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Title: A Synopsis of Uranium Enrichment: The Technology, the Safeguards, and the International Concerns

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Form 836 (7/06)

TITLE: A Synopsis of Uranium Enrichment: The Technology, the Safeguards, and the International Concerns
AUTHOR: Brian D. Boyer

ABSTRACT:

Once during WWII it became apparent that enrichment of the uranium's U-235 isotope was needed to produce a uranium-fueled weapon, the U.S. raced to produce technologies to get an enrichment level capable of use in a weapon. While the gas centrifuge was too immature a technology to work during the wartime Manhattan Project, developments by captured German scientists in the USSR and later in the West made the gas centrifuge the state of the art for producing enriched uranium for peaceful use in power reactors by the last decades of the 20th Century. However, the technology drifted to States who could use this technology for building nuclear weapons. This talk covers the above issues and gives some insight into the technology and science behind enriching uranium. The speaker also will talk about International Atomic Energy Agency (IAEA) safeguards on enrichment and his own experiences as an IAEA inspector working in the field at various enrichment facilities. The talk will culminate in a discussion of the headlines and proliferation possibilities in Iran and other States with possible nuclear weaponization ambitions and how the world community might respond.

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The Pennsylvania State University Student Chapter of the INMM

A Synopsis of Uranium Enrichment: The Technology, the Safeguards, and the International Concerns

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Nuclear Nonproliferation Division / N-4
Los Alamos National Laboratory

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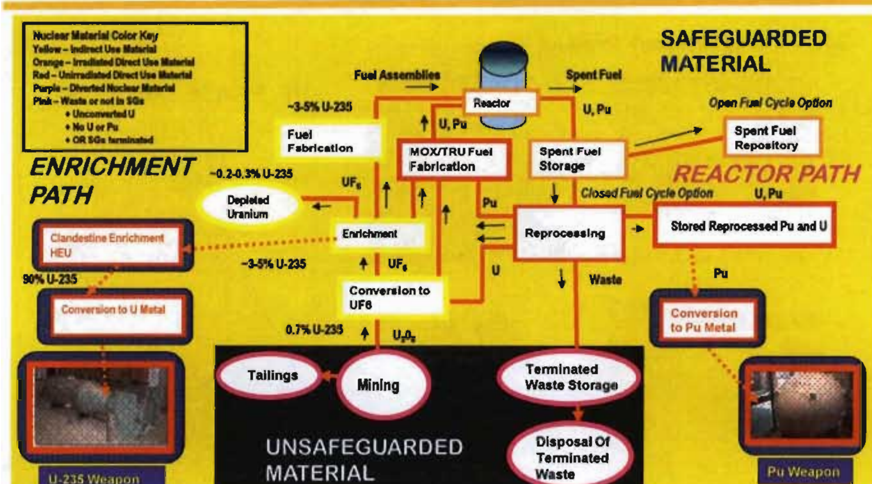
Nuclear Fuel Cycle – Proliferation Aspects

Enrichment – Key to the Uranium Path



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Safeguards Concerns at LEU GCEPs
Why So Much Concern Over Indirect Use Material?

Detectability of Undeclared Facilities		Detectability (Selected Criteria)		
		Identifiable Structure	Thermal Signature	Effluents
Plutonium Production	Reactor	Yes	Yes	No
	Reprocessing	No	No	(Yes)
Uranium Enrichment	Calutron/EMIS	No	Yes	Yes
	Gaseous diffusion	Yes	Yes	Yes
	Centrifuge	No	No	No

Enrichment with Centrifuges has potential to go from Natural Uranium or LEU to HEU By misuse of declared facility or through undeclared facility

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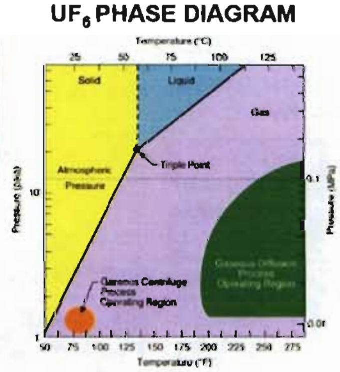
What is a UF6 Cylinder
Where U and U-235 Material Spend Most of Their Time

30B Product (2.5 ton)- Product

48G (14 ton) - Tails

UF$_6$ PHASE DIAGRAM



48Y (14 ton) - Feed

5a (25 kg) - HEU

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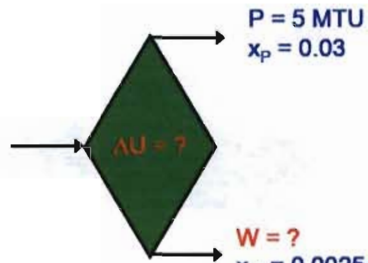
Enrichment Physics
Separative Work Problem



HOW MUCH SEPARATIVE WORK IS REQUIRED TO PRODUCE 5 MTU CONTAINING 3% ^{235}U FROM NATURAL FEED CONTAINING 0.711% ^{235}U WITH WASTE CONTAINING 0.25% ^{235}U?

