From Charlottesville to Natanz: The Journey of the Gas Centrifuge

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Overview

- Introduction
- History
- How a centrifuge works
- Cascades
- How proliferators might operate a cascade
- Safeguards counter methods
- Conclusions
- Recommendations

Terminology

- Gas centrifuge – a device that can alter the isotopic composition of material.
- Isotope – one of two or more atoms having the same atomic number but different mass numbers.
- Enrichment – increased abundance of a desired isotope.

Uranium

- Natural uranium has two isotopes – ^{235}U and ^{238}U.
- ^{235}U is an atomic fuel.
- Natural uranium contains 0.711% ^{235}U.
- ^{235}U is enriched to ~5% for power reactors and ~90% for weapons.
- Uranium can be in a gas state as UF_6.

Introduction

- Gas centrifuges are the economic choice for enriching uranium.
- Gas centrifuge cascades are more easily concealed than other processes.
- Technology tightly guarded by most nations.
- Technology spread by a clandestine network.
- Difficult for inspectors to get information they need to assess what is being produced.

Early Days

- Isotopes were discovered in early 1900's.
- Centrifuge separation of isotopes first suggested by Lindemann and Aston (1919)
- Chapman, Mulliken, Harkens and others tried unsuccessful experiments.
- First successful experiments at UVA in 1934 by Prof. Jesse Beams with isotopes of Chlorine.
- Attempts to use centrifuges in Manhattan project were unsuccessful.

Professor Jesse W. Beams

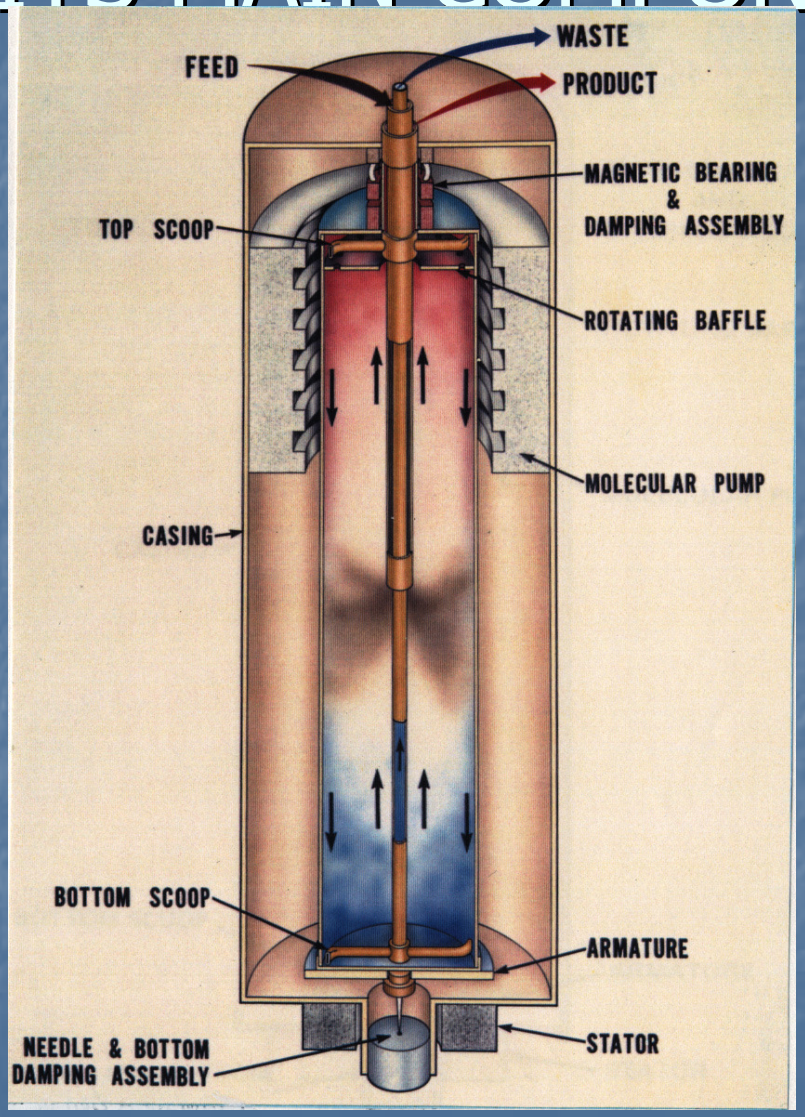
University of Virginia
1898 - 1977

Dr. Gernot Zippe

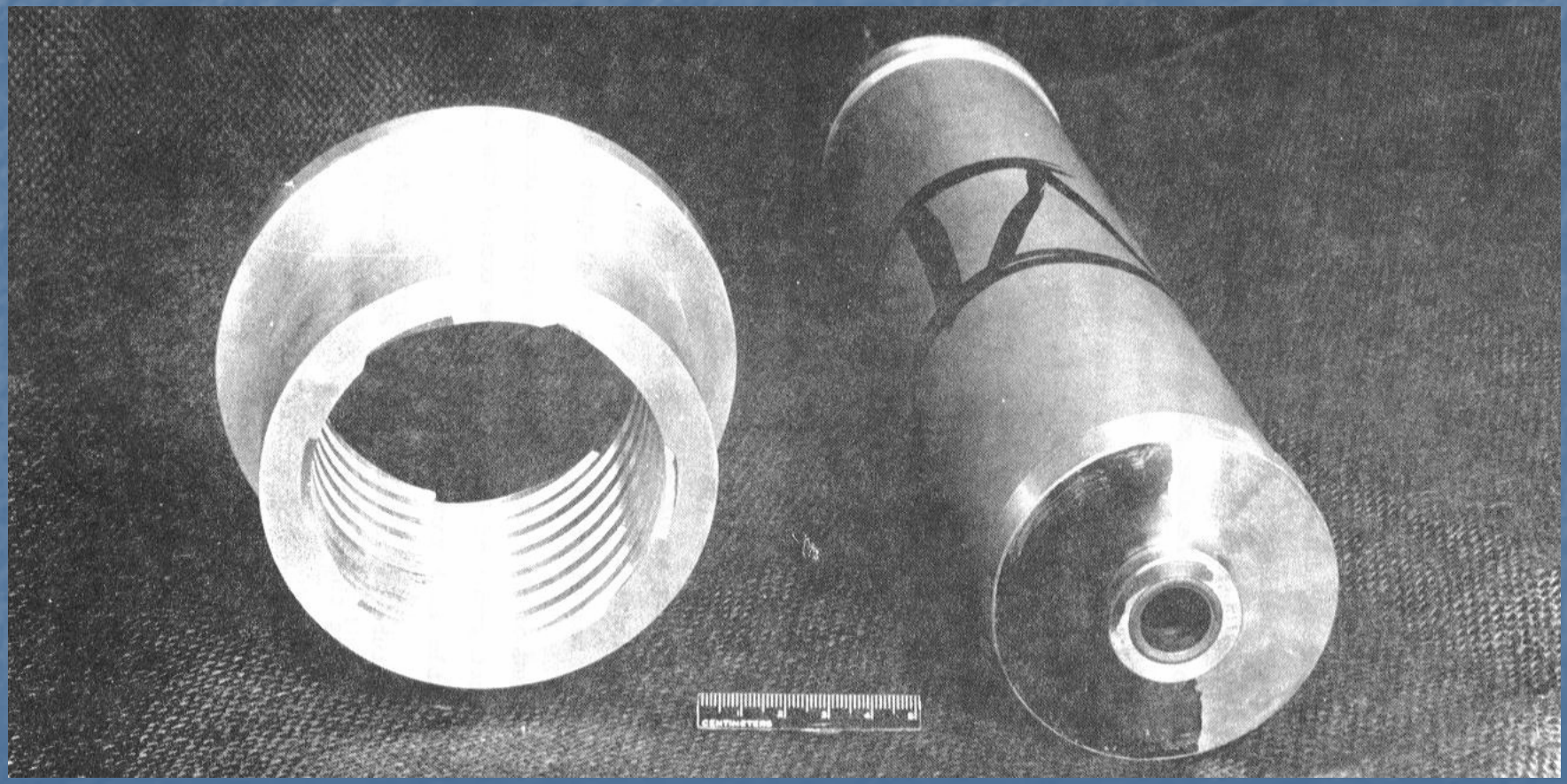
- He was a flight instructor for Germany during WW II.
- Became POW in Russia after the War.
- He and Steenbeck made a deal with Russians to build gas centrifuges.
- After 7 years, Zippe was finished with the project. Given freedom 3 years later.
- Worked with Prof. Beams at UVA 1958-1960

