NE/PP 285C

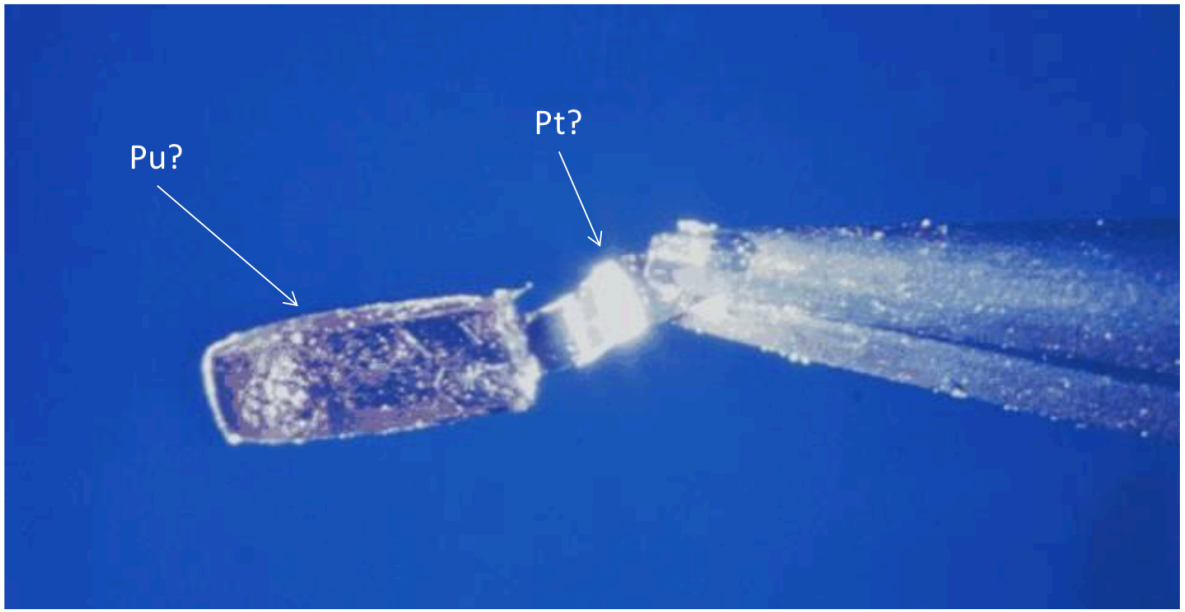
Spring 2019

Where Does the Fuel Come From?

Technical Lecture 9

March 4 & 6, 2019

Nuclear Weapons Require ^{235}U or ^{239}Pu as their Fuel



The first sample of ^{239}Pu containing 2.7-micrograms of oxide was weighed on September 10, 1942, at the University of Chicago's Metallurgical Laboratory. It is shown here as a deposit on a platinum foil held by forceps.

By 1940, the world's separated ^{235}U was a tiny smudge on a metal foil in Nier's mass spectrograph, and by 1942, the world's supply of ^{239}Pu was a fleck of pepper. But by 1945, the US would be producing hundreds of kilograms of fuel per year.

Enrichment and Reprocessing

^{235}U exists as a tiny component of natural uranium, (0.72%); to get weapons-grade uranium (>90%) requires *enrichment*.

^{239}Pu does not exist naturally, but is created as a by-product of reactor operation. To get weapons-grade plutonium requires *reprocessing*.

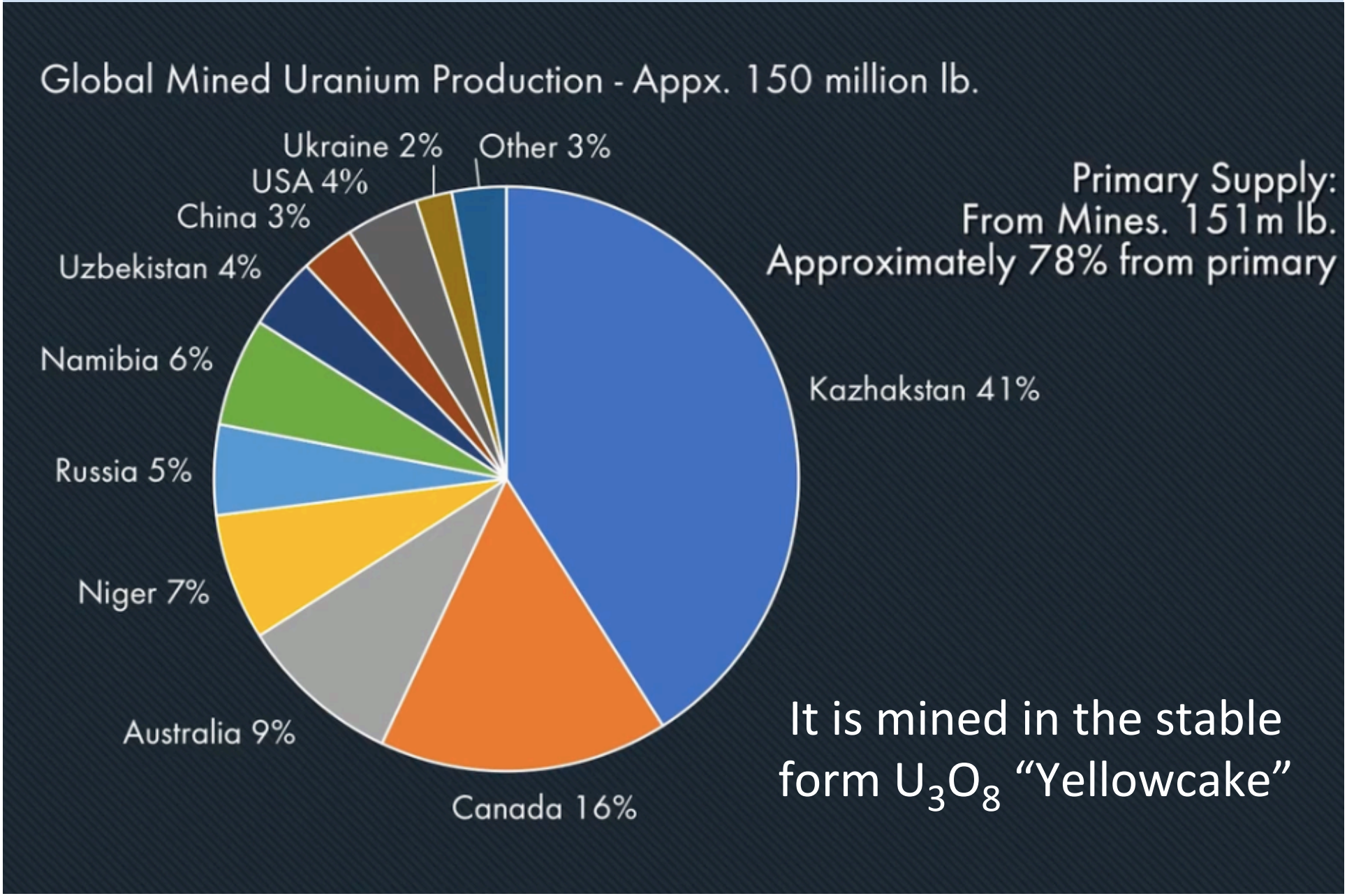
I will only talk about enrichment technologies today; reprocessing will be discussed by Prof. Rebecca Abergel later.

Known Recoverable Resources of Uranium (2009)		
Country	Tonnes U	Percentage of world (%)
Australia	1,673,000	31
Kazakhstan	652,000	12
Canada	485,000	9
Russia	480,000	9
South Africa	295,000	5
Namibia	284,000	5
Brazil	279,000	5
Niger	273,000	5
USA	207,000	4
China	171,000	3
Jordan	112,000	2
Uzbekistan	111,000	2
Ukraine	105,000	2
India	80,000	1.5
Mongolia	49,000	1
Other	150,000	3
World total	5,404,000	

Where is U found?
(data 2009)

BTW, Seawater is 3 ppb Uranium, x500 all reserves currently known.

Where is Uranium being produced?