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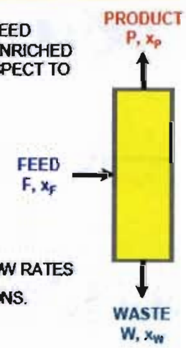
Separation Element Definitions

A *SEPARATING ELEMENT* DIVIDES A FEED STREAM INTO TWO STREAMS – ONE ENRICHED AND THE OTHER DEPLETED WITH RESPECT TO THE FEED



F, P, AND W ARE TOTAL URANIUM FLOW RATES

x_F, x_P, and x_W ARE ^{235}U CONCENTRATIONS.

NOTE THAT $x_P > x_F > x_W$

Where X_F is the concentration of ^{235}U in the feed stream
Where X_P is the concentration of ^{235}U in the product stream
Where X_W is the concentration of ^{235}U in the tails stream

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Solve for Masses

SOLVE FOR MASSES

TOTAL URANIUM: $F = P + W$

^{235}U: $Fx_F = Px_P + Wx_W$

$$\frac{F}{P} = \frac{1}{\theta} = \frac{(x_P - x_W)}{(x_F - x_W)} = \frac{0.03 - 0.0025}{0.00711 - 0.0025} = 5.9653$$

$$F = \left(\frac{F}{P}\right)P = 5.9653 \times 5\ \text{MTU} = 29.8265\ \text{MTU}$$

$$W = F - P = 29.8265 - 5 = 24.8265\ \text{MTU}$$

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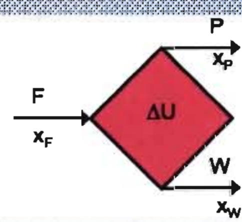
Define Value Function

$$\Delta U = P\,V(x_P) + W\,V(x_W) - F\,V(x_F)$$



$$V(x_P) = (2x_P - 1)\ln\left(\frac{x_P}{1 - x_P}\right)$$

$$V(x_W) = (2x_W - 1)\ln\left(\frac{x_W}{1 - x_W}\right)$$

$$V(x_F) = (2x_F - 1)\ln\left(\frac{x_F}{1 - x_F}\right)$$

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The Solution

$$\Delta U = P\,V(x_P) + W\,V(x_W) - F\,V(x_F)$$

MASS (MTU)	VALUE FUNCTION	COL. 1 × COL. 2 (MTU)
P = 5.0000	V(0.03) = 3.267533	16.338
W = 24.8265	V(0.0025) = 5.959017	147.941
F = 29.8265	V(0.00711) = 4.868883	145.222

$$\Delta U = 16.338 + 147.941 - 145.222 \text{ MTSWU}$$

$$= 19.057 \text{ MTSWU} = 19057 \text{ kgSWU}$$

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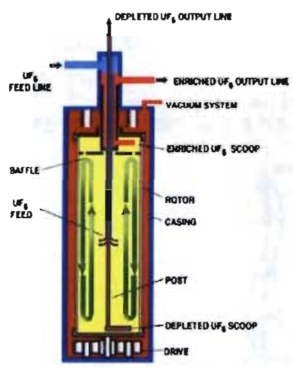
Technology for Enrichment
What Is a Centrifuge?



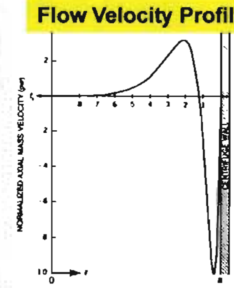
Schematic of Gas Centrifuge

Countercurrent Gas Centrifuge

- UF_6 gas enters the interior of the centrifuge from
  - Pipe at the center of the centrifuge rotor.
- Gas is removed
  - More ^{235}U at one end of centrifuge rotor
  - More ^{238}U at the opposite end of centrifuge rotor
- Gas is removed inside the centrifuge by
  - "Scoops" - stationary pipes

URENCO
Almelo, NL Plant
"WURX"

Flow Velocity Profile



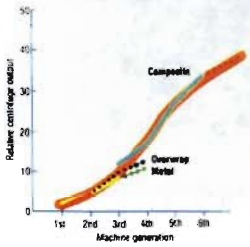
Source: ORNL - SAFEGUARDS TRAINING COURSE
NUCLEAR MATERIAL SAFEGUARDS FOR URANIUM ENRICHMENT PLANTS