Zippe's Return to Russia in 2000

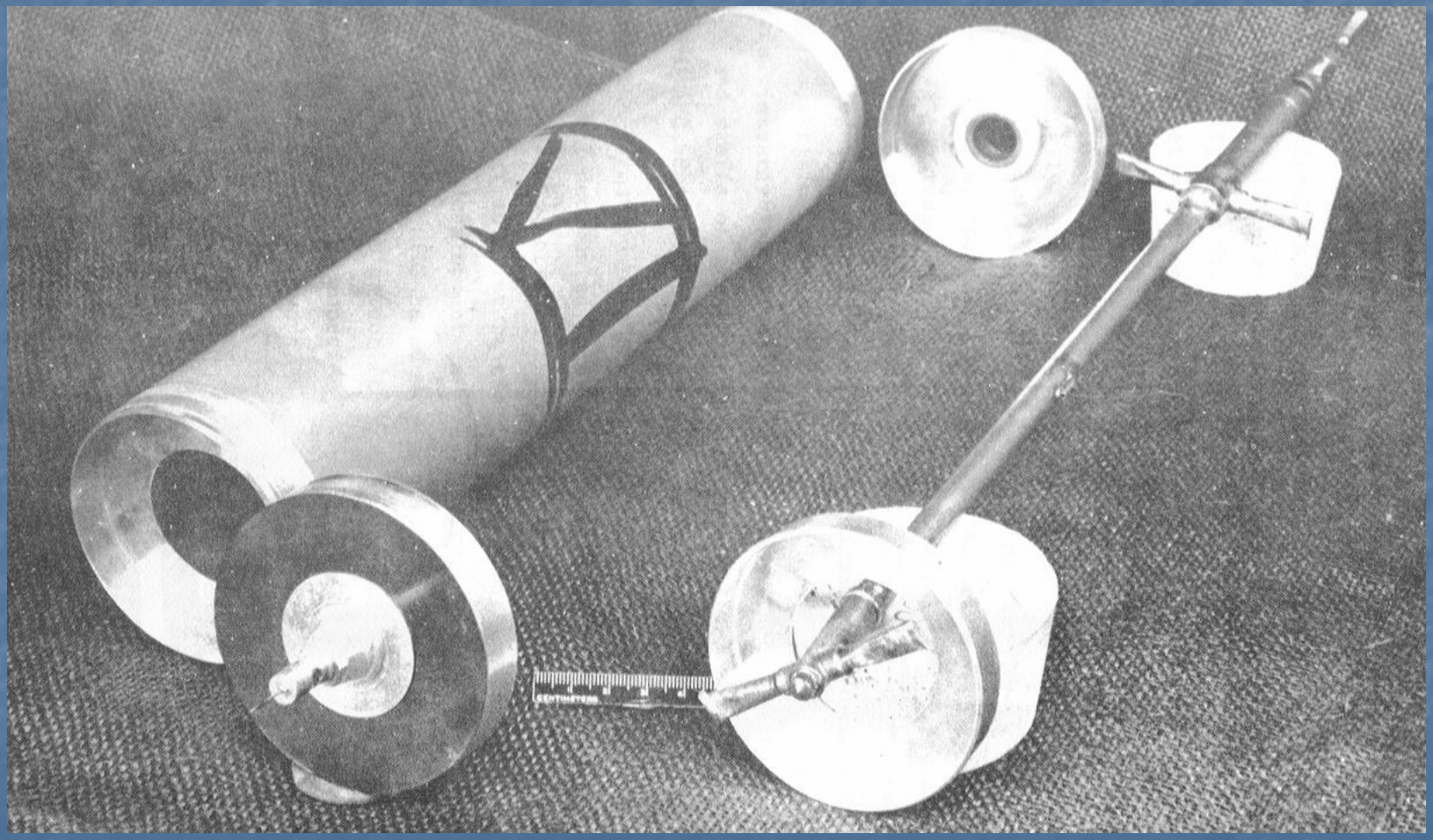
THE MODERN GAS CENTRIFUGE AND ITS MAIN COMPONENTS



Molecular Pump & Rotor



Scoop Assembly



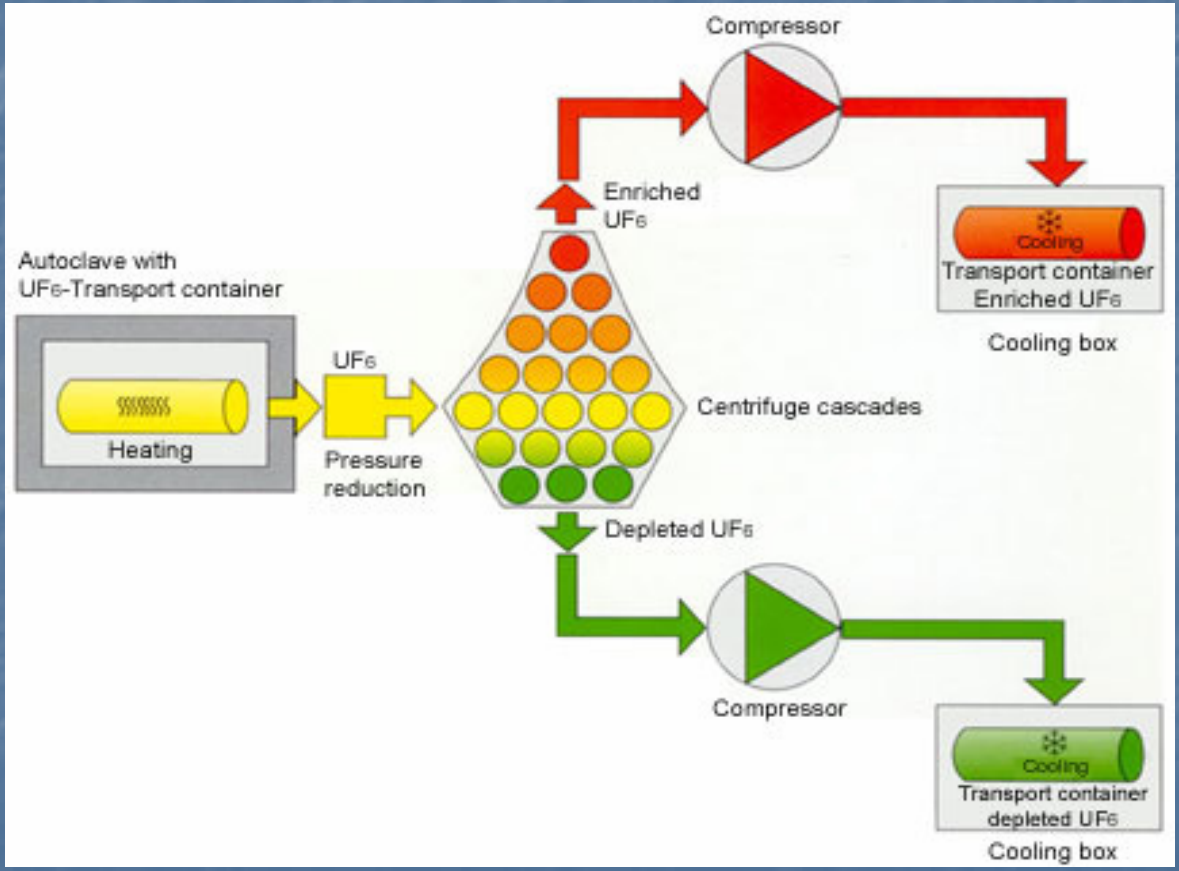
Cascades

- Centrifuges do not generally produce desired enrichment in one machine.
- Machines are connected in series to attain the desired enrichment and in parallel to attain the desired product flow rate.
- This arrangement is called a *Cascade*.
- The amount of enrichment performed is called Separative Work and is measured in Separative Work Units (SWU).
- SWU usually has units kgU/year.

Centrifuge Characteristics

Materials	Speed (m/sec)	Diameter (meters)	Length (meters)	SWU kgU/yr
Aluminum, maraging steel, Carbon fiber	350 to >1000	0.13 – 0.60	0.5 - 15	1 - 400