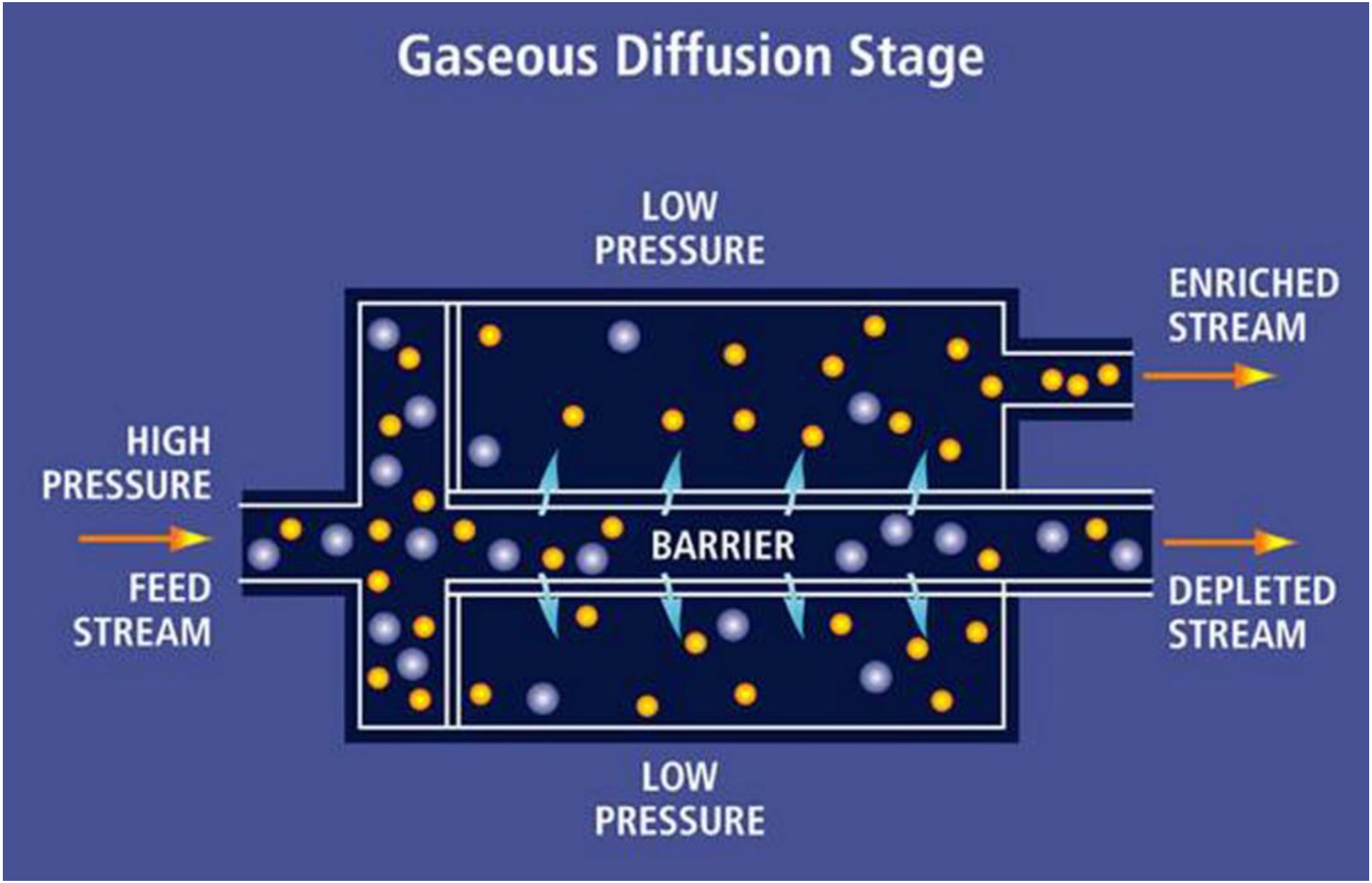


Four Methods of Enrichment of ^{235}U

After conversion to Uranium Hexafluoride UF_6 (highly corrosive):

- Gaseous Diffusion
- Electromagnetic Separation
- Gas Centrifuge
- Laser Isotope Separation

All have been used; the first two being how ^{235}U was separated for the Manhattan Project



The diffusion barrier is a semipermeable membrane (e.g. sintered nickel) with nanometer-scale pores

Gaseous Diffusion – Physics Basis

The Diffusion Coefficient D is inversely proportion to the square root of the mass of the species i :

$$D_i \propto \sqrt{\frac{1}{m_i}}$$

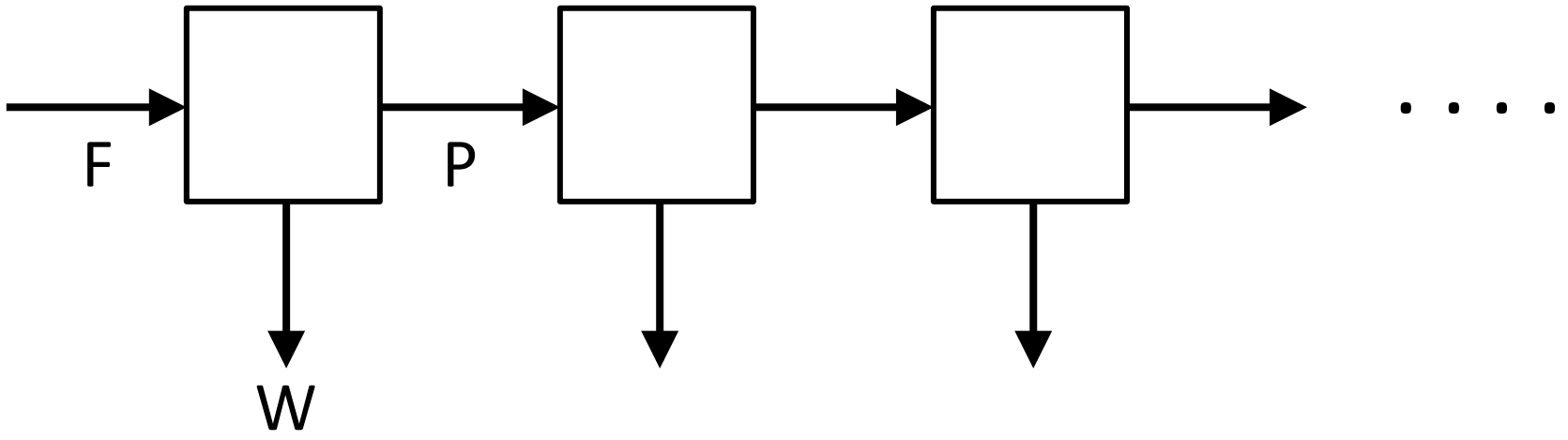
The atomic weight of $^{235}UF_6$ is 349; that for $^{238}UF_6$ is 352. Thus the ratio of the two differs by a small degree:

$$\frac{D_{235}}{D_{238}} = \sqrt{\frac{352}{349}} \approx 1.0043$$

The enriched output of a stage is optimized when half the gas passes through the barrier, and including non-ideal performance, a typical enrichment per stage is r ≈ 1.0014

Gaseous Diffusion - Cascade

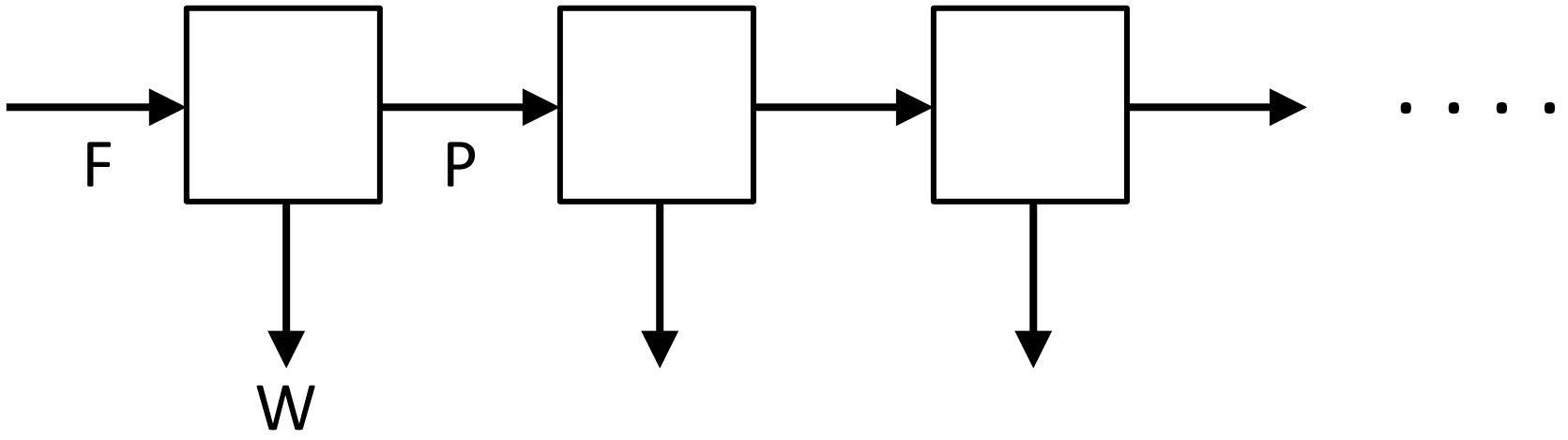
This might suggest a cascade like this:



Where F = Feed, P = Product, W = Waste

Gaseous Diffusion - Cascade

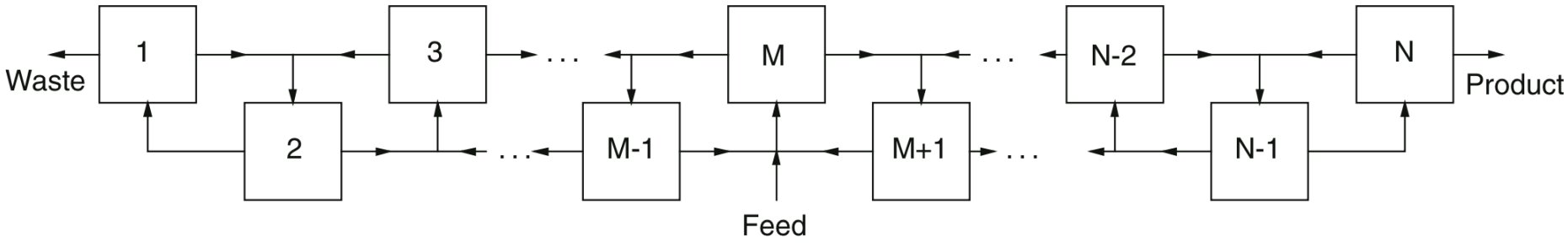
This might suggest a cascade like this:



