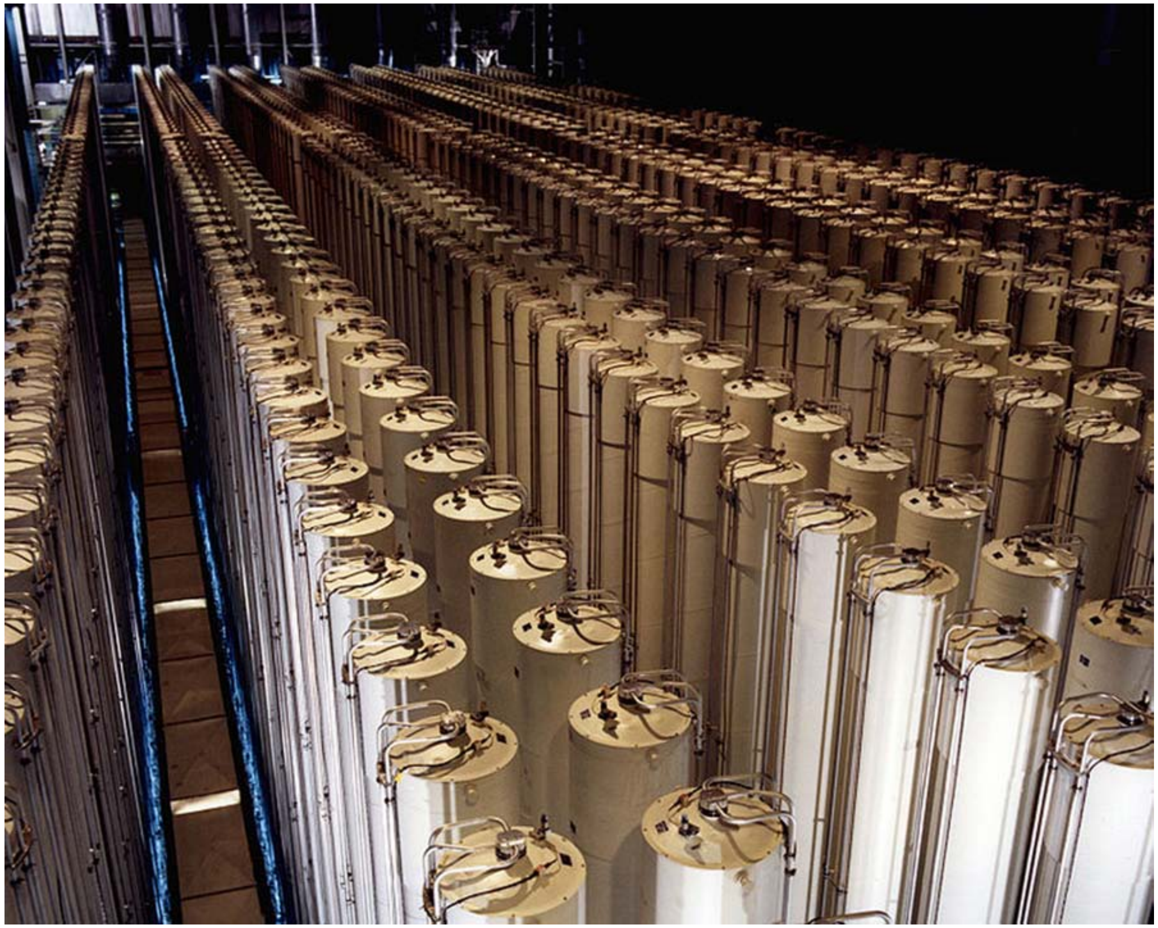
Photo of the centrifuge uranium enrichment plant in Almelo, the Netherlands removed due to copyright restrictions.

COMMERCIAL-SCALE FACILITY FOR CARBON ISOTOPE SEPARATION IN KALININGRAD

Photo of the Molecular Laser Isotope Separation project at IMP-KIAE removed due to copyright restrictions.

CENTRIFUGE CASCADES





Images by U.S. Nuclear Regulatory Commission and U.S. Department of Energy.

LWR Rod Bundle

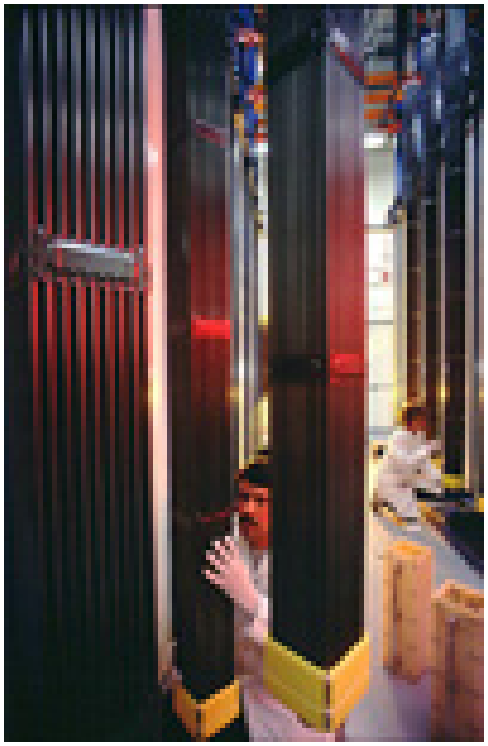


Photo by U.S. Nuclear Regulatory Commission.

Thousands of uranium dioxide pellets fill these nearly 15-foot-long zirconium alloy fuel-rod tubes. Several of these massive bundles sit in the core of a commercial nuclear reactor providing intense heat from fission reactions.

Breeder Reactor Rod Bundle

UO_2 POWDER

Photo of uranium dioxide powder removed due to copyright restrictions.

LaHAGUE REPROCESSING PLANT

Photos of the nuclear fuel reprocessing plant in La Hague, France

removed due to copyright restrictions.

The French keep all of the nuclear waste from the last thirty years of energy production in one room, the storage vault at La Hague.

22.081J / 2.650J / 10.291J / 1.818J / 2.65J / 10.391J / 11.371J / 22.811J / ESD.166J
Introduction to Sustainable Energy
Fall 2010