Cascade Schematic



After 1960

- Based on Beams and Zippe's work, U.S. began development of gas centrifuges to replace gaseous diffusion.
- Zippe went to Europe and helped start EURENCO – a consortium of Britain, Germany and Netherlands.

Other Developments

- Other countries began independent programs to develop centrifuges including France, Italy, Japan, Sweden.
- All work was highly classified.
- It was not public knowledge that Russia had gas centrifuge plants until the 1990's.
- China had R&D efforts, but purchased plants from Russia in the 1990's.

Kurchotov Institute - Moscow

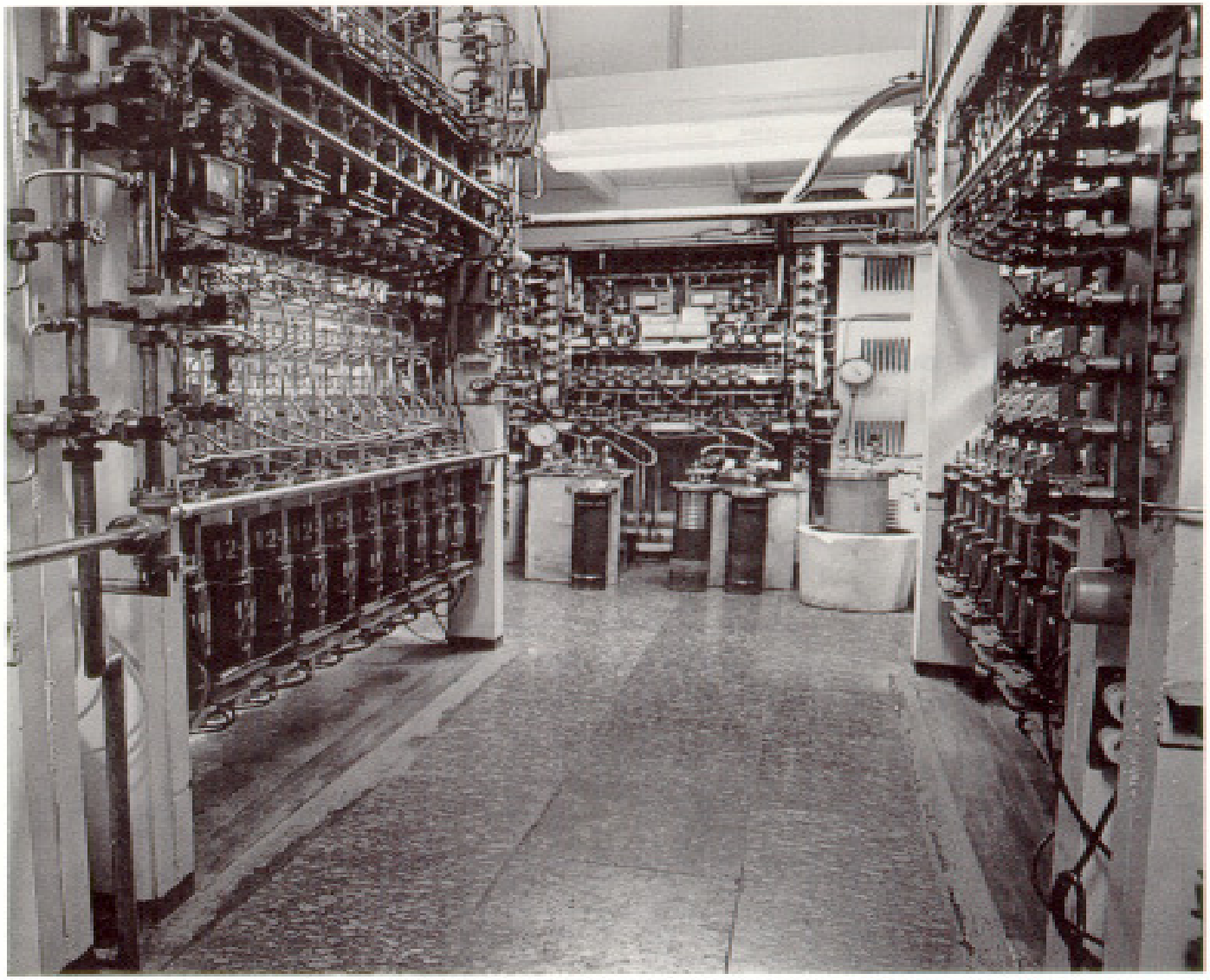


Fig. 2. The separation centrifuge facility for production of chromium-50.