Where F = Feed, P = Product, W = Waste

But this would be a terrible idea ! Think

Gaseous Diffusion – Simple Symmetric Cascade



If : r = enrichment factor

x_F = enrichment of the Feed

x_P = enrichment of the Product

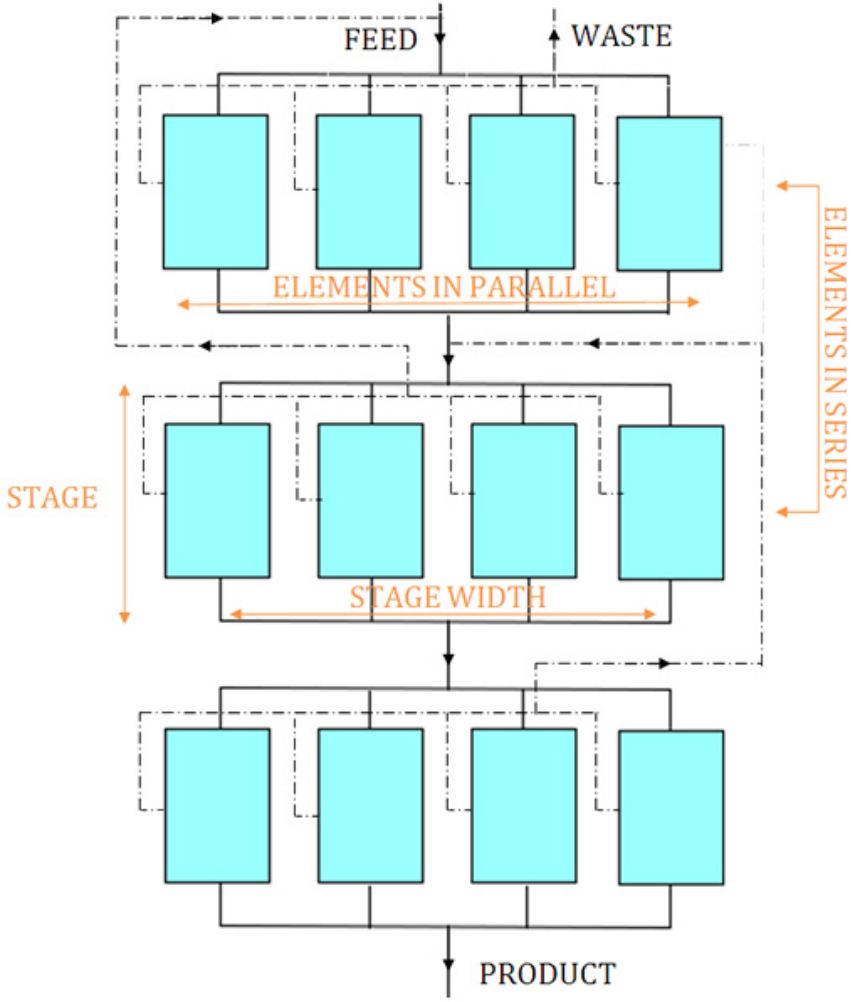
x_W = enrichment of the Waste

Then it is easy to show the number of stages is given by

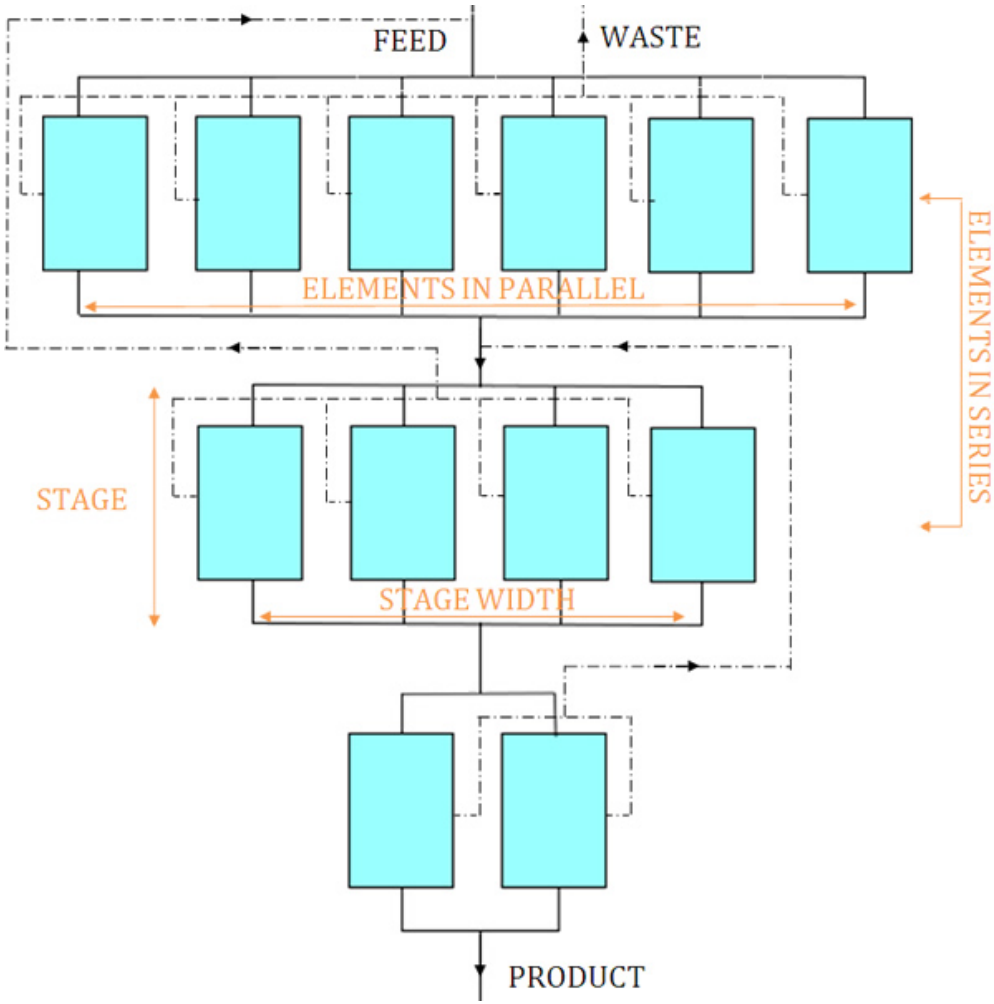
$$r^N = x_P/x_W \quad , \quad \text{or} \quad N = \ln (x_P/x_W) / \ln(r)$$