Rotor Materials
Strength allows size and speed

- Need high strength-to-density ratio – speed stressed outer walls
- Calculating V_{max}, Maximum Peripheral Velocity with
  T = Tensile Strength (kg/mm²)
  = Density (g/cm³)

$$V_{max} = \sqrt{\frac{T}{\rho}}$$

Source: ORNL - SAFEGUARDS TRAINING COURSE
NUCLEAR MATERIAL SAFEGUARDS FOR URANIUM ENRICHMENT PLANTS



Material	T (kg/mm²)	(g/cm³)	V_{max}(m/sec)
Aluminum Alloy	50	2.8	425
Titanium Alloy	90	4.6	440
High-Tensile Steel	170	8	455
Maraging Steel	250-300	8.1	550-600
Glass Fiber/Resin	70	1.9	600
Carbon Fiber/Resin	160	1.55	950

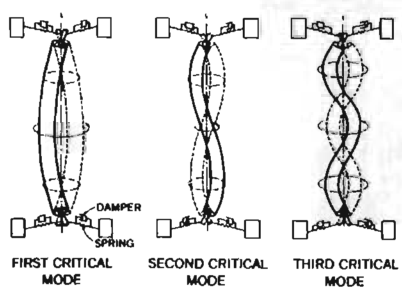
$$\omega = \frac{2\pi}{T} = 2\pi f = \left|\frac{V}{r}\right|$$

Relationship of Frequency and v

Challenges in Making Centrifuges

- Spinning the rotors at near bursting strength
- Run for years with low MTBF – repair or discard mode of operation
- Supercritical speeds
- Design and Fabrication
  - Low cost
  - Mass production
  - Thousands of machines
  - High quality standards

MODE SHAPES OF FIRST THREE FLEXURAL CRITICALS OF A CENTRIFUGE ROTOR



Source: ORNL - SAFEGUARDS TRAINING COURSE
NUCLEAR MATERIAL SAFEGUARDS FOR URANIUM ENRICHMENT PLANTS

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Centrifuge Data: Dimensions / Operating Conditions

3rd Workshop On Gases In Strong Rotation, Rome, 1979*

Radius Of Centrifuge, a = 25 cm, Z = 500 cm	Assume: Z>> a
Optimum Rectifier Length, Z^*_p = determined by axial position of feed length, Z_p	Z (1 - θ)(1 + L/F) / (1- θ + L/F)
Countercurrent-to-feed ratio, k	Assume μL/F* = 2
Feed rate, F F ~ F*	51.4 mg/s of UF6
Cut, θ	Assume ~ 0.5
Radii of two-shell profile, r_1, r_2	in m
Average Operating Temperature, T_0	320°K
Pressure At Rotor Wall, p(a)	100 torr
Peripheral Velocity of Centrifuge, v_a	600 m/s
Uranium Gas-Phase Inventory	~50 g U
Molecular Weight of the Process Gas, M	0.352 kg/mole UF_6
Mass Difference Between The Components, ΔM	3
The Gas Constant, R	8.31×10^7 erg/mol/°K
No. of Scale Heights In Centrifuge, A^2 with $A^2 = MV^2/(2RT_0)$	23.8
Density Diffusivity of UF_6 at Temperature T_0, ρD	2.4×10^{-5} kg/m-s

Assume that $r_2/a \sim 0.975$ Assumption from Rätz, *Analytische Lösungen*

Assume ρ = 1000 kg/m³

***The ROME MACHINE**

Composite standard centrifuge useful for academic research and discussion in open forum

Source: ORNL - SAFEGUARDS TRAINING COURSE
NUCLEAR MATERIAL SAFEGUARDS FOR URANIUM ENRICHMENT PLANTS

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Centrifuge Design

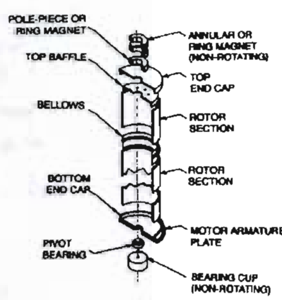
Maximum Theoretical Separative Capacity Equation

P.A.M. Dirac Equation

$$\Delta U(max) = \frac{\rho D \pi Z}{2}\left[\frac{\Delta M V^2}{2RT_0}\right]^2$$

With Z = Length of the Centrifuge:

1. **ΔU(max)** is proportional to **Z**
2. **ΔU(max)** is proportional to **V⁴**
3. **ΔU(max)** is independent of **a**