Kurchotov Institute - Moscow

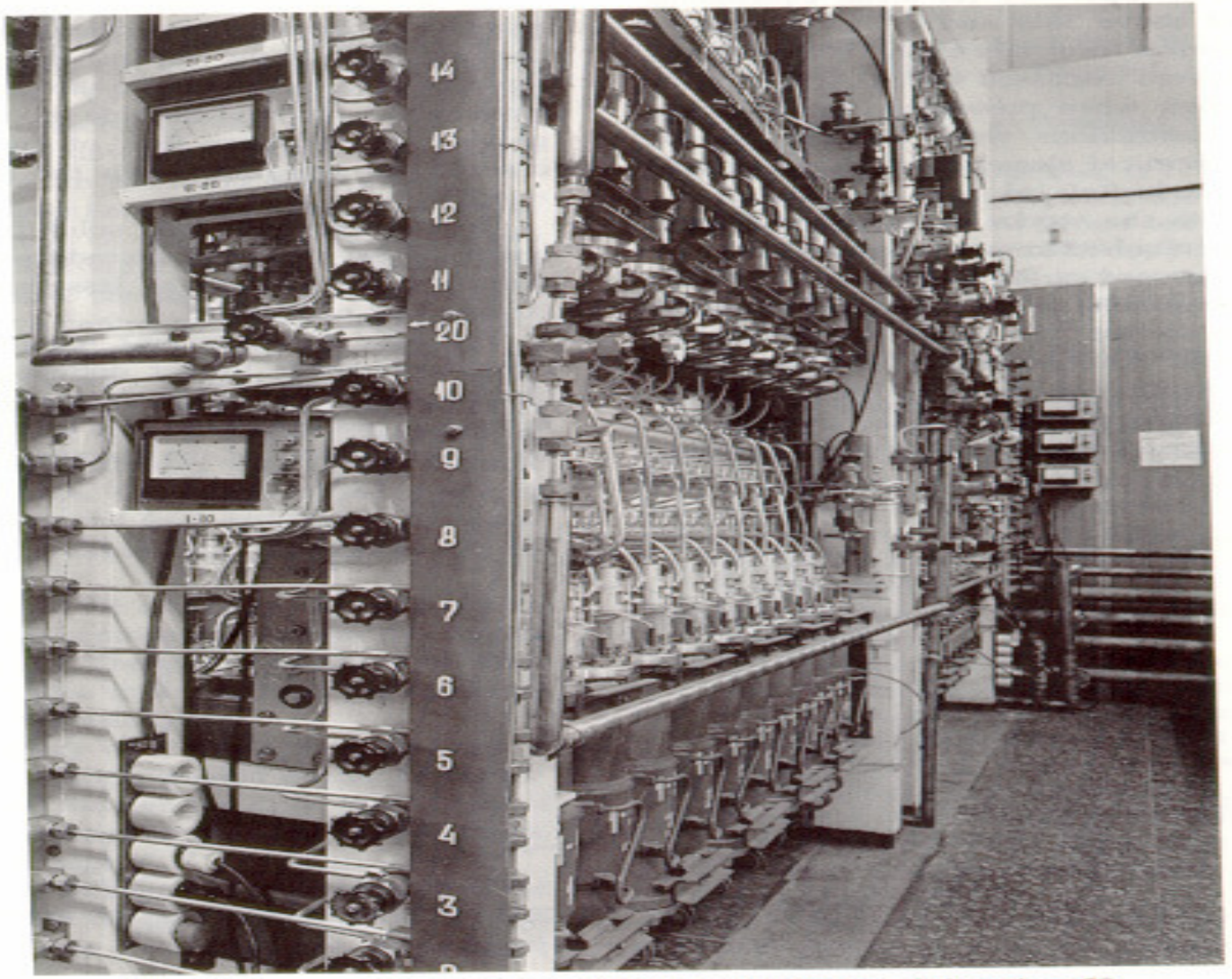


Fig. 3. The separation centrifuge facility for production of chromium-50.

Source: Zippe G., Development and status of gas centrifuge technology, *Proc. 7th Workshop on Separation Phenomena in Liquids and Gases,* July 24-28, 2000, Moscow, Russia, pp.35-53.