Thus for $x_P = 0.93$, $x_W = 0.004$, $N \approx 3900$

More cascades …



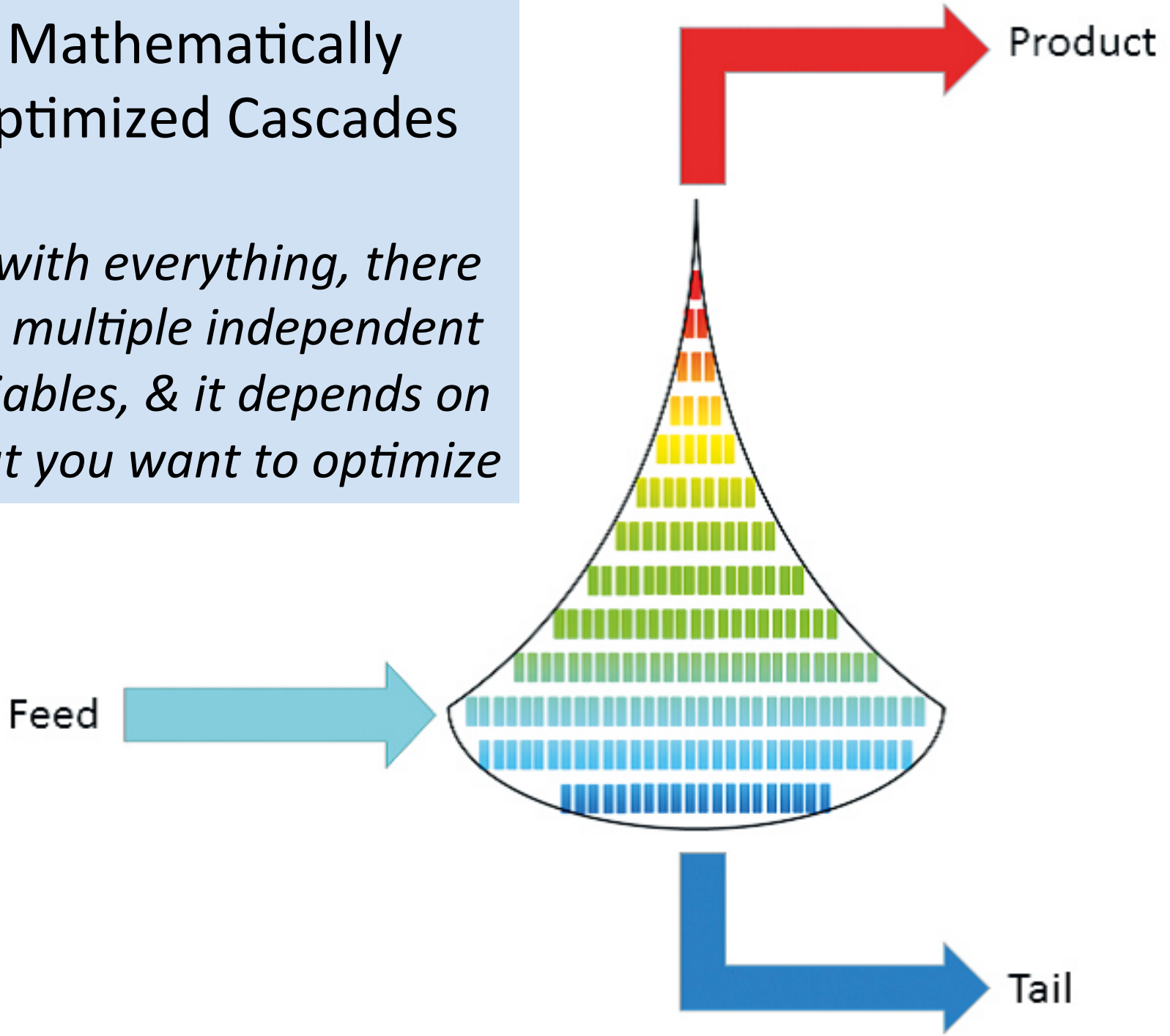
Square cascade



Symmetric cascade

Mathematically Optimized Cascades

As with everything, there are multiple independent variables, & it depends on what you want to optimize

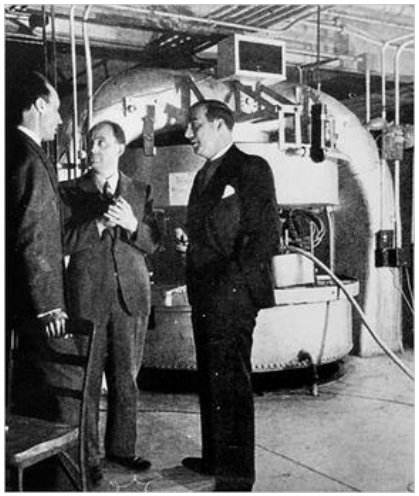


The K-25 Plant in Oak Ridge from WW-II (more recent photo)
The scale was staggering – a mile long, taking 3 GW of power

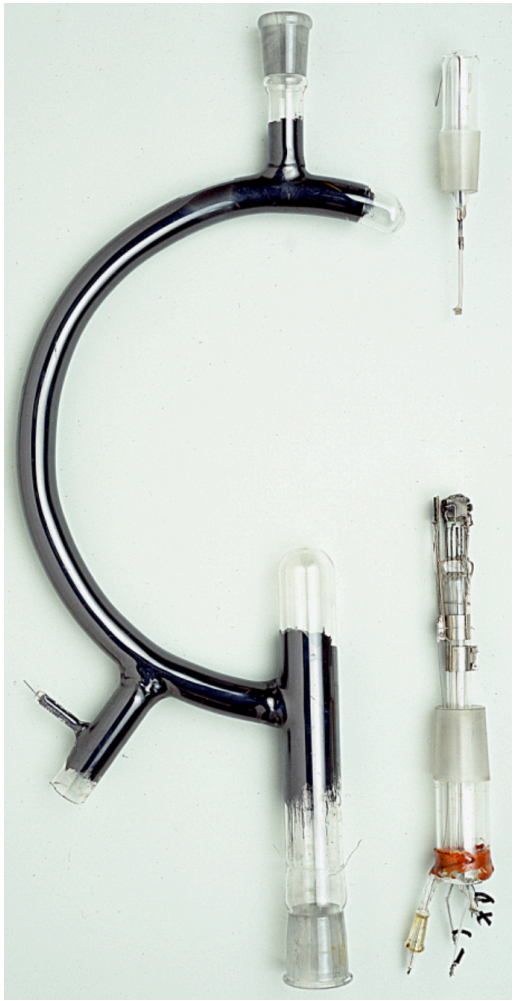
Portsmouth Gaseous Diffusion Plant, Pike County, OH (1954-2001)

Electromagnetic Separation

Remember Nier's spectrometer? EM Separation is nothing more than a massively scaled up version.



Nier & Dunning



Nier's mass spectrometer

Mass spec ion source

Foil catcher

Electromagnetic Separation – Physics

When one accelerates an ion of charge q across a voltage drop V, it has a kinetic energy $K = qV$, independent of mass.

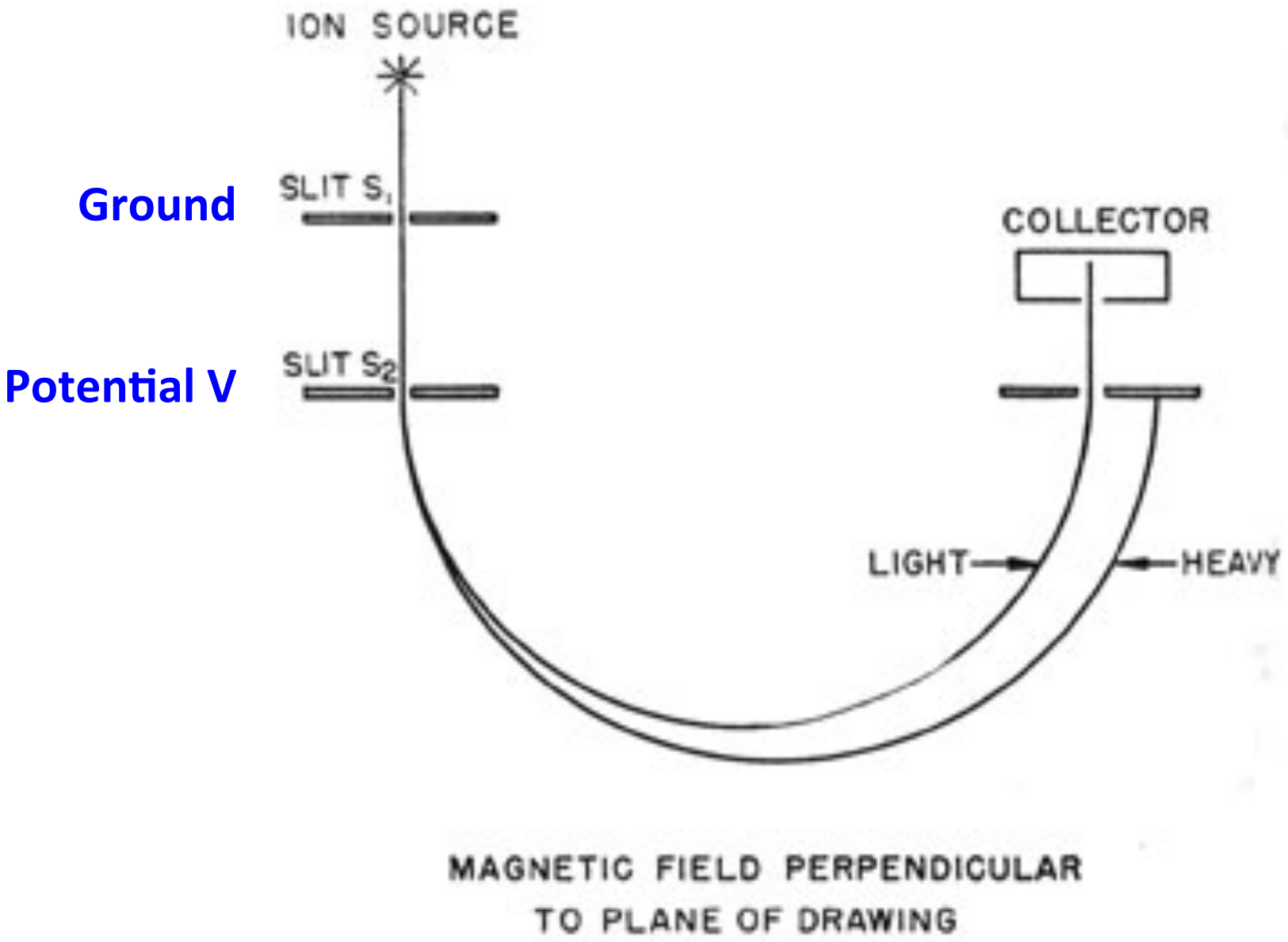
But the momentum p does depend on its mass: $p = \sqrt{2mK}$

And the radius of curvature ρ in a magnetic field B is proportional to its momentum:

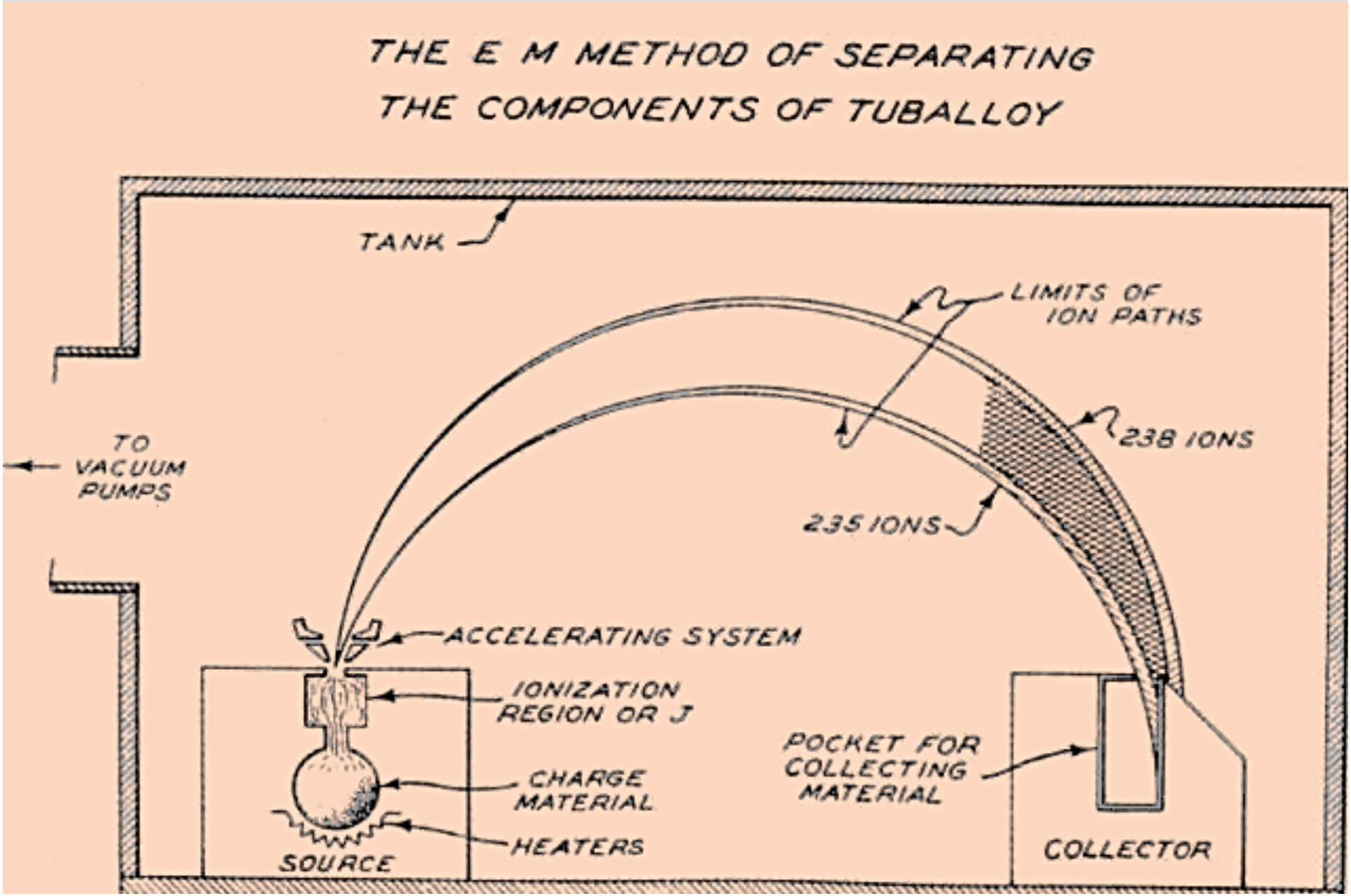
$$\frac{p}{q} = B \cdot \rho$$

For a singly-charged ion, $q = e$, p [GeV/c] = 0.3 B [T] ρ [m] .

