LA-UR-17-20887

Approved for public release; distribution is unlimited.

Title:	Uranium Conversion & Enrichment
Author(s):	Karpius, Peter Joseph
Intended for:	Introductory Course on the Nuclear Fuel Cycle for NA-21 Personnel
Issued:	2017-02-06

Uranium Conversion & Enrichment

Pete Karpius

February 2017

Introduction

- The isotopes of uranium that are found in nature, and hence in ‘fresh’ Yellowcake’, are not in relative proportions that are suitable for power or weapons applications.

- The process of obtaining the proper proportions of these isotopes is called enrichment

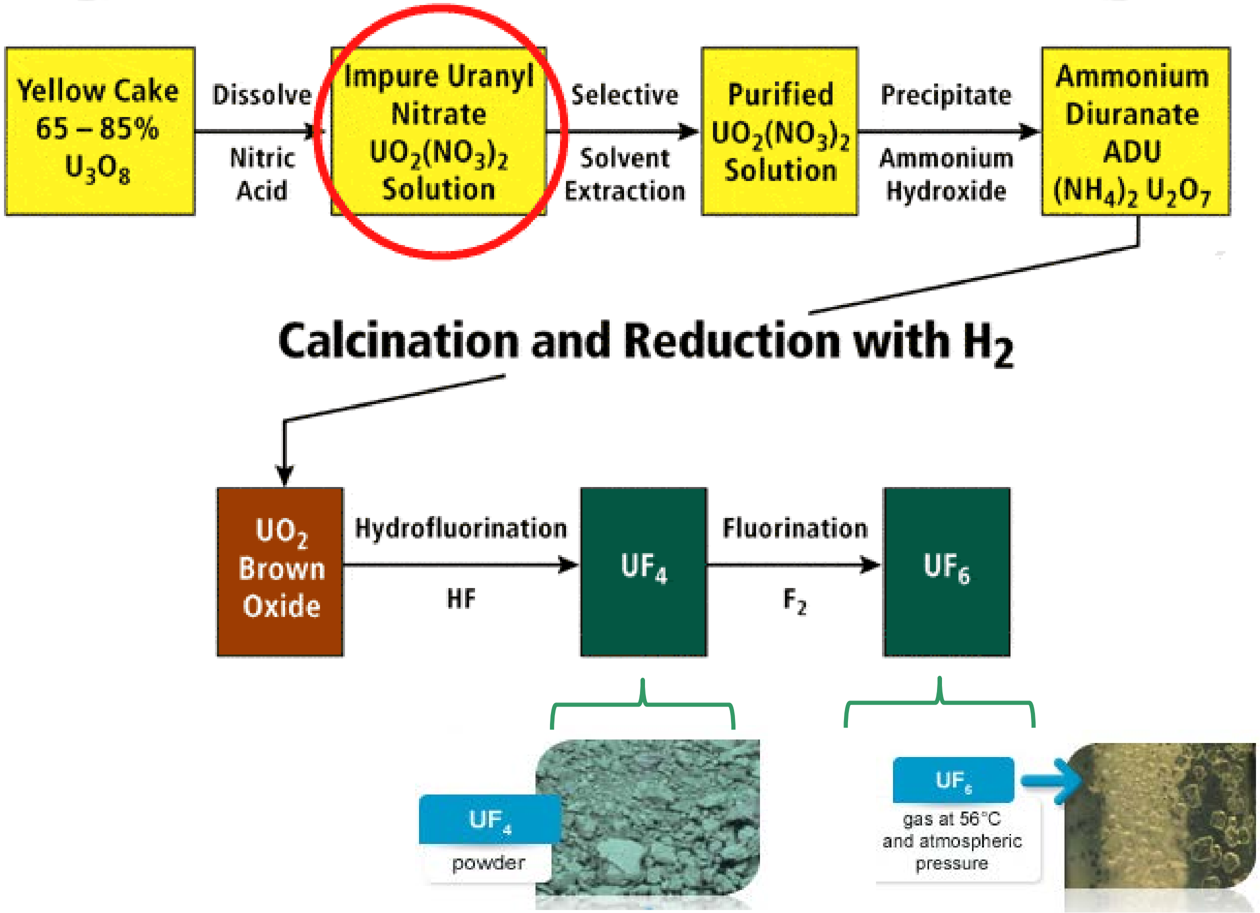
- Yellowcake is not in a form that is suitable for enrichment methods so the material must first go through a process called ‘conversion’

Conversion Introduction

- Enrichment technologies require uranium to be in a gaseous form and not a solid or powder such as U_3O_8 yellowcake
- Uranium Hexafluoride (UF_6) is solid at standard atmospheric pressure but will transform directly to a gas above 134°F (57°C)
  - The direct solid-gas transformation is called 'sublimation'
- The goal of conversion then is to transform the U_3O_8 yellowcake into UF_6

Wet Process Conversion Overview

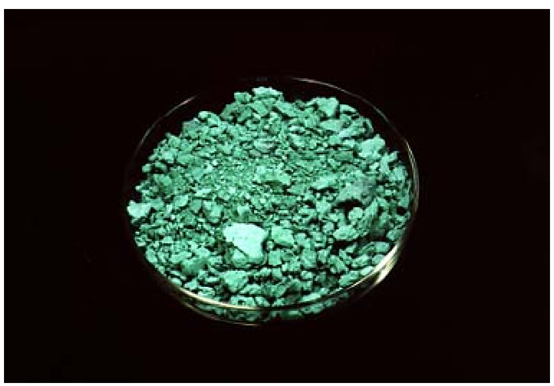
e.g. at **COMURHEX-Malvési** plant in Narbonne, France.