Source: ORNL - SAFEGUARDS TRAINING COURSE
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Centrifuge Design

Maximum Theoretical Separative Capacity Equation

E. Rätz Equation(1983) Ph.D. Thesis T.U. Berlin –
Analytische Loesungen fuer die Trennleistung von Gaszentrifugen zur Urananreicherung

$$\delta U_{\mathrm{Raetz}}(L, F, \theta, Z_P) = \frac{1}{2} F\,\theta(1-\theta)\left(\frac{\Delta M}{2RT}v_a^2\right)^2 \left(\frac{r_2}{a}\right)^4 \left[1-\left(\frac{r_1}{r_2}\right)^2\right]^2$$
$$\times \left[\left(\frac{1+L/F}{\theta}\right)(1-\exp[-A_P(L, F, \theta)Z_P]) + \left(\frac{L/F}{1-\theta}\right)\{1-\exp[-A_W(L, F, \theta)(Z-Z_P)]\}\right]^2$$

Where

$$A_P = \frac{2\pi D\rho}{\ln(r_2/r_1)}\,\frac{1}{F}\,\frac{\theta}{(1+L/F)(1-\theta+L/F)}$$

and $$A_W = \frac{2\pi D\rho}{\ln(r_2/r_1)}\,\frac{1}{F}\,\frac{(1-\theta)}{(L/F)(1-\theta+L/F)}$$

$$D\,p = \frac{RT}{M}D\rho = const. \quad \text{and} \quad D\rho \approx 2.2\times10^{-5}\ \mathrm{kg/(m\,s)}$$

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Centrifuge Design

Maximum Theoretical Separative Capacity Equation

Mass Velocity Profile and defining r_1 and r_2 – from E. Raetz work

For Slower Machines

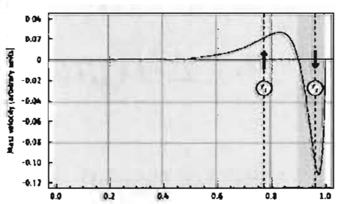
$$\max\left\{\left[1-\left(\frac{r_1}{r_2}\right)^2\right]^2 \times \left[\ln\left(\frac{r_2}{r_1}\right)\right]^{-1}\right\} \rightarrow \left(\frac{r_1}{r_2}\right) \approx 0.534$$

Rätz, *Analytische Lösungen*, ch. 8, p. 8.17.

For Fast Machines

$$\left(\frac{r_1}{r_2}\right) \approx \left(\frac{r_1}{a}\right) = \sqrt{1-\frac{2RT}{M}(\ln x)\frac{1}{v_a^2}}$$

Assume pressure ratio *x of, say, 1000:1* Rätz, *Analytische Lösungen*, ch. 2, pp. 2.4–2.5.



Typical mass-velocity profile for centrifuge

This table gives K values for the equation $\Delta U \propto V^K$

Rotor velocity (m/s)	Separative capacity Scaling Exponent, K
313	4
344	3.4
438	2.7
563	2.4
751	2.2

Reference: E. Raetz, "Uranium isotope separation in the gas centrifuge", presented at the VKI lecture series on aerodynamic separation of gases and isotopes, May 29-June 3, 1978, The Von Karman Institute for Fluid Dynamics, Belgium, 1978.

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Compare Dirac vs. Rätz for Rome Machine From Our Dirac and Rätz Equations

Dirac	**Rätz**
166 SWU/yr	**35.0 SWU/yr**

Eff. = 21%

1) Dirac overestimates the SWU capacity of faster machines – Rätz is more empirical and gives a better estimate of performance. (V^4 vs. V^2)

2) My conversations with URENCO engineers shows that URENCO has a lot of empirical engineering experience that the textbook equations do not show.

3) What URENCO knows – classified and proprietary

4) You cannot look at a CENTRIFUGE and "eyeball" performance

Source: Carl Taylor – Urenco (Jan 2011) – TC11 vs. TC12

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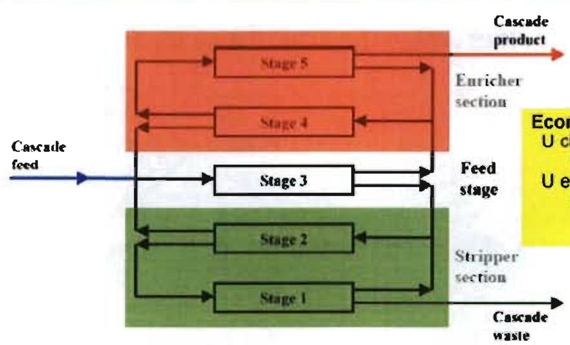
Enricher and Stripper Sections