Electromagnetic Separation - Schematic

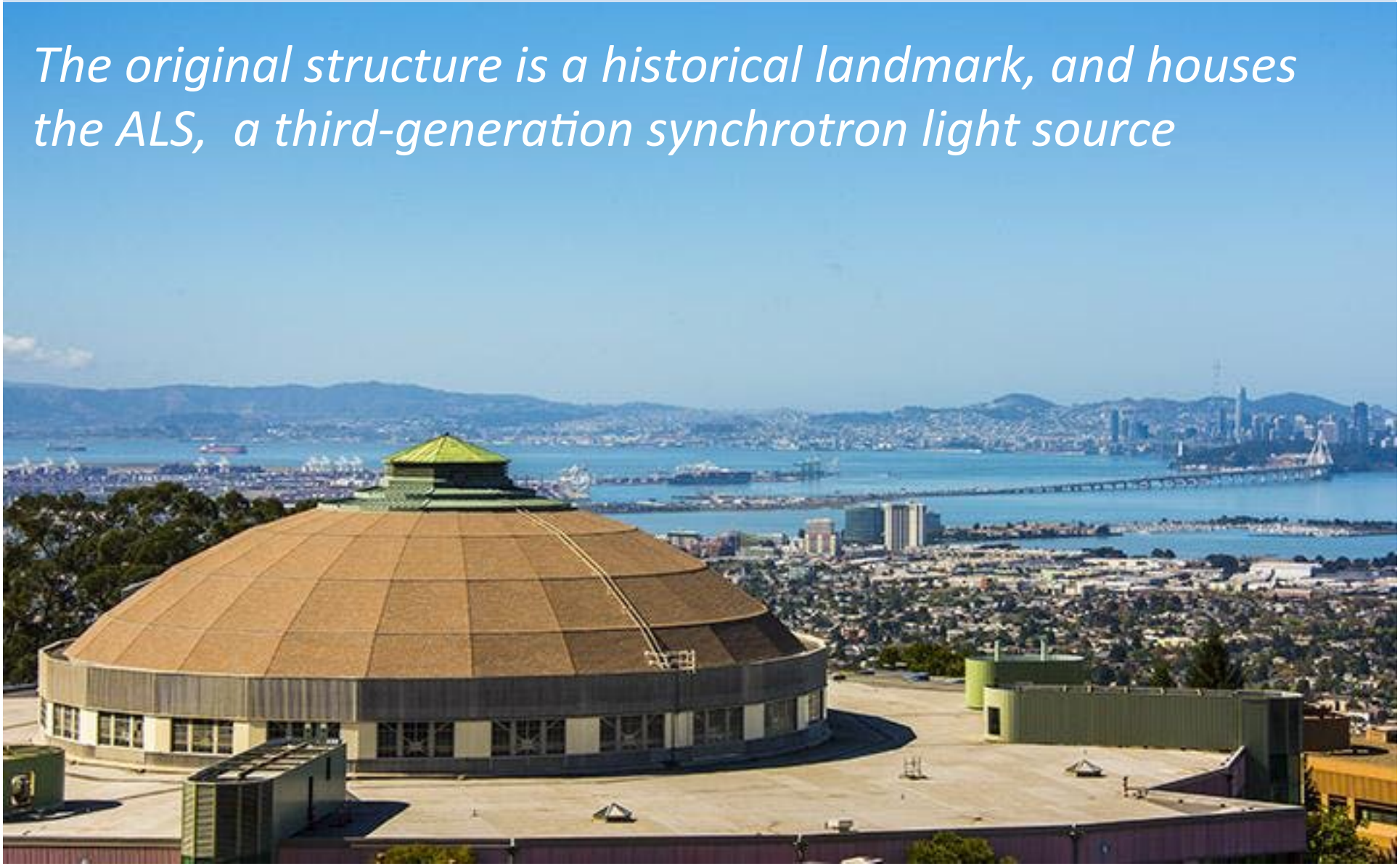


Ernest Lawrence's conception of the Calutron

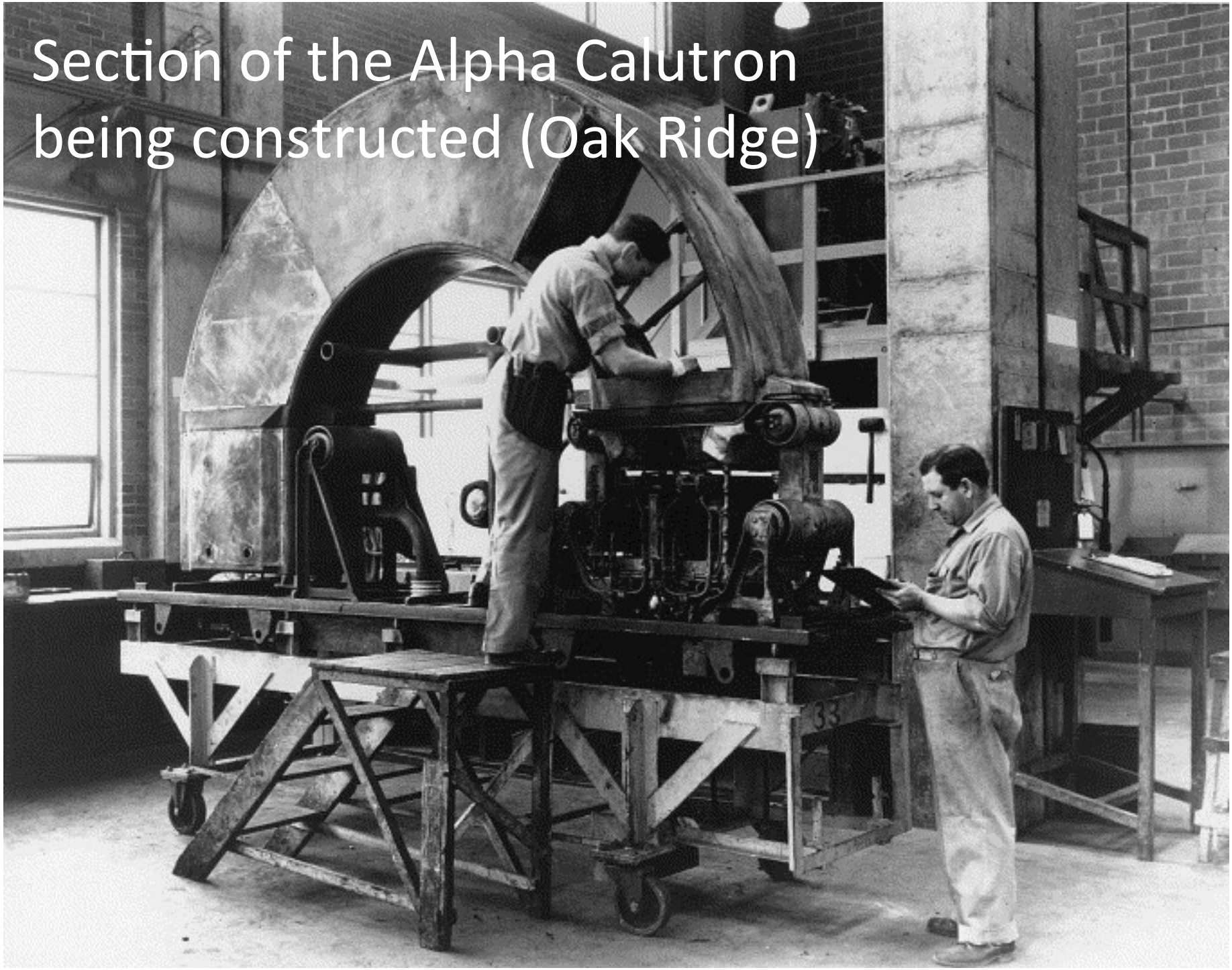


EM Separation – Prototype at 184” Cyclotron

The original structure is a historical landmark, and houses the ALS, a third-generation synchrotron light source



The 184” Cyclotron was hijacked to test the principal


Section of the Alpha Calutron
being constructed (Oak Ridge)

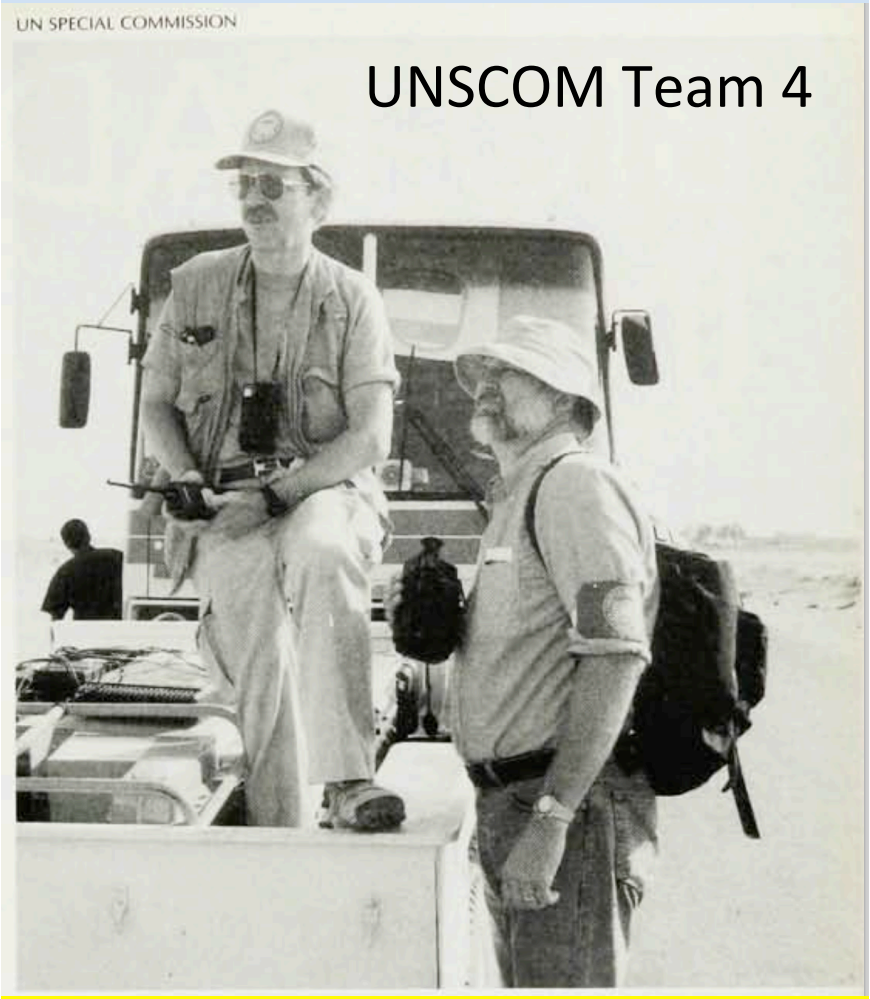

The Alpha Calutron Racetrack

The “Calutron Girls” of Oak Ridge

Summary of the EM Separation with the Calutron

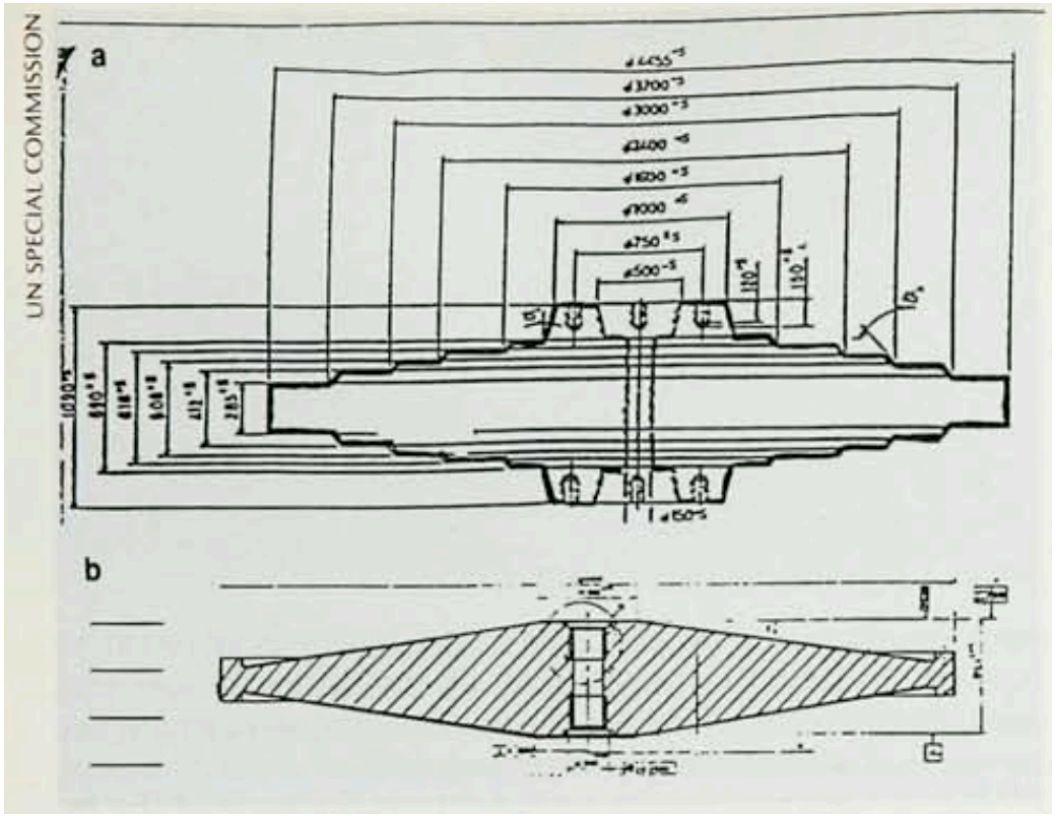
- The Calutron was a difficult technology; there were constant maintenance and reliability issues; in the end, the Alpha Calutron was only partially successful, but the Beta Calutron was much better and ultimately produced 95% enriched ^{235}U.
- In fact, the K-25 Gaseous Diffusion plant and the Calutrons worked in tandem, passing uranium at different levels of enrichment back and forth, to optimize yield.
- Calutrons were very lossy and inefficient; only 1/6000 of the feedstock became usable fuel. The uranium splattered all over the inside of the machine, and it had to be scraped off for recovery.
- It was also very expensive; the whole Calutron program cost $9B.
- Due to wartime shortages of copper, which went to artillery shells, the Manhattan project used all 14,000 tons of silver (!) from Ft. Knox for high-conductivity wire. Every last ounce was returned.
- But within the context of the crash program – it did its job.