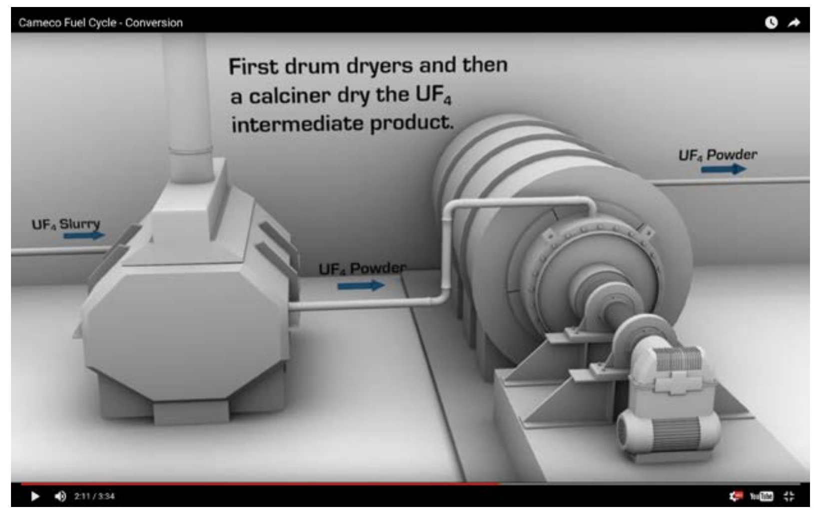
UNCLASSIFIED

Hydrofluorination ($UO_2 \rightarrow UF_4$)

- Highly corrosive hydrofluoric acid (HF) is used to convert UO_2 to uranium tetrafluoride (UF_4)
  - $UO_2 + 4HF \rightarrow UF_4 + 2H_2O$
- The UF_4 slurry is then dried and calcined to remove all water



UF$_4$ reacts slowly with water to produce HF



https://www.youtube.com/watch?v=xTFFTQ-bCPI

Fluorination ($UF_4 \rightarrow UF_6$)

- HF is dissociated via electric current and forms H_2 and F_2 diatomic molecules
- UF_6 is made by contact of gaseous fluorine with the UF_4 powder in a flame reactor.

The reaction is exothermic and occurs at very high temperatures

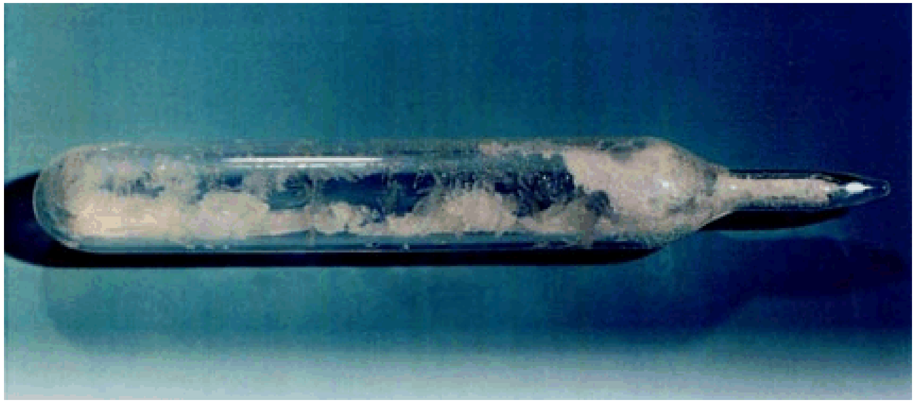
Unburned UF_4 collects at the bottom of the reactor and is re-circulated back into the reactor inlet

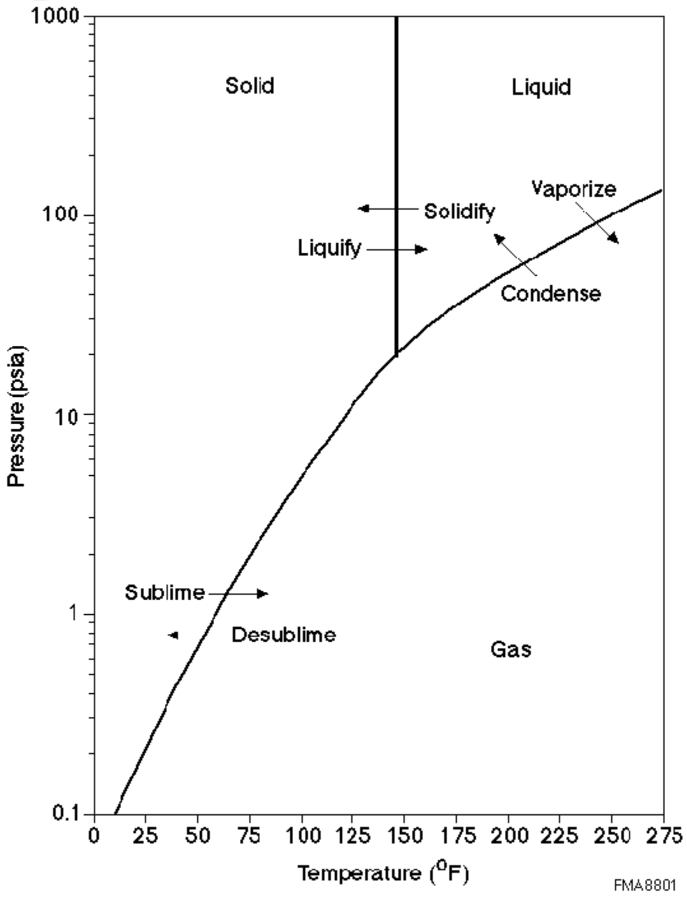
UF_6 gas is filtered and then chilled and recovered in crystalline form

http://www.areva.com/EN/operations-757/conversion-the-fluorination-of-uranium-in-2-stages.html