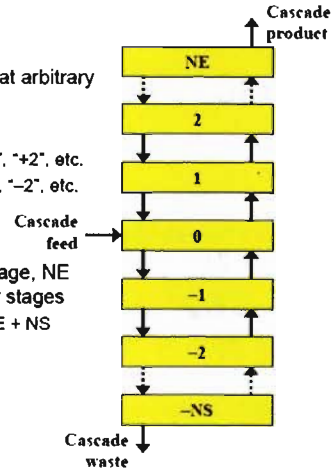


Economics dictates staging
- U cheap
  - More enriching
- U expensive
  - More stripping

- ENRICHER SECTION: ALL STAGES "ABOVE" THE FEED STAGE
  - ADD ENRICHER STAGES TO INCREASE % ^{235}U OF CASCADE PRODUCT
- STRIPPER SECTION: ALL STAGES "BELOW" THE FEED STAGE
  - ADD STRIPPER STAGES TO DECREASE CASCADE UF_6 FEED REQUIREMENT

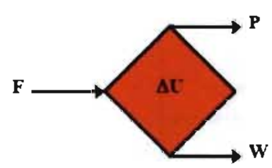
Stage Numbering and Order

- Numbering of stages is somewhat arbitrary
- Equations are simplest if
  - Feed stage is labeled "0"
  - Enricher stages are labeled "+1", "+2", etc.
  - Stripper stages are labeled "−1", "−2", etc.
- Cascade consists of one feed stage, NE enricher stages, and NS stripper stages
  - Total number of stages = 1 + NE + NS



Determining Size of a Cascade

- **FOUR Parameters define the size of a cascade**
  - F
  - P
  - W
  - $\Delta U = N_{cent}\,\Delta u$



- **Given any one of these parameters – determine other 3 using**
  - $P = \theta F$
  - $W = (1-\theta)F$
  - $\Delta U = (\Delta U/F)F$
  - $N_{cent} = \Delta U / \Delta u$

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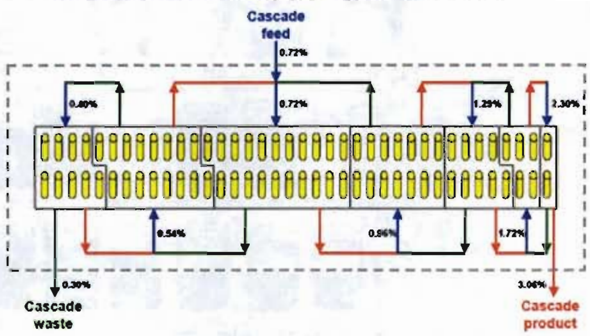
A Typical Layout

- Centrifuges usually arranged in two parallel rows
- Stages determined by piping, not location



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Safeguards Concerns at LEU GCEPs
Three Major Concerns and IAEA Goals

- **Safeguards Concerns**
  - Production of a SQ of undeclared HEU (≥20% ^{235}U)
    - ➢ Misuse of plant to create HEU for weapons program
  - Diversion of a SQ of declared LEU, NU, or DU (DNLEU)
    - ➢ Divert declared material for weapons program and enrich in clandestine HEU plant
  - Production of LEU in excess of declared amounts
    - ➢ Take undeclared material / enrich as feed for weapons program clandestine HEU plant

- **IAEA Safeguards Detection Goals (Quantity & Timeliness)**
  - Detection of HEU (≥20% ^{235}U) Production
    - ➢ Detect 25 kg ^{235}U in U in one MONTH
  - Detection of Diversion of DNLEU (<20% ^{235}U)
    - ➢ Detect 75 kg ^{235}U in U in one YEAR

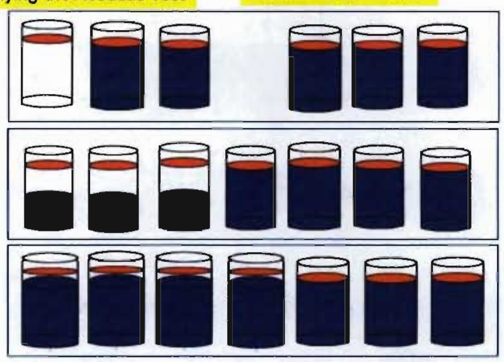
IAEA Accountancy Verification Methods
Application to Centrifuge – Cylinder Verification

- Three levels of defects to detect with NDA Instruments – Key concept
  - *Gross defect*
  - *Partial defect*
  - *Bias defect*