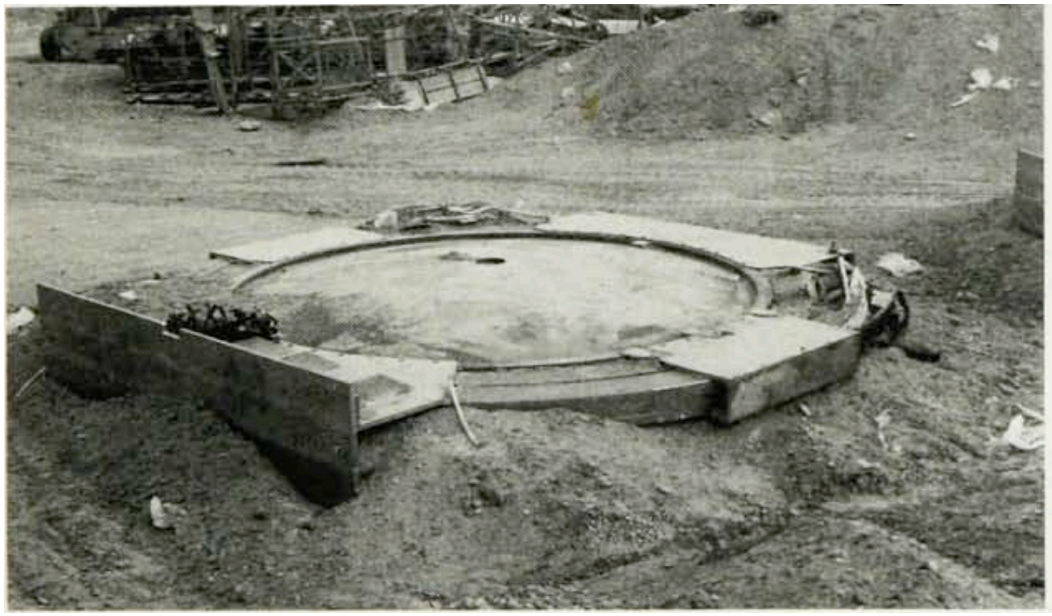
Iraq developed a sophisticated EMS system as part of their nuclear weapons program