Properties of UF_6

- Solid UF_6 is a white, dense, crystalline material that resembles rock salt
- UF_6 sublimates at standard atmospheric pressure above 134°F (57°C)
- UF_6 reacts with water to form highly corrosive hydrofluoric acid (HF)





http://web.evs.anl.gov/uranium/guide/uf6/propertiesuf6/index.cfm

Storage & Transport of UF_6

- Following conversion UF_6 is stored in large robust cylinders
- These cylinders are then transported to enrichment facilities by various means

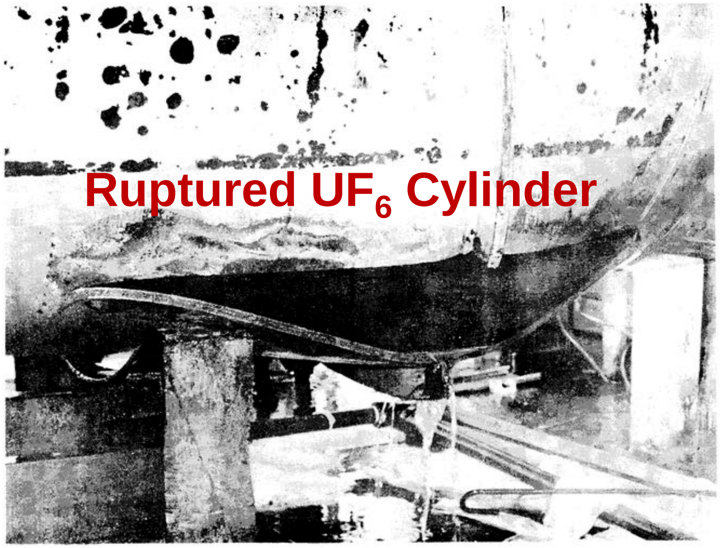
Type 48Y UF_6 Cylinders

- Used for natural and depleted uranium
- Holds 12,500 kgs of UF_6 (8,450 kgs U)
- A 48Y cylinder filled with natural uranium contains 60.1 kgs of ^{235}U.
- Nominal wall thickness 16 mm

UF6 Cylinder Rupture

EXECUTIVE SUMMARY

On January 4, 1986, at 11:30 a.m., a Model 48Y cylinder filled with uranium hexafluoride (UF_6) ruptured while it was being heated in a steam chest at the Sequoyah Fuels Corporation facility near Gore, Oklahoma. The incident resulted in the death of one plant worker and injuries to several others as a result of exposure to hydrofluoric acid, a reaction product of UF_6 and airborne moisture.



https://en.wikipedia.org/wiki/Uranium_hexafluoride

Sequoyah Fuels Corporation Gore, Oklahoma:

1 fatality
37 workers hospitalized
21 locals hospitalized
Shut down 1993

https://en.wikipedia.org/wiki/Sequoyah_Fuels_Corporation

Who does Uranium Conversion?

Company	Nameplate capacity (tonnes U/yr as UF_6)	Approx capacity utilisation 2015	Capacity utilisation 2015, tU/yr
Cameco, Port Hope, Ont, Canada	12,500	70%	8750
Springfields Fuels, UK	(closed August 2014)	0%	0
TVEL at Siberian Chemical Combine, Seversk, Russia	12,500	100% assumed	12,500
Comurhex (Areva), Malvesi (UF_4) & Tricastin (UF_6), France	15,000	70%	10,500
Converdyn, Metropolis, USA	15,000	70%	10,500
CNNC, Lanzhou, China	5000	unknown	4000
IPEN, Brazil	100	70%	70
World Total	60,100		**46,320**

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/conversion-and-deconversion.aspx

Uranium Enrichment

Definition of Uranium Enrichment

- Only three isotopes of uranium are found in nature
  - ^{238}U (99.27%)
  - ^{235}U (0.72%)
  - ^{234}U (0.006%)
- Categories of Enrichment (E = % of ^{235}U)

– Depleted Uranium (DU)	E < 0.72 %
– Natural Uranium (NU)	E = 0.72 %
– Enriched Uranium	E > 0.72%
• Low Enriched Uranium (LEU)	0.72% < E < 20.0 %
• High Enriched Uranium (HEU)	E ≥ 20.0 %

Enrichment Methods

- Gaseous Diffusion
  - 1st generation developed in 1940's
  - Least efficient
  - Huge footprint and energy requirements
- Gas Centrifuge
  - 2nd generation developed in 1940's
  - Mid efficiency
  - Smaller footprint and energy requirements
    - Centrifuge plants only require ~ 5% energy as gas diffusion facilities
- Laser Isotope Separation
  - 3rd generation developed in the 2000's
  - Most efficient
  - Potentially smallest footprint and energy requirements

Separative Work Units

Separative Work Units (SWUs) represent the effort required to separate ^{235}U from ^{238}U. SWUs are tallied in kilograms or metric tons

To produce 100 kg with 0.3% tails requires[1]:			
		Approx. Electricity Required (MW-hr)	
Enrichment	kg SWU Required	Gaseous Diffusion	State-of-the-Art Centrifuge
3.0%	342	855	17.1
4.0%	528	1,320	26.4
20.0%	3,832	9,580	191.6
90.0%	19,294	48,235	964.7
3.5 → 20.0%	1,160		
20 → 90.0%	1,848		

[1] Uranium SWU calculator: www.fas.org

Online SWU Calculator

http://www.urenco.com/swu-calculator/

The URENCO SWU Calculator

SWU stands for Separative Work Unit.
It is the standard measure of the effort required to increase the concentration of the fissionable ^{235}U isotope.

Choose your relevant calculator from the list below. Enter the known quantities before pressing the calculate button to see the result.

Calculate Feed and SWU for 1kgU EUP

-

Product Assay :	3.67	$\%^{235}U$	
Tails Assay :	0.3	$\%^{235}U$	
Feed Assay :	0.711	$\%^{235}U$	

Calculate

For 1kgU EUP :

Feed Quantity:	8.2	kgU as UF_6
SWU Quantity:	4.656	SWU

Note that the independent variables do not include energy or $$$

SWUs and the 20 % Level

Los Alamos
NATIONAL LABORATORY
EST. 1943

Separative Work Unit (SWU): This is a complex unit that represents the effort that is required to enrich uranium.