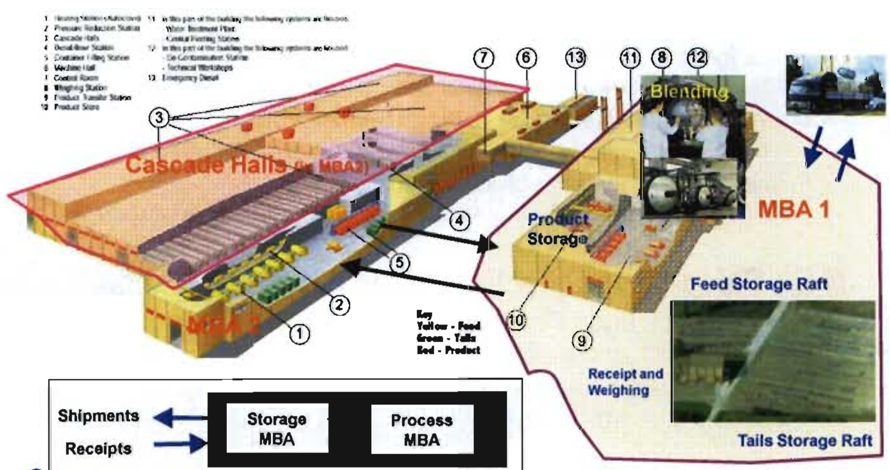
Applying the Acoustic Test

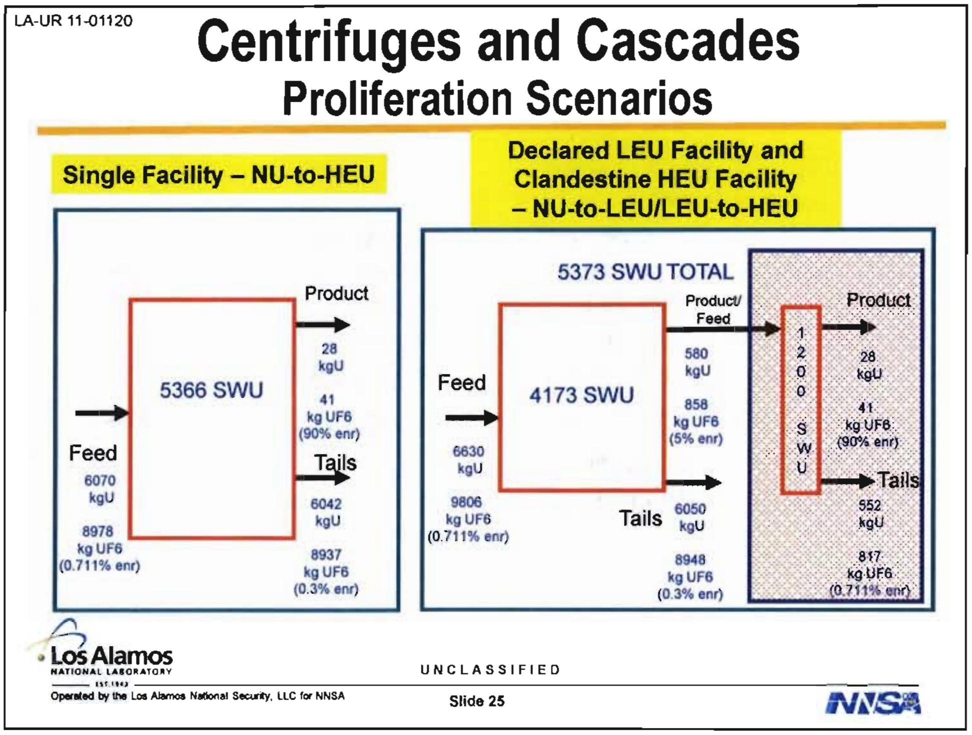
Product to be verified

- Examples in GCEPS:
  - *Gross defect*
    - No U present
    - Cylinder diverted
  - *Partial defect*
    - Lower ^{235}U content
    - Part of U missing
  - *Bias defect*
    - Minor ^{235}U content change
    - Detectable at bias level only