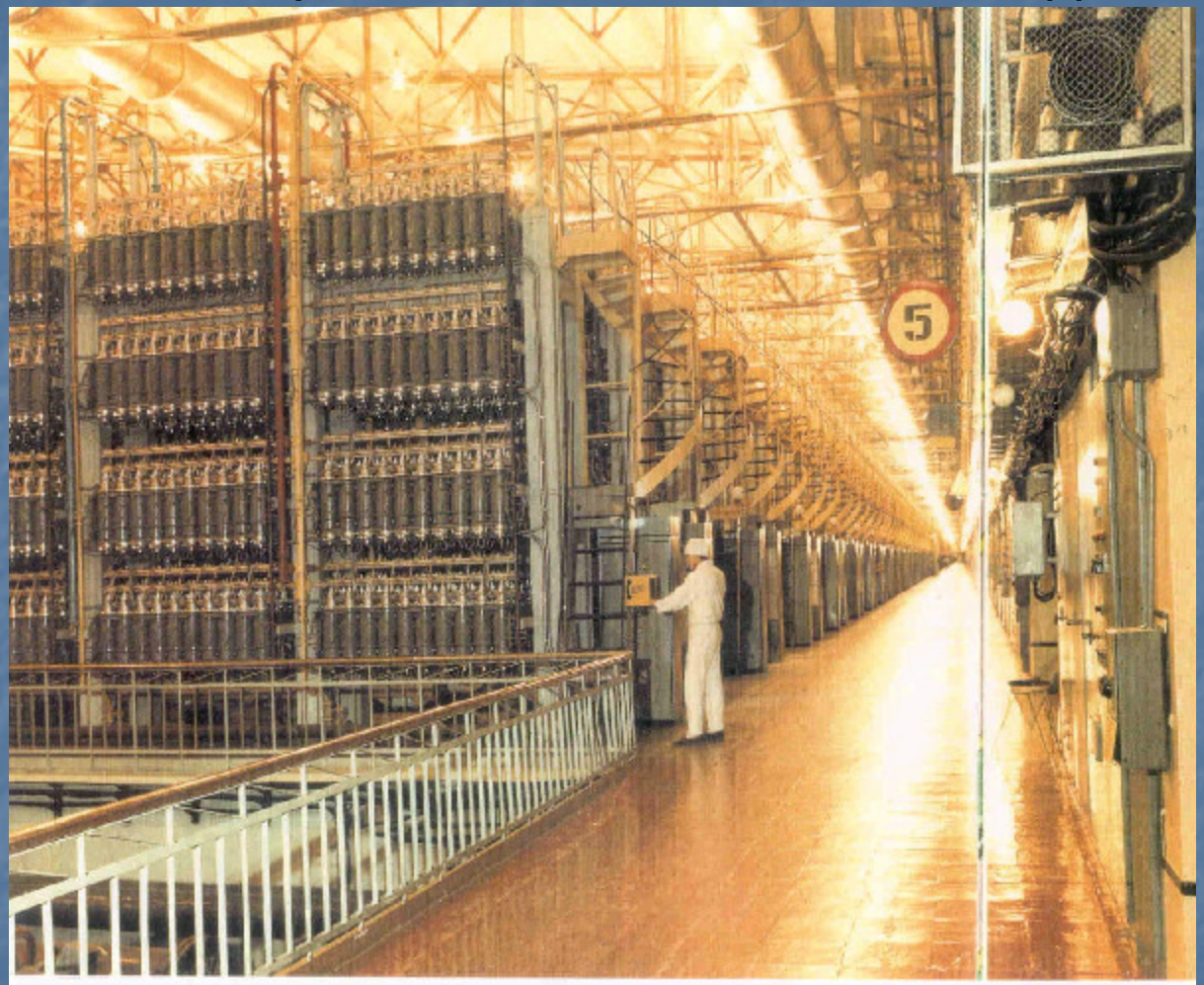
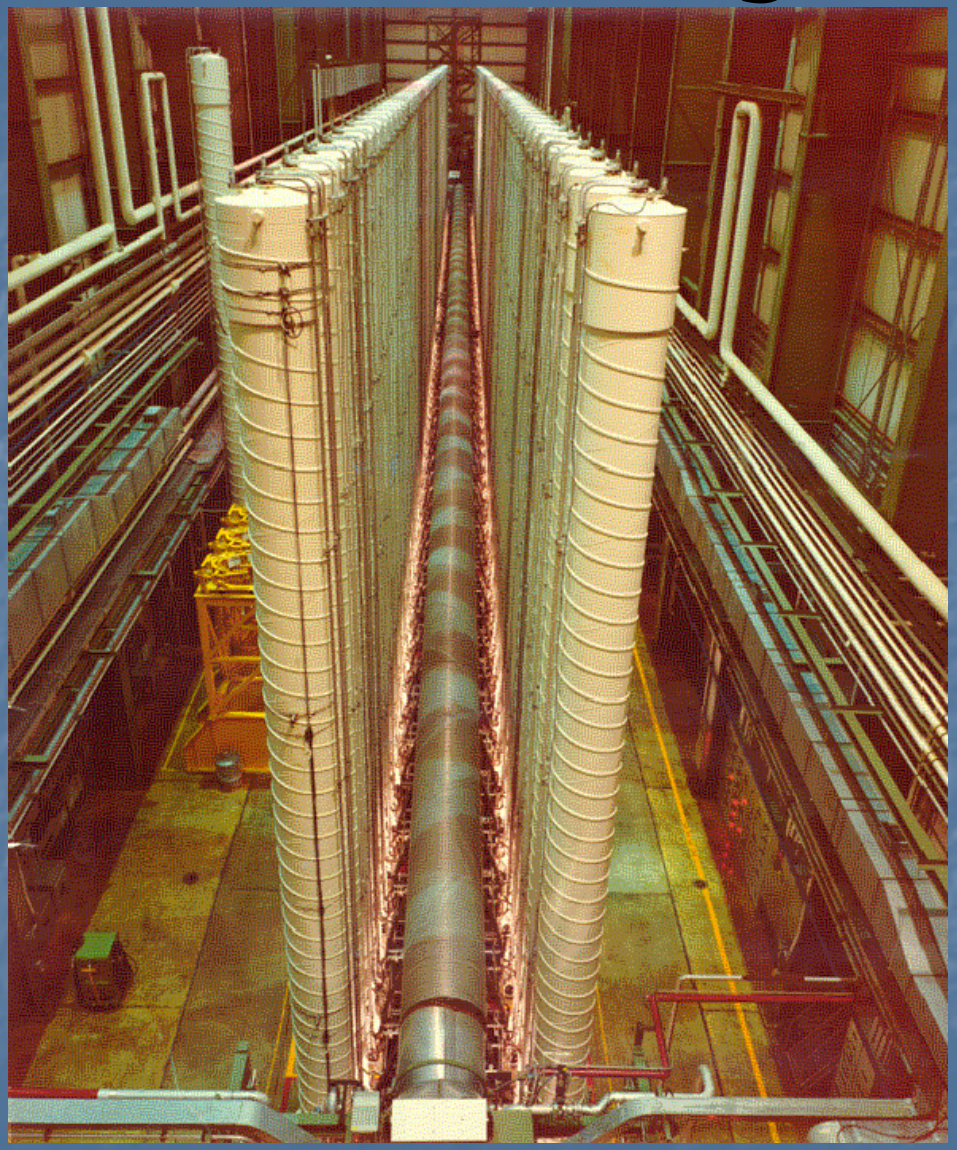
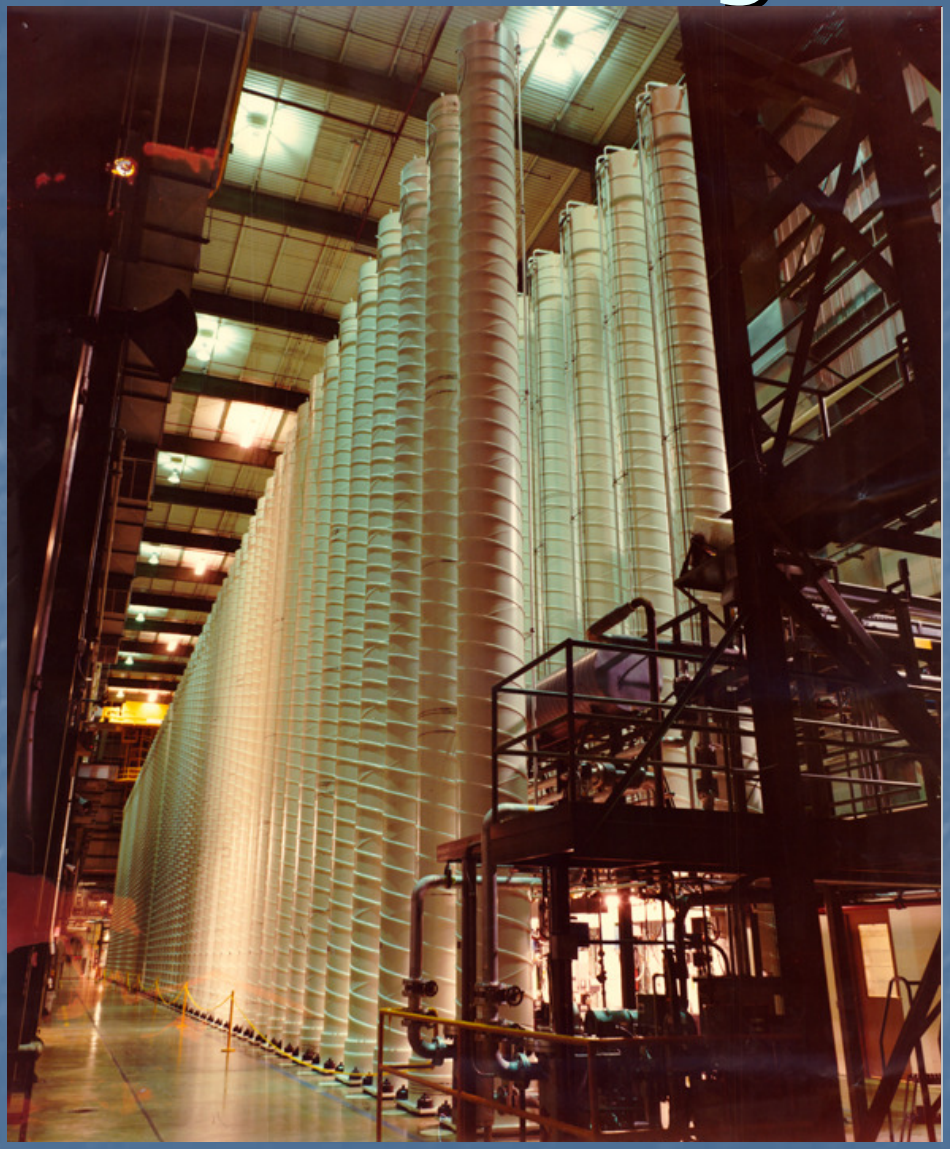