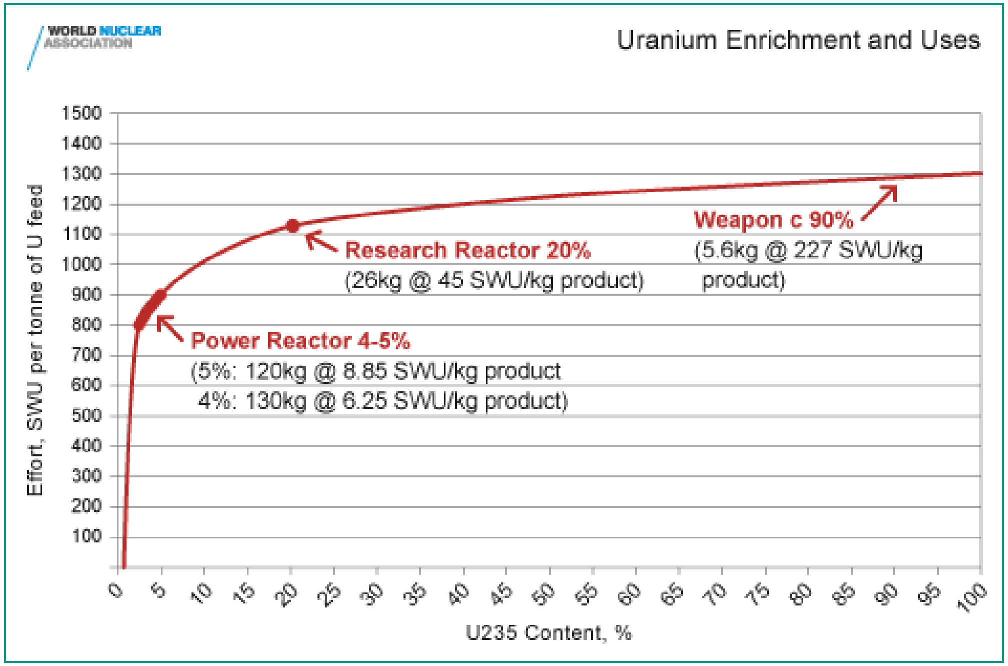
The bulk of the effort is in taking the enrichment from NU to 20 %!

Congressional Research Service
Informing the legislative debate since 1914

Natanz Pilot Enrichment Plant

Iran is using IR-1 centrifuges in this facility to produce LEU containing approximately 20% uranium-235. Iran is also testing several types of centrifuges in the facility. Iran's production of LEU enriched to this level has caused concern because such production requires approximately 90% of the effort necessary to produce weapons-grade HEU, which, as noted, contains approximately 90% uranium-235.[14]

http://fpc.state.gov/documents/organization/234999.pdf



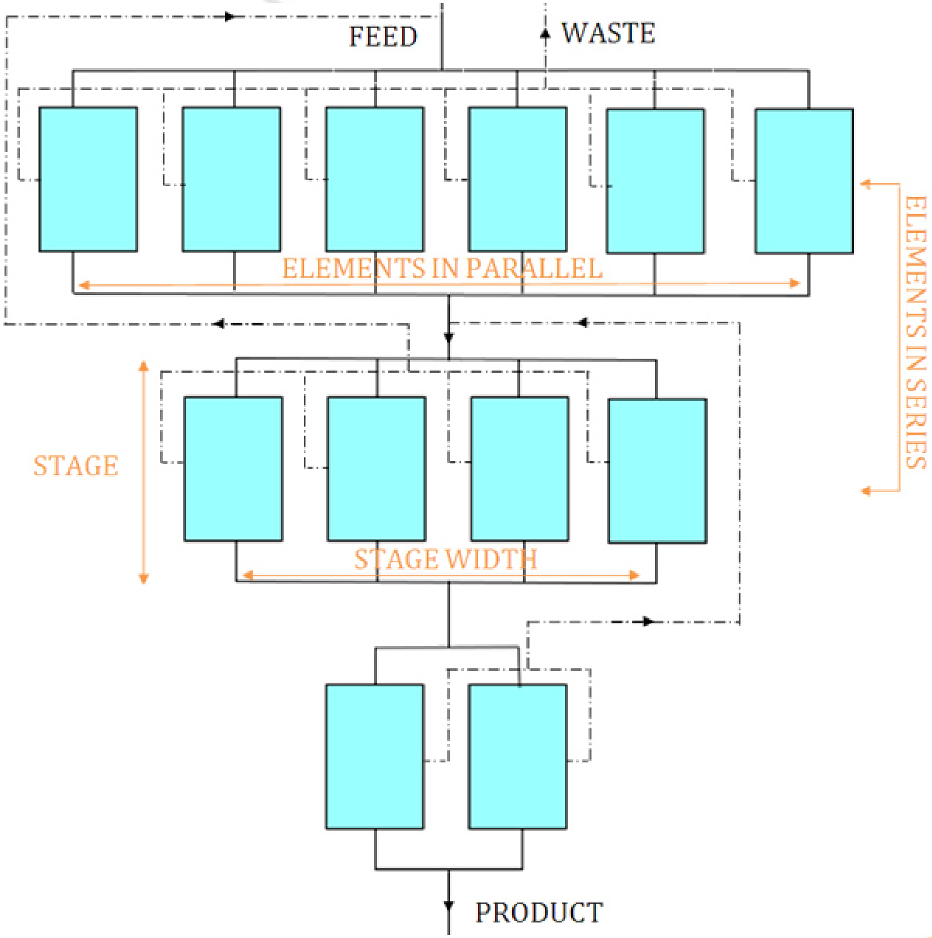
http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/

Enrichment Cascade

A single pass through one stage of a gaseous diffusion or centrifuge process is insufficient to achieve practical levels of enrichment.