Gas Centrifuge Enrichment Plant (GCEP)
Process Areas

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Centrifuges and Cascades
Proliferation Scenarios
Single Facility – NU-to-HEU
Product
5366 SWU
28
kgU
41
kg UF6
(90% enr)
Tails
Feed
6070
kgU
8978
kg UF6
(0.711% enr)
6042
kgU
8937
kg UF6
(0.3% enr)
Declared LEU Facility and
Clandestine HEU Facility
– NU-to-LEU/LEU-to-HEU
5373 SWU TOTAL
Product/
Feed
Feed
4173 SWU
580
kgU
858
kg UF6
(5% enr)
6630
kgU
9806
kg UF6
(0.711% enr)
Tails
6050
kgU
8948
kg UF6
(0.3% enr)
1200 SWU
Product
28
kgU
41
kg UF6
(90% enr)
Tails
552
kgU
817
kg UF6
(0.711% enr)
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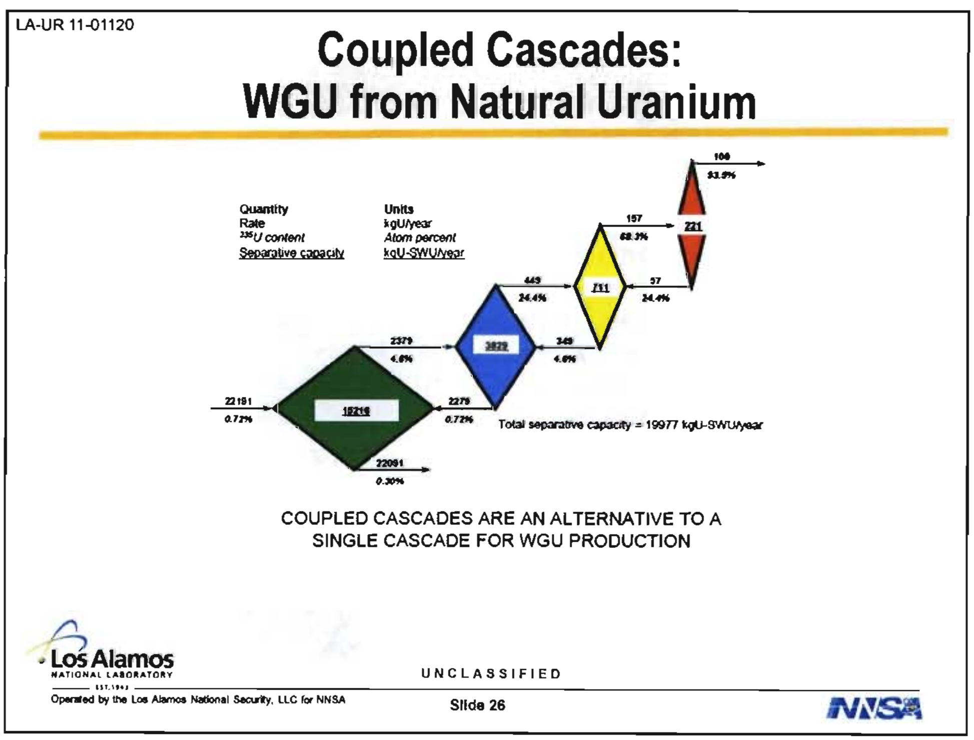
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Coupled Cascades:
WGU from Natural Uranium
Quantity
Rate
235U content
Separative capacity
Units
kgU/year
Atom percent
kgU-SWU/year
100
157
221
449
24.4%
711
57
24.4%
2379
4.6%
3829
349
4.6%
22191
0.72%
15216
2279
0.72%
Total separative capacity = 19977 kgU-SWU/year
22091
0.30%
COUPLED CASCADES ARE AN ALTERNATIVE TO A
SINGLE CASCADE FOR WGU PRODUCTION
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IAEA Measures to Detect Diversion of Uranium

- Inspection regime includes:
  - Annual PIT/PIV
  - 11 monthly interim inspections for flow verification
  - IAEA verifies feed, product, and tails cylinders - receipts and shipments
    - ➢ OPERATOR holds feed before feeding to process
    - ➢ OPERATOR holds tails and product before shipment off-site
- Auditing of records and reports (ICR, PIL, MBR)
- Verification of nuclear material quantities (flows and inventories)
- Material balance evaluation
- Application of seals to UF_6 cylinders

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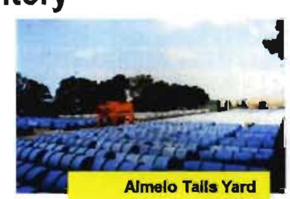
Performing Verification of UF6 Cylinder

- **PIV or IIV – shipments/receipts**
  - PIV or IIV – Cylinders in Process
  - PIV or IIV – Sampling of Cylinders
    - ➢ By Stratum
    - ➢ UFN, UFE, UFD – Feed, Product, Tails
    - ➢ Method H – NDA– acoustic, detect with NDA U, ^{235}U
    - ➢ Method F,B – NDA – weigh cylinder, get ^{235}U enrichment with NDA
    - ➢ Method D,B – DA samples - weigh cylinder, take DA sample for ^{235}U enrichment


URENCO Process F/W Stations


Almelo Product Store

- **PIV - Static UFD tails cylinder inventory**
  - PIV - Sampling of Cylinders
    - ➢ UFD - Tails
    - ➢ Method H,F,B


Almelo Tails Yard

Iran - Questions for IAEA BOG and UNSC

- **Iran has enough LEU feed for weapon**
- **>3/4 of the SWU for getting 90% HEU complete**
- **Will Iran divert LEU to Qom? Make HEU at Qom?**
- **Will Iran breakout at Natanz? Qom?**
- **Can Iran make HEU?**
- **STUXNET – what is the result?**
- **Less than optimal LEU production so far**
- **Breakout? 3 months? 6 months?**
- **Consequences?**
  - More sanctions?
  - More isolation?
  - Military action?