Fig. 9: Subcritical, short Centrifuges in Russia

U.S. Centrifuges



U.S. Centrifuges



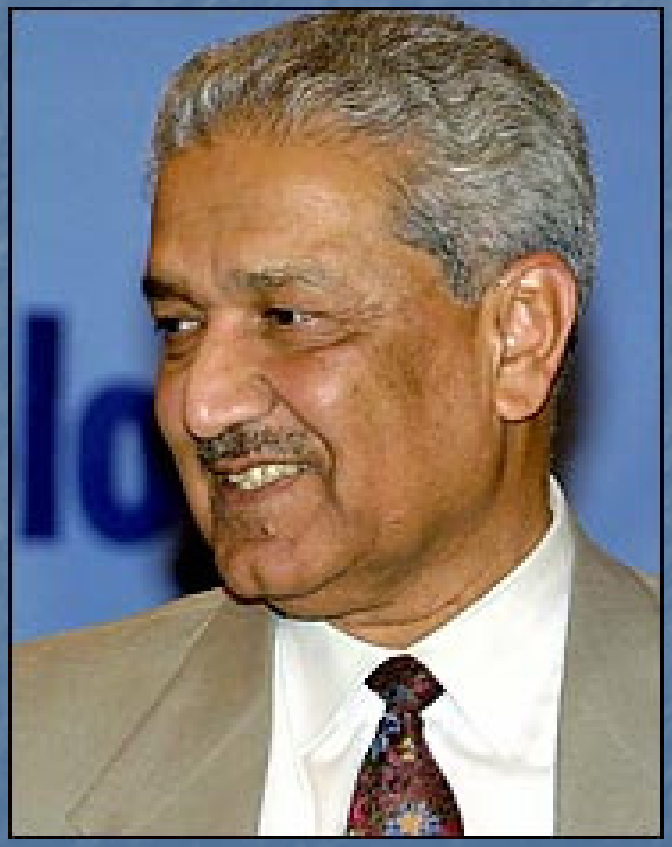
Centrifuge Hall / Almelo

URENCO / Almelo, Netherlands

Dr. A. Q. Khan

- Native Pakistani who worked for Urenco in the Netherlands.
- Defected with drawings circa 1974
- Developed gas centrifuge program in Pakistan and headed A. Q. Khan Research Institute.

Abdul Qadeer Khan



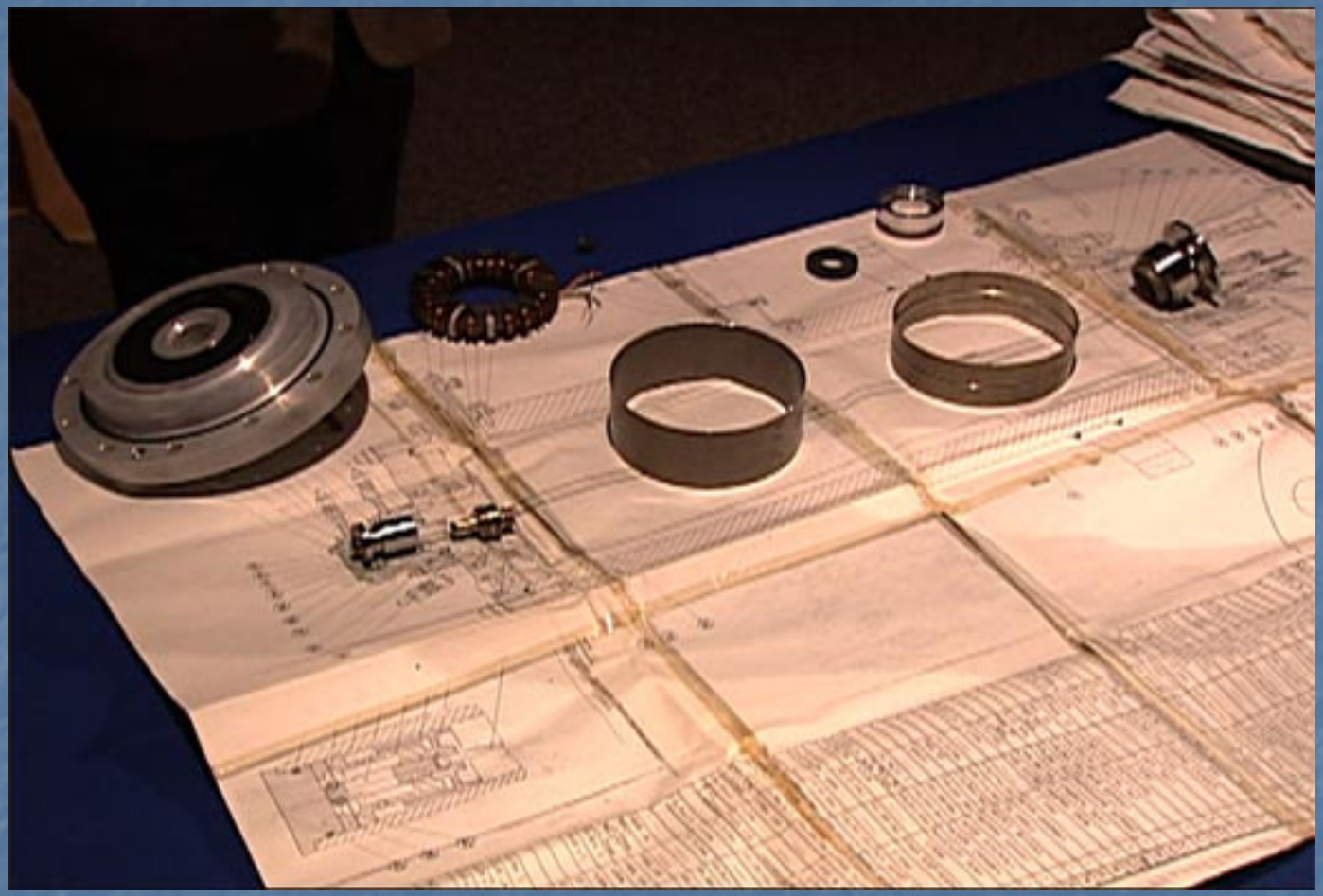
Spread of Centrifuges

- After first Gulf War in 1991, IAEA inspectors discovered centrifuges in Iraq.
- In 2002, Aluminum tubes headed for Iraq were alleged to be for centrifuges.
- This was proven to be false, but the long secret subject was now being discussed in the media.
- In October 2002, DPRK stated they were building a centrifuge plant.
- It was known A. Q. Khan visited DPRK.
- By January 2003, DPRK denied this.