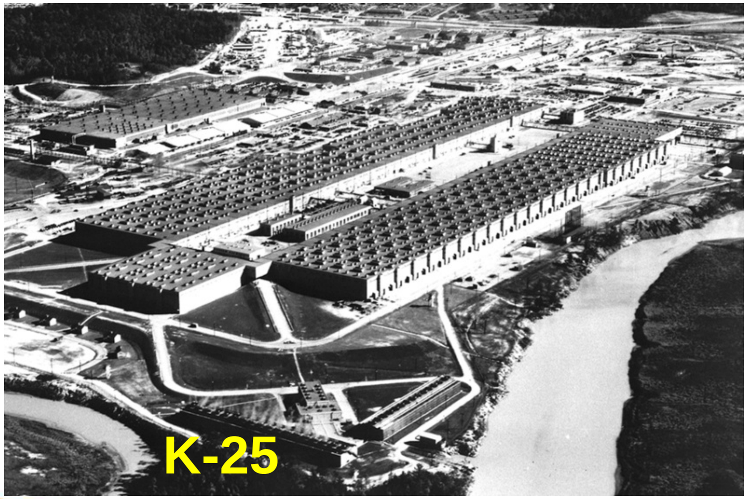
Therefore, enrichment stages may be connected in both parallel and series in what is called a ‘cascade’.

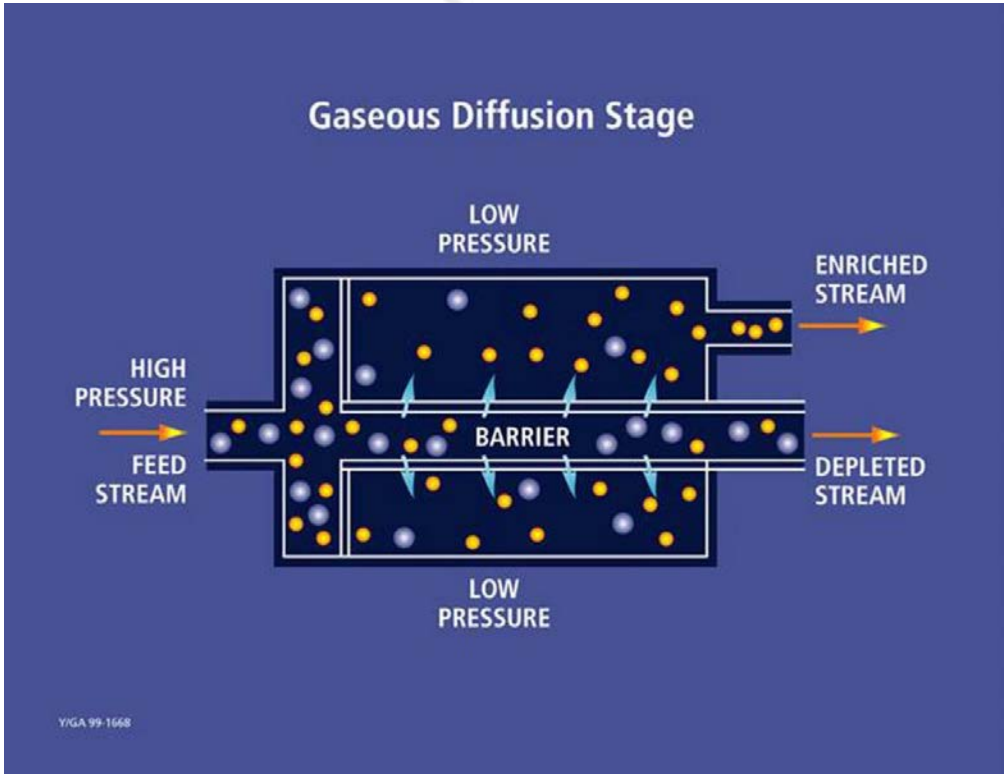
Many cascades may be linked together in a single enrichment facility.



Enrichment: Gaseous Diffusion

In the gaseous-diffusion process UF6 gas is filtered by a semi-porous membrane. The less massive ^{235}U atoms reach and transit the membrane more easily than ^{238}U atoms.