IAEA Nackaerts and Yonemura– Fall 2009 Trip to Qom

Summary of Gas Centrifuge Enrichment

- Present SOA enrichment technology
  - How much future improvements are possible?
  - Challenge from GE Hitachi – GLE – laser enrichment?
- Safeguards – what to reach for in the future
  - Unattended systems – flow (mass) and enrichment
  - RFIDs/Laser ID – follow cylinders
- Sensitive technology – export/import watch
- Will more States try to be like DPRK?
  - DPRK has bomb – wasn't attacked
  - Iraq had no bomb – attacked
  - Libya gave up weapons works – regime collapsed
  - Lesson for Iran and others?

Centrifuges From Libya

Former LANL Director Sig Hecker in DPRK

LA-UR 11-01120

Iran – GCEPs In the News – Status 2011

NU to LEU

	Conversion NU UF6	FEP Feed	Product	Tails
kg UF6	371000	64366	4543	59823
Purity	0.6761	0.6761	0.6761	0.6761
kg U	250833	43518	3071	40446
Enrichment	0.711%	0.711%	3.490%	0.5%
kg U-235	1783	309	107	202
SQ DNLEU U-235	24	4.1	1.4	2.7
SQ U-235 (25kg)	71	12.4	4.3	8.1
Cylinders 48 in	30	5		5
Cylinders 30 in			2	

LEU to HEU

	PFEP Feed	PFEP Product	PFEP Tails
kg UF6	673	71	602
Purity	0.6761	0.6761	0.6761
kg U	455	48	407
Enrichment	3.490%	20%	1.6%
kg U-235	16	9.6	6.3
SQ DNLEU U-235	4.1	[redacted]	0.08
SQ U-235 (25kg)	0.6	0.4	0.3
Cylinders 30 in	0.3		0.3
Cylinders 5 in		2	

Isfahan UCF

Natanz FEP
PFEP GCEP

Qom GCEP

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Iran Dilemma – GCEPs In the News – Status 2011

ASSUME Centrifuges have separative capacity of 0.89 SWU/yr from D. Albright analysis

STAGE	CYCLE 1 Feed U235 atom%	CYCLE 2 Cut	CYCLE 3 Feed Rate (kgU/yr)	CYCLE 4 Sep Cap (SWU/yr)	# of Cent./Cascade
9	3.0%	16.9%	58.0%	90.4%	2.8
8	2.6%	14.4%	53.3%	88.6%	5.3
7	2.2%	12.2%	48.5%	86.5%	7.4
6	1.9%	10.3%	43.7%	84.1%	9.3
5	1.6%	8.6%	39.1%	81.3%	11.1
4	1.4%	7.2%	34.6%	78.3%	12.8
3	1.2%	6.1%	30.4%	74.8%	14.4
2	0.98%	5.1%	26.5%	71.0%	16.1
1	0.84%	4.2%	23.0%	67.0%	17.9
FEED 0	0.71%	3.5%	19.8%	62.6%	19.9
-1	0.61%	2.9%	16.9%	58.0%	16.0
-2	0.52%	2.4%	14.4%	53.3%	12.5
-3	0.44%	2.0%	12.2%	48.5%	9.3
-4	0.37%	1.7%	10.3%	43.7%	6.2
-5	0.32%	1.4%	8.6%	39.1%	3.1
FINAL XP	3.5%	19.7%	62.6%	91.9%	164.0
FINAL XW	0.27%	1.1%	7.2%	34.6%	
CASCADES	53	32	32	6	
TIME (DAYS		105	17	23	
PREP		14	14	14	
TOTAL DAYS	173				

Gregory S. Jones assessed that Iran could currently enrich a stock of 3.5 percent LEU and existing 19.75 percent LEU to enough weapon-grade material for one bomb's worth in 62 days at the FEP.
The Washington Post, The New Republic, and a Bipartisan Policy Center publication

D. Albright analysis = 6 months for breakout

My one afternoon rough estimate = 6 months