Spread – II

- In Feb. 2003, IAEA inspector ElBaradei visited enrichment plant at Natanz.
- During 2nd Gulf War in 2003, Mahdi Obeidi turned over centrifuge parts buried in his back yard.
- In 2004, Libya gave up their centrifuges.
- Khan network of centrifuge and weapon design was involved in all of these.

Obeidi's Centrifuge



Natanz

Natanz

Safeguard Inspections

- Technically, Iran is required to submit to IAEA inspections.
- How can a centrifuge plant under inspections be operated to produce highly enriched uranium clandestinely?
- One possibility is to operate centrifuges with lower off-design feed rate.

Approach

- Consider hypothetical Iguaçu centrifuge.
- Optimize centrifuge performance.
- Determine α as a function of feed rate.
- Design cascade for enrichment to 5%.
- Vary feed rate in two ways:
  - Change only centrifuge feed rate.
  - Re-optimize centrifuge for each feed rate.

Iguaçu Centrifuge Parameters

Peripheral velocity	600 m/sec
Radius	6.0 cm
Height	48 cm
Wall pressure	60 torr
Axial position of feed	H/2

Pancake Calculations

- Four flow cases were computed linearly and combined to produce optimum separative work:
  - Feed with cut = 0
  - Feed with cut = 1
  - Linear wall temperature
  - Scoop drive

Optimized Iguaçu Centrifuge

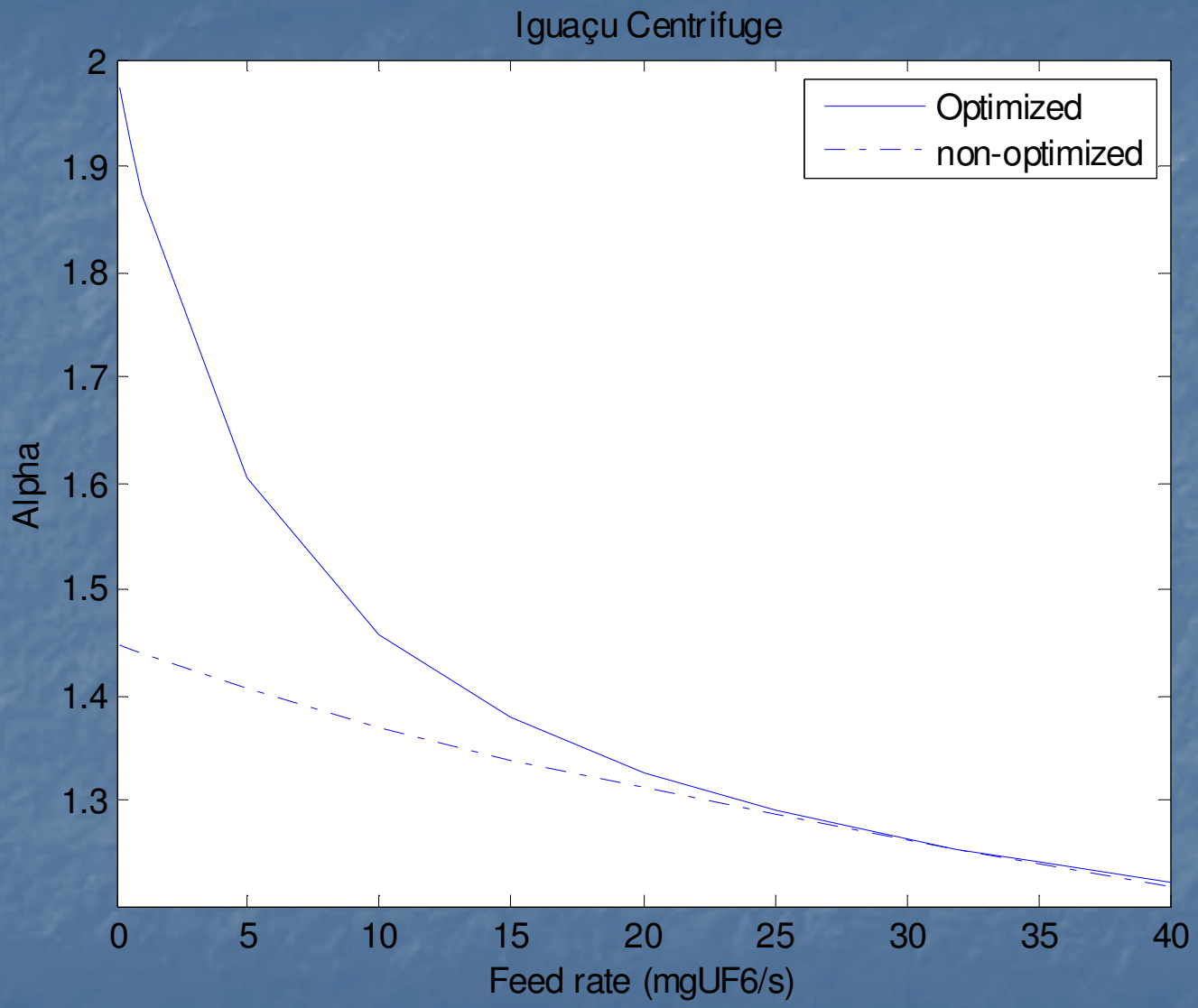
Feed Rate	31.81 ($mgUF_6/sec$)
Cut (held fixed)	0.5
Delta T	11.69 K
Scoop Force	854 dynes
Delta U max	16.97 SWU
Delta U	4.34 SWU
Alpha	1.254