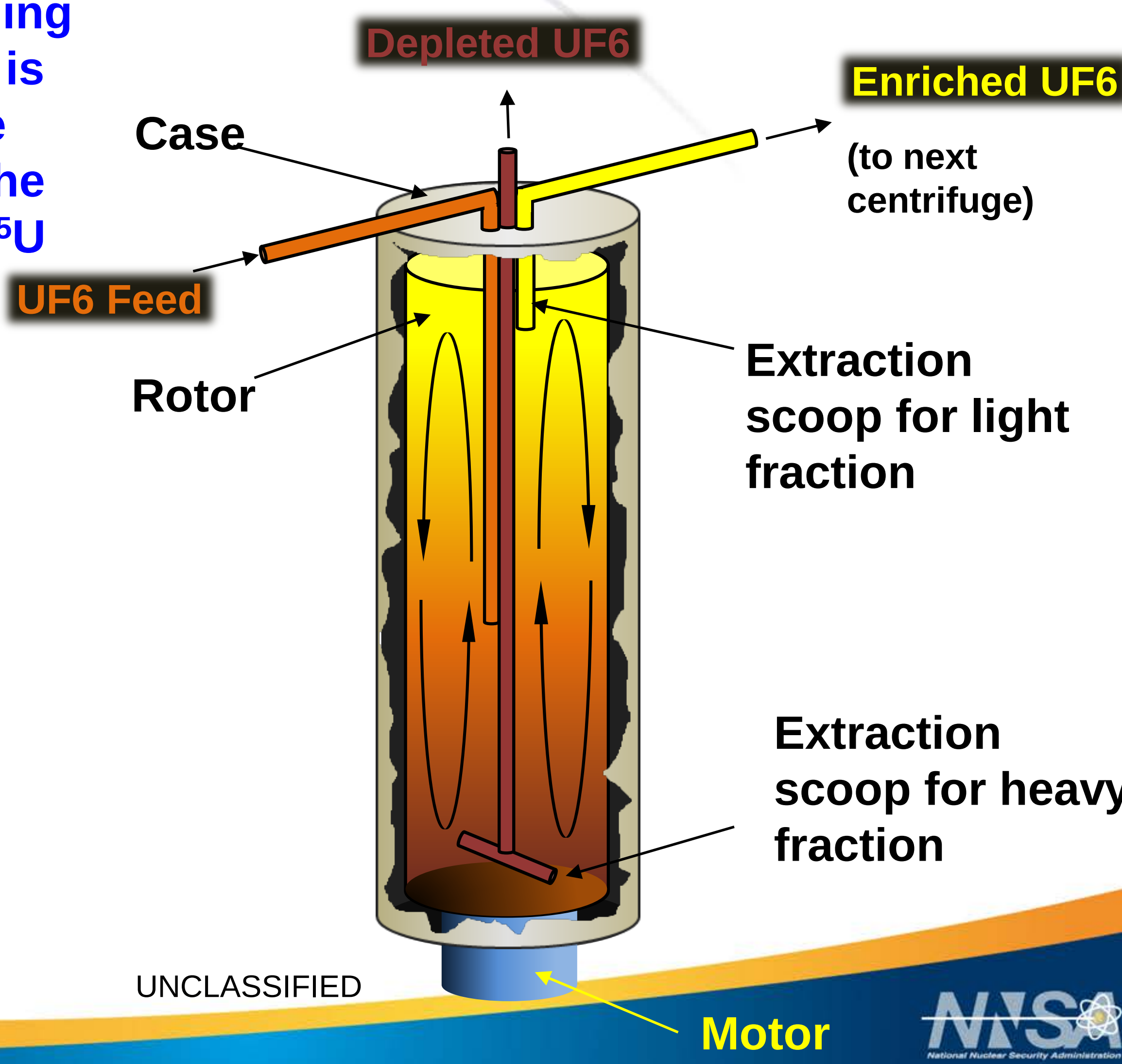
Gaseous Diffusion

- Used mainly by USA and France
  - Also Russia, China, UK, and Argentina on smaller scales
- E.g. Paducah, Kentucky
  - Produced enriched uranium from 1952 – 2013
  - Covered 740 acres
  - Peak power usage >3000 Megawatts & > 10 million SWU/yr

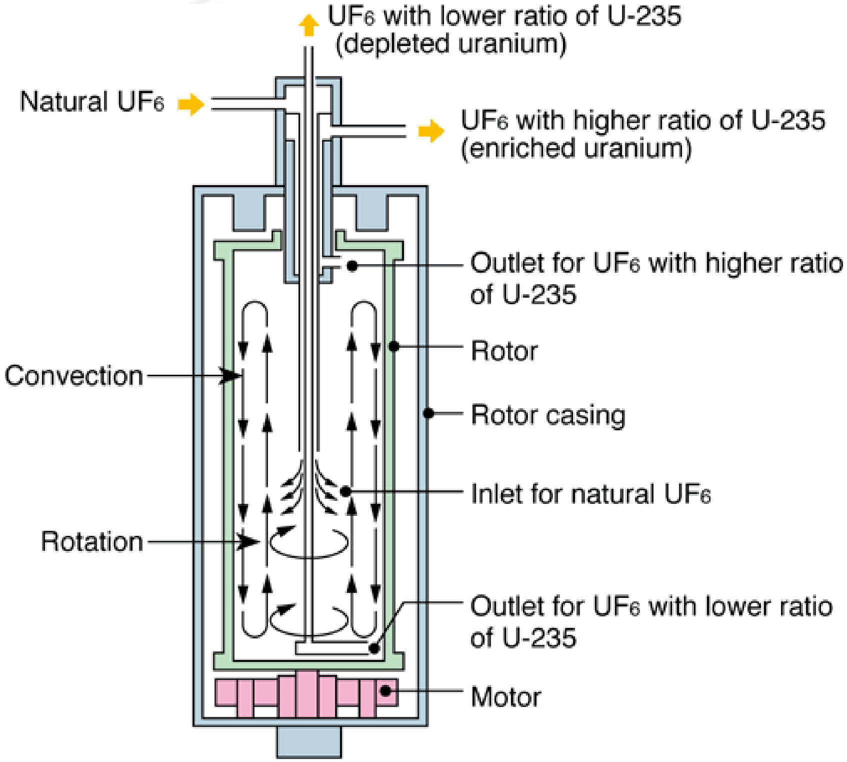
Gas Centrifuge

A gas centrifuge has a spinning rotor within a case. UF_6 gas is fed to the rotor and the more massive ^{238}U atoms drift to the outside leaving the lighter ^{235}U atoms in the center.

Thermal gradients induce convection currents, which further aid in the separation of ^{238}U and ^{235}U.