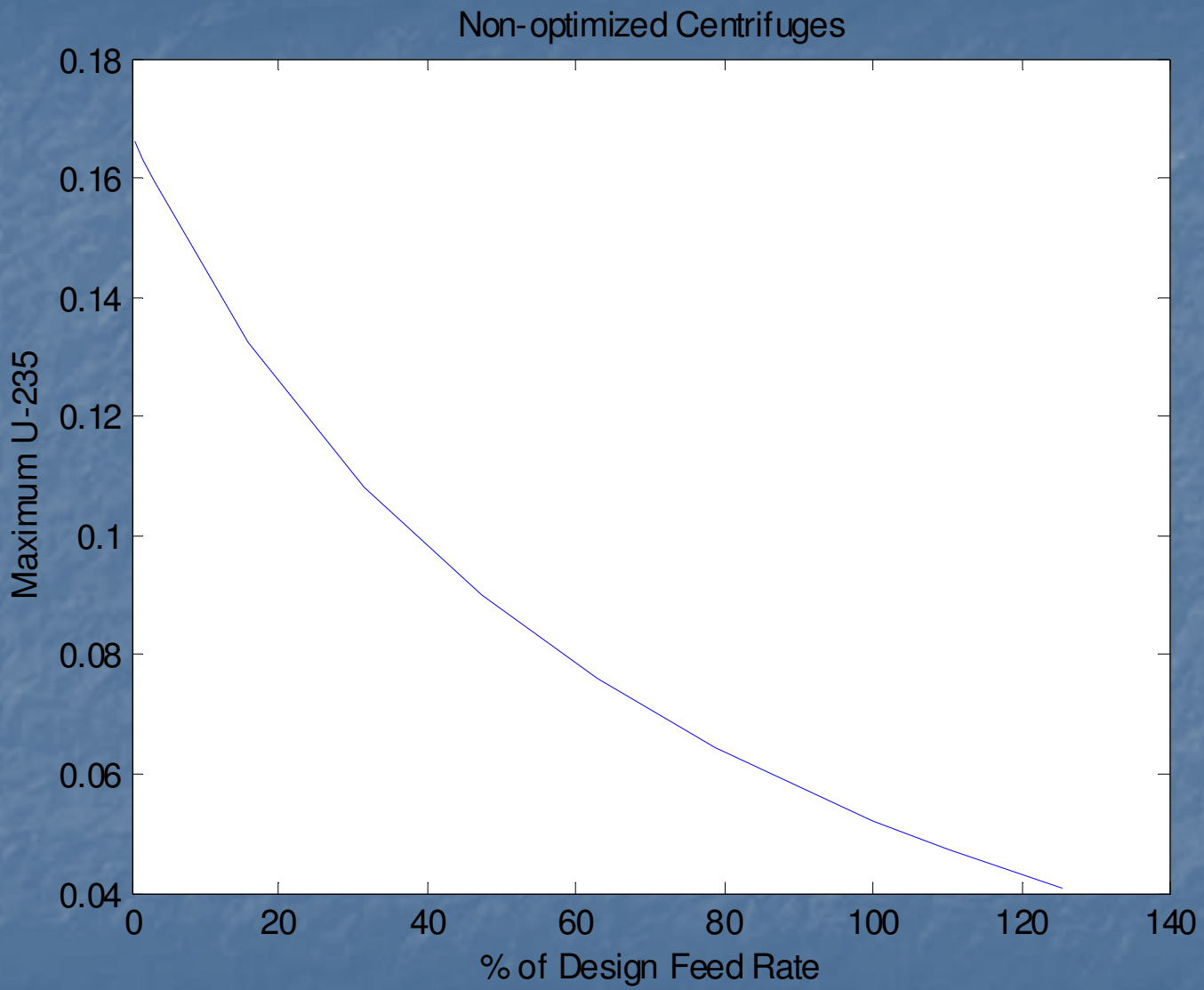
Cascade Design

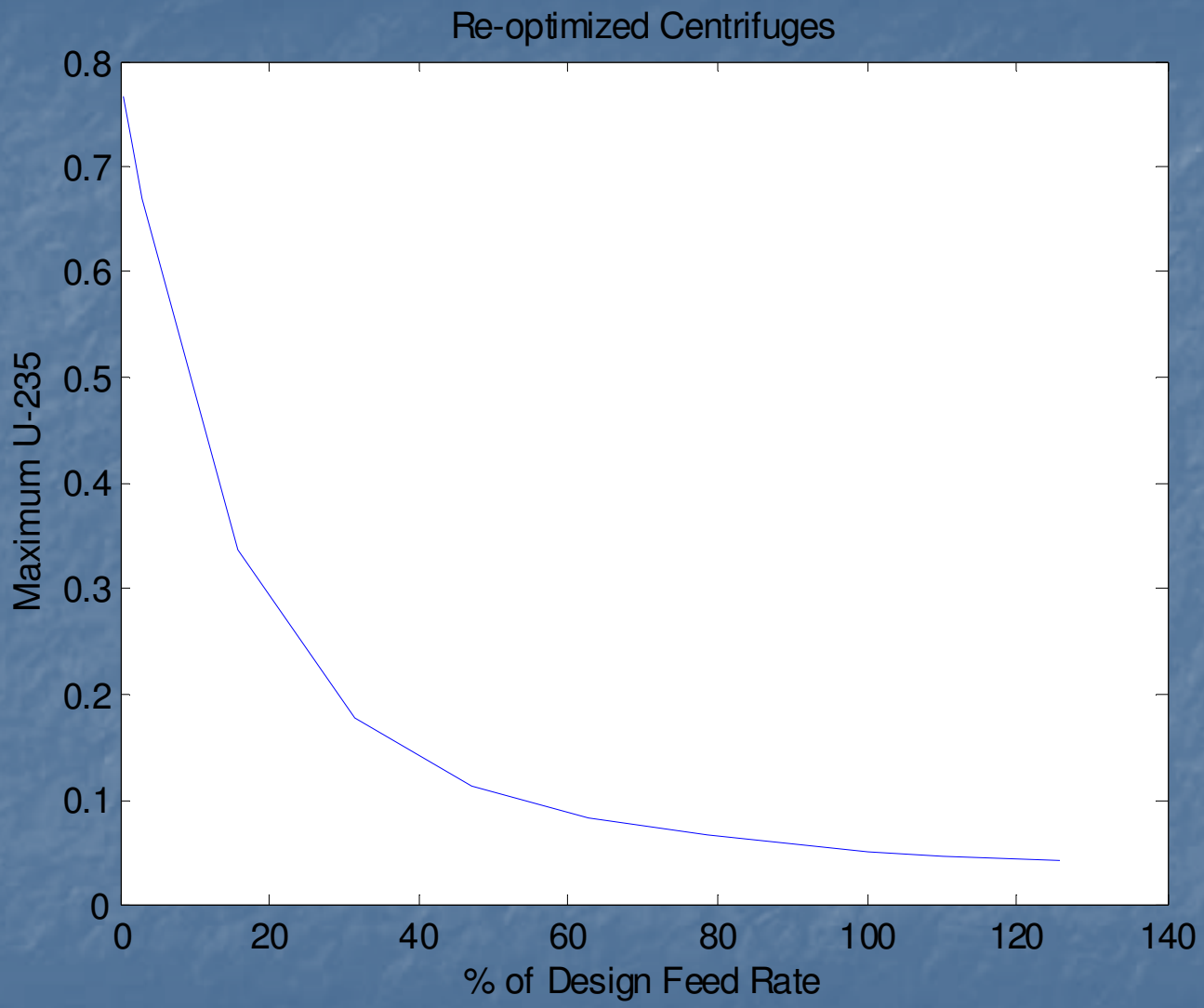
- The centrifuge α is the cascade stage α, and is constant through the cascade.
- All centrifuges have the same feed rate.
- An M^* cascade is designed for producing reactor grade fuel (~ 5% ^{235}U).

Iguaçu Centrifuge Cascade

Number of Enricher Stages	6
Number of Stripper Stages	3
U-235 Product Concentration	5.21%
U-235 Tails Concentration	0.18%
Cascade Recovery Factor (P/F)	0.105


Iguaçu Centrifuge
Optimized
non-optimized
Alpha
Feed rate (mgUF6/s)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
0
5
10
15
20
25
30
35
40


Non-optimized Centrifuges
Maximum U-235
% of Design Feed Rate
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0
20
40
60
80
100
120
140


Re-optimized Centrifuges
Maximum U-235
% of Design Feed Rate
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
20
40
60
80
100
120
140

Conclusions

- There is a potential for uranium to be enriched to a higher level than that for which the cascade is designed.
- The rate of production of higher enriched material would be lower than for the design level of enrichment.
- Inspectors need access to information to reveal such operations.

Recommendations

- Nations not in good standing with regards to NPT (e.g. Iran) should be subjected to extra protocols.
- Safeguards inspectors must be given access to more cascade information such as interstage flow rates and assays.
- For a nation pursuing nuclear energy, this could provide trust building.

Questions?

Comments?