Gas Centrifuge Performance



Separative Power $\sim \frac{\pi L}{2} \rho D \left(\frac{\Delta M v^2}{2RT} \right)^2 \eta$

L = Rotor length
ρ= Gas density
D = Coeff. of self-diffusion
ΔM = Isotope mass Δ
v = Peripheral rotor velocity
R = Universal gas const.
T = Gas temperature
η= Circulation efficiency

Gas Centrifuge Plants

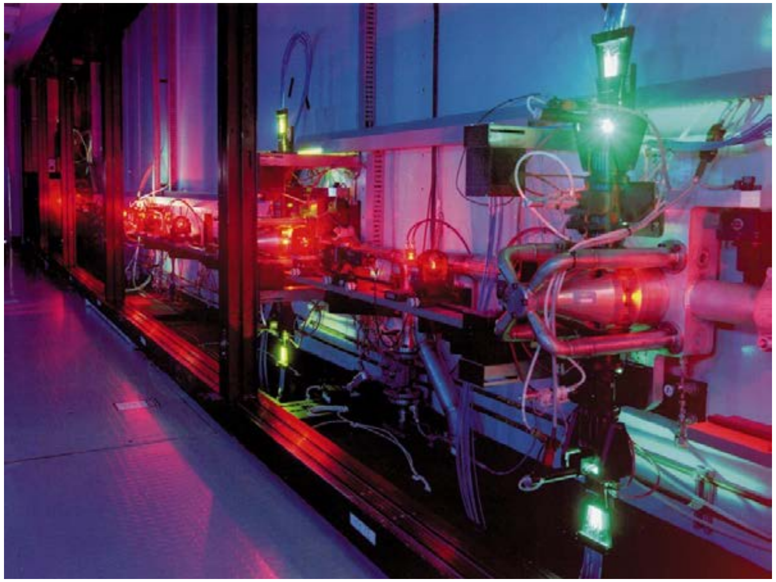
- Operated by :
  - URENCO in UK, the Netherlands, Germany, and USA
  - Areva in France
  - Russia, China, Japan
- Eunice, New Mexico
  - URENCO
  - 3.7 Million SWU/yr*

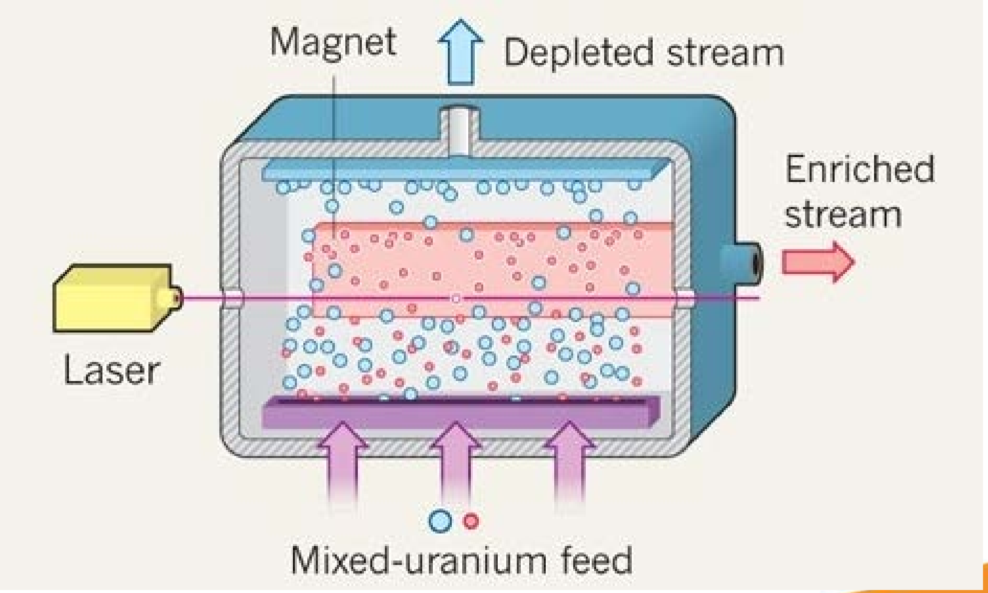
- Areva is planning to build a 3.3 million SWU centrifuge plant at Eagle Rock in Idaho

*http://www.world-nuclear-news.org/ENF-Celebrations-at-US-centrifuge-plant-1004147.html

Laser Isotope Separation

In laser-isotope separation, a tunable laser excites and ionizes ^{235}U atoms*. These charged atoms are then collected electrostatically or electromagnetically and separated from the neutral ^{238}U atoms.





* Or molecules in MLIS

Laser Isotope Separation

- Even though the interaction is between the laser light and the atomic electrons, it is tuned to ionize based on hyperfine transitions
  - Hyperfine States arise due to interactions between the atomic electrons and the nucleus
  - because the interaction involves the nucleus, the laser can be tuned to a specific isotope and not just an element

Laser Isotope Separation

- The SILEX process was developed in Australia by Dr. Michael Goldsworthy and Dr. Horst Struve, working at Silex Systems Limited, a company founded in 1988*

- General Electric (GE) currently has exclusive rights to use the SILEX laser separation process to enrich natural UF6 gas**
  - SILEX: separation of isotopes by laser excitation
  - On September 25, 2012, NRC staff issued a construction and operating license for the facility.

*https://en.wikipedia.org/wiki/Separation_of_isotopes_by_laser_excitation

**https://www.nrc.gov/materials/fuel-cycle-fac/laser.html

Tails

- Tails are what remain from the enrichment process
- Depleted Uranium
  - ~0.25 – 0.3% ^{235}U

Depleted UF_6 Cylinder Storage Yard at Portsmouth, OH

Deconversion: chemical removal of the fluorine from UF_6 so that a less-toxic uranium oxide material can be stored as low-level waste

https://www.nrc.gov/materials/fuel-cycle-fac/ur-deconversion.html

GLE Hitachi and DU Tails

- The US Department of Energy (DOE) has agreed to sell around 300,000 tonnes of depleted uranium hexafluoride to GE Hitachi Global Laser Enrichment (GLE) for re-enrichment at a proposed plant to be built near DOE's Paducah site in Kentucky.*
- Once the plant is complete it is estimated to take 40 years to enrich the stockpile of tails.

** http://www.world-nuclear-news.org/UF-US-DOE-sells-depleted-uranium-for-laser-enrichment-1111167.html

UF6 Cylinder Types v. Enrichment

Cylinder Model	Nominal Diameter inches	Maximum UF_6 kgs	Maximum U kgs	Maximum Enrichment % ^{235}U	Maximum ^{235}U kgs
1S	1.5	0.45	0.30	100	0.30
2S	3.5	2.22	1.50	100	1.50
5A/5B	5	24.95	16.9	100	16.9
8A	8	115.7	78.2	12.5	9.8
12A/12B	12	208.7	141.1	5.0	7.1
30B	**30**	**2,277**	**1,540**	**5.0**	**77**
48A/X	48	21,030	14,219	4.5	640
48F	48	27,030	18,276	4.5	822
48G	48	26,840	18,148	1.0	181
48Y	**48**	**27,560**	**18,634**	**4.5**	**839**
48H/HX/OM	48	27,030	18,276	1.0	183

George Eccleston & Ed Wonder, NMMSS Users Group Meeting, Las Vegas, NV, May 18, 2010

Who Enriches Uranium?

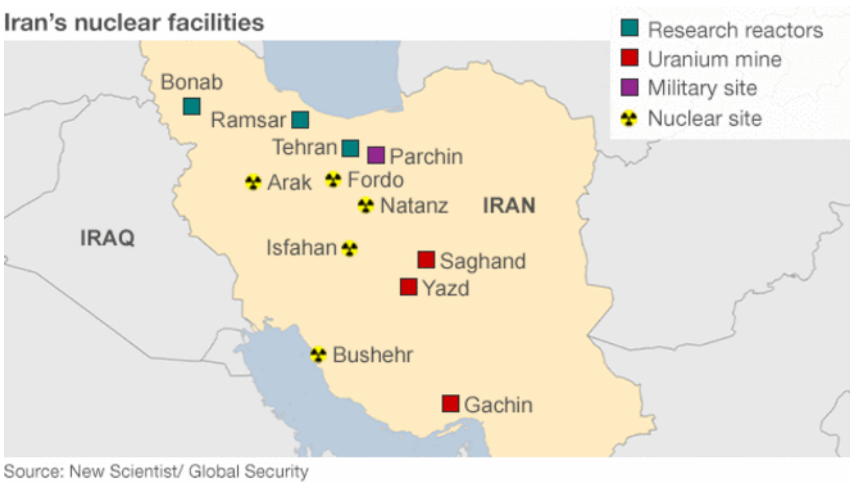
World Enrichment capacity – operational and planned (thousand SWU/yr)

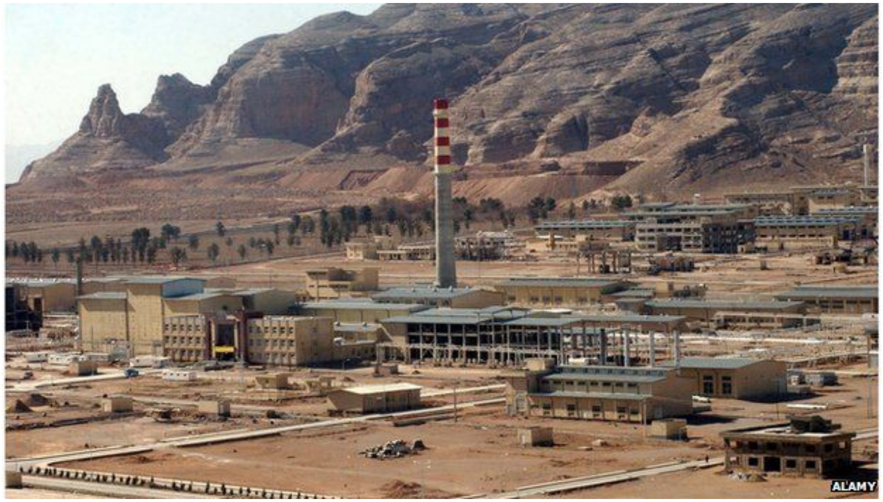
Country	Company and plant	2013	2015	2020
France	Areva, Georges Besse I & II	5500	7000	8200
Germany-Netherlands-UK	Urenco: Gronau, Germanu; Almelo, Netherlands; Capenhurst, UK.	14,200	14,200	15,700
Japan	JNFL, Rokkaasho	75	1050	1500
USA	USEC, Paducah & Piketon	0*	0	3800
USA	Urenco, New Mexico	3500	5700	5700
USA	Areva, Idaho Falls	0	0	3300?
USA	Global Laser Enrichment	0	0	3000?
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	26,000	30,000	37,000
China	CNNC, Hanzhun & Lanzhou	2200	3000	8000
Other	Various	75	500	1000?
	Total SWU/yr approx	**51,550**	**61,450**	**87,200**
	Requirements (*WNA reference scenario*)	49,154	51,425	59,939

http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Uranium-Enrichment/

Iran's Enrichment Facilities*

- Iran has declared enrichment sites at Natanz and Fordow
- It also conducts conversion operations at Isfahan**





*http://www.bbc.com/news/world-middle-east-11927720

**also spelled Esfahan per https://www.state.gov/documents/organization/245318.pdf

DPRK and Uranium Enrichment*

- 2010: Sig Hecker visits DPRK and is shown new enrichment facility at Yongbyon
  - Told there were 2000 centrifuges
- In February 2012, North Korea announced that it would suspend uranium enrichment at Yongbyon, and not conduct any further tests of nuclear weapons while productive negotiations involving the United States
- Restart of facilities occurred in 2013

*http://www.bbc.com/news/world-asia-pacific-11813699

Summary

- Conversion and enrichment of uranium is usually required to obtain material with enough ^{235}U to be usable as fuel in a reactor or weapon
- The cost, size, and complexity of practical conversion and enrichment facilities aid in non-proliferation by design
  - Although some approaches lend themselves more easily to proliferation than others