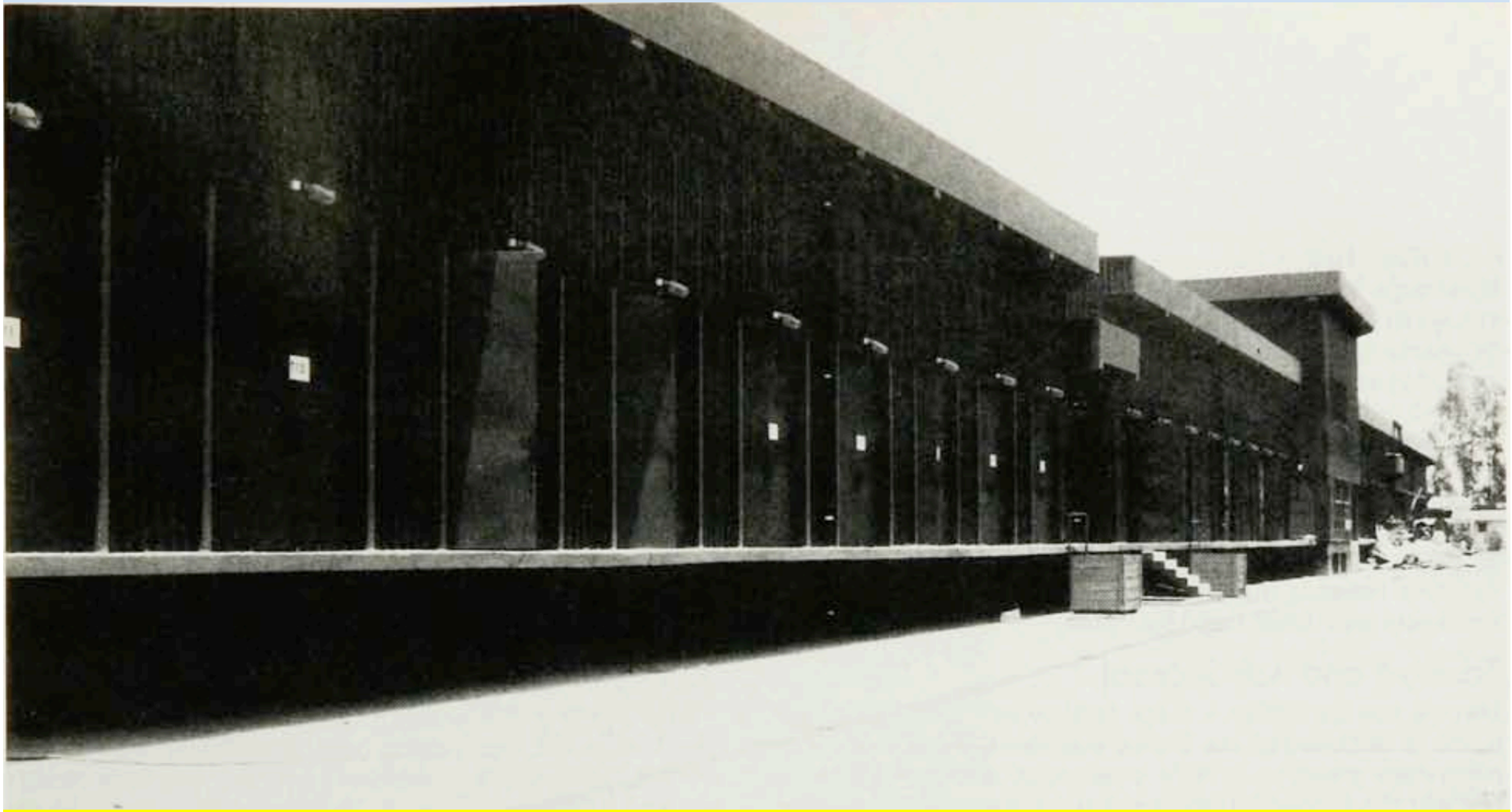
UNSCOM Team 4

David Kay & Jay Davis, cover of Physics Today, July 1992





The EMS Facilities were at Tarmiya & Al Sharqat

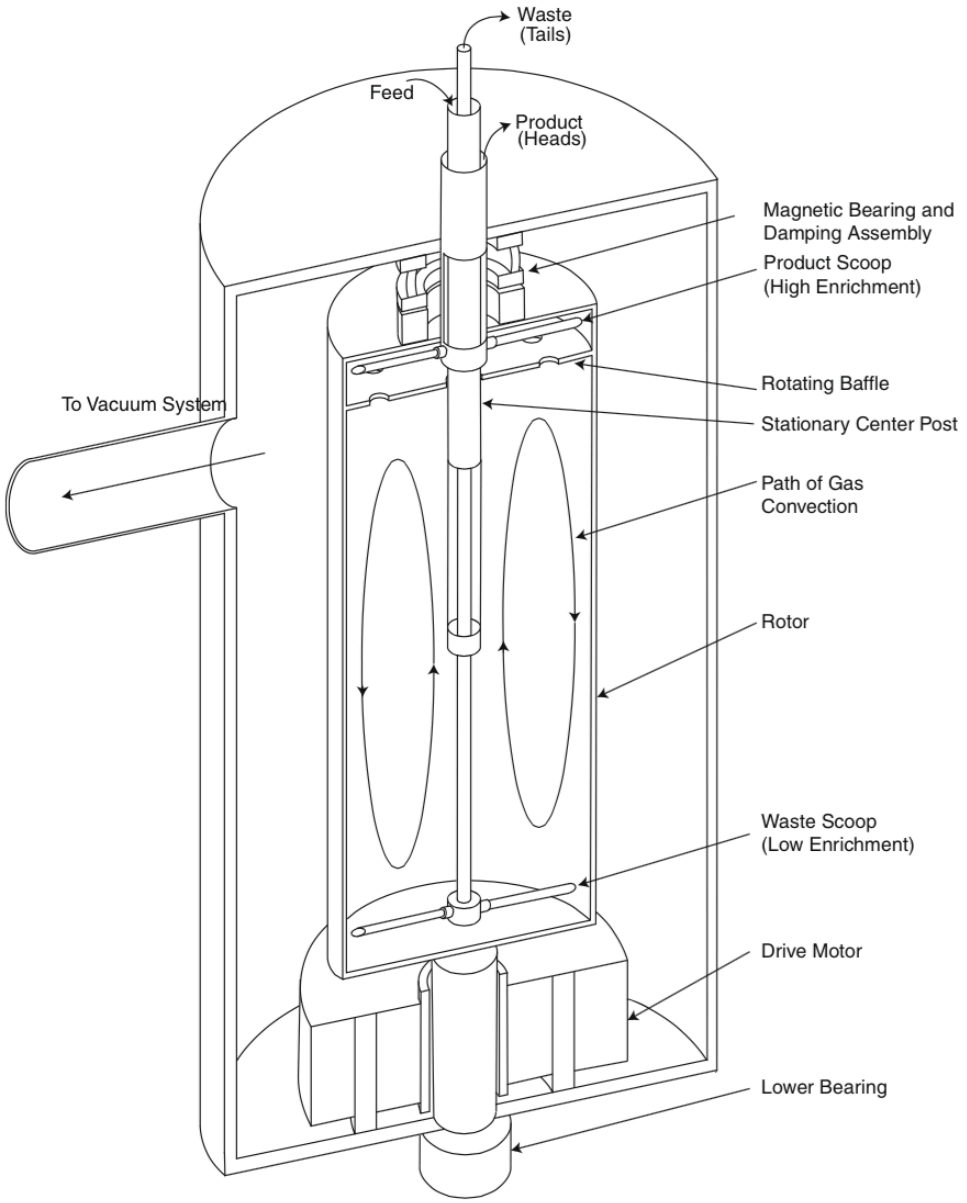


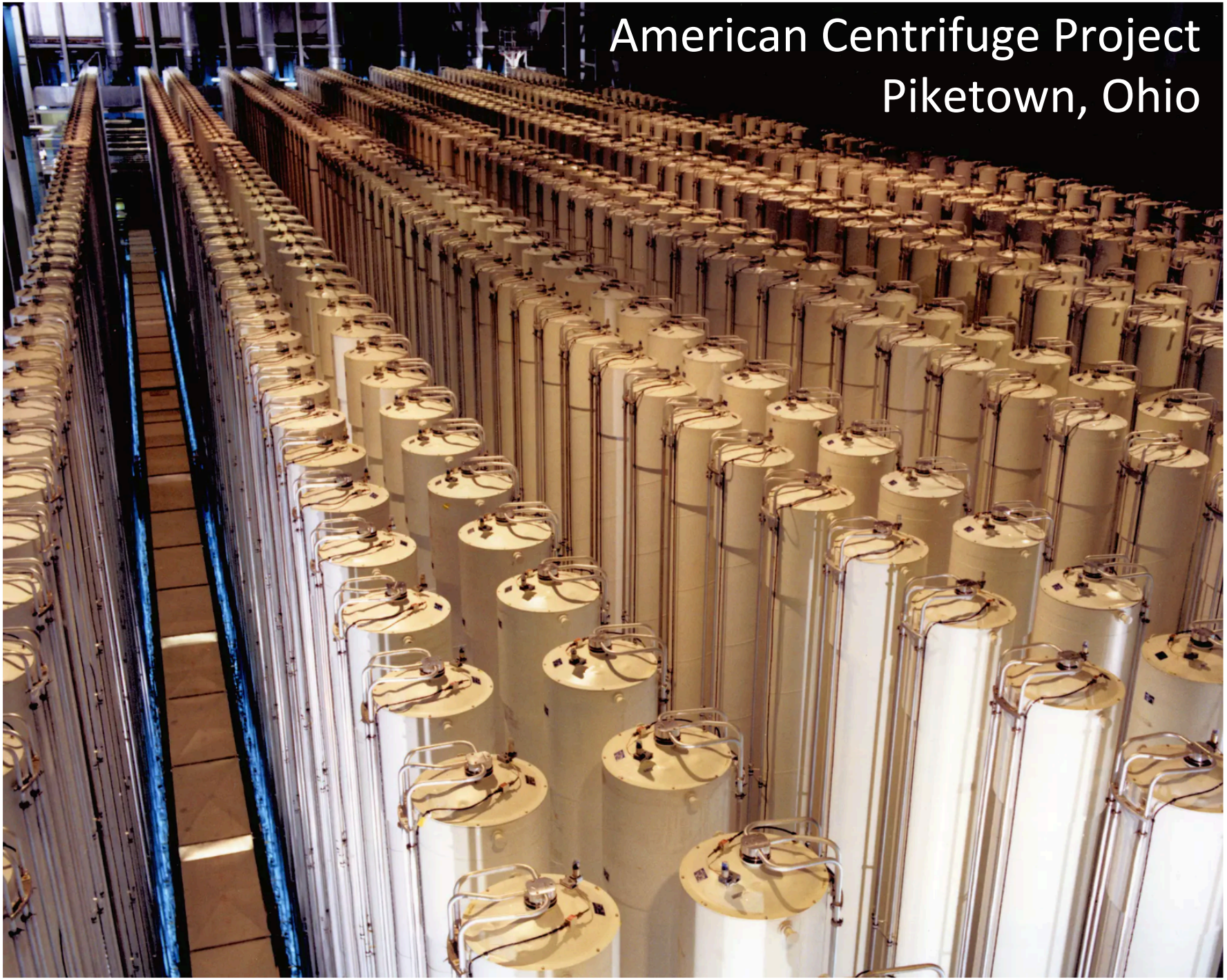
One of two Transformer buildings at Tarmiya with 64 1-MW transformers each. The Iraqis had buried the power lines to conceal the plant from NTM.

Iraqi convoy of trucks trying to surreptitiously spirit away components of their EMS plant

The Gas Centrifuge

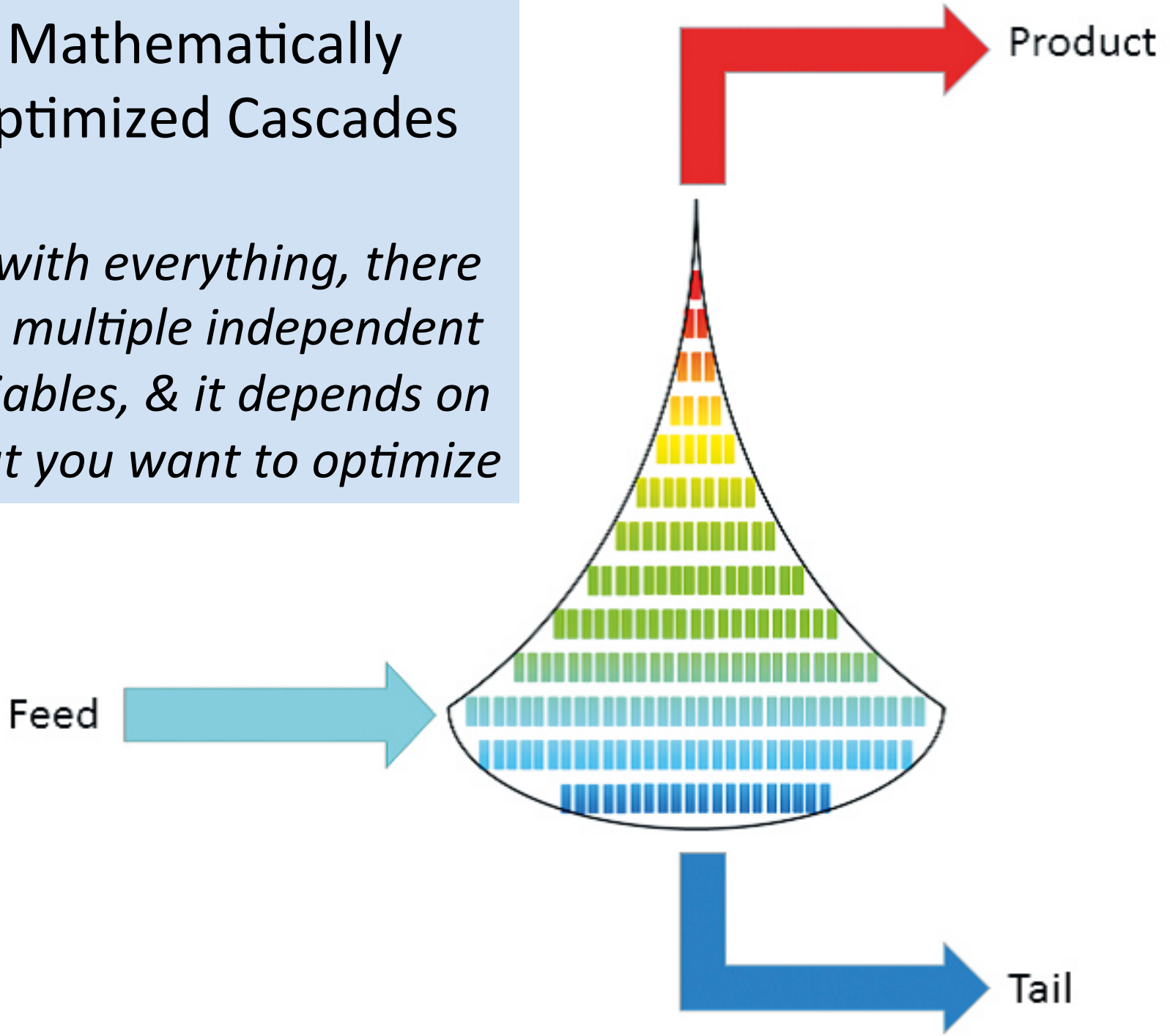
- Principle is old, but practical design derives from post-war German & Austrian scientists taken to the USSR (Zippe centrifuges)
- Much higher separation factor than for gaseous diffusion, ideally $\alpha \approx 1.3$
- Requires sophisticated engineering and specialized components, mostly under Export Control Laws
- Operates at very high rotational speeds, 60,000 rpm or higher
- A.Q. Khan, working for Urenco brought this technology to Pakistan for their nuclear weapons program, and then exported it to North Korea, Iran & Libya
- Centrifuges are *the* proliferation risk today (see article by R. Scott Kemp)




American Centrifuge Project
Piketown, Ohio

Mathematically Optimized Cascades

As with everything, there are multiple independent variables, & it depends on what you want to optimize



The proliferation issue in numbers

- Natural Uranium: 0.72 %
- Low-Enriched Uranium (LEU): < 20 %
  - Typical reactor-grade 3-5 %
- High-Enriched Uranium (HEU) > 20 %
  - Bomb grade Uranium > 90 %

LEU enriched to ≈ 20% poses the question of "breakout time"

The surprising logic of enrichment cascades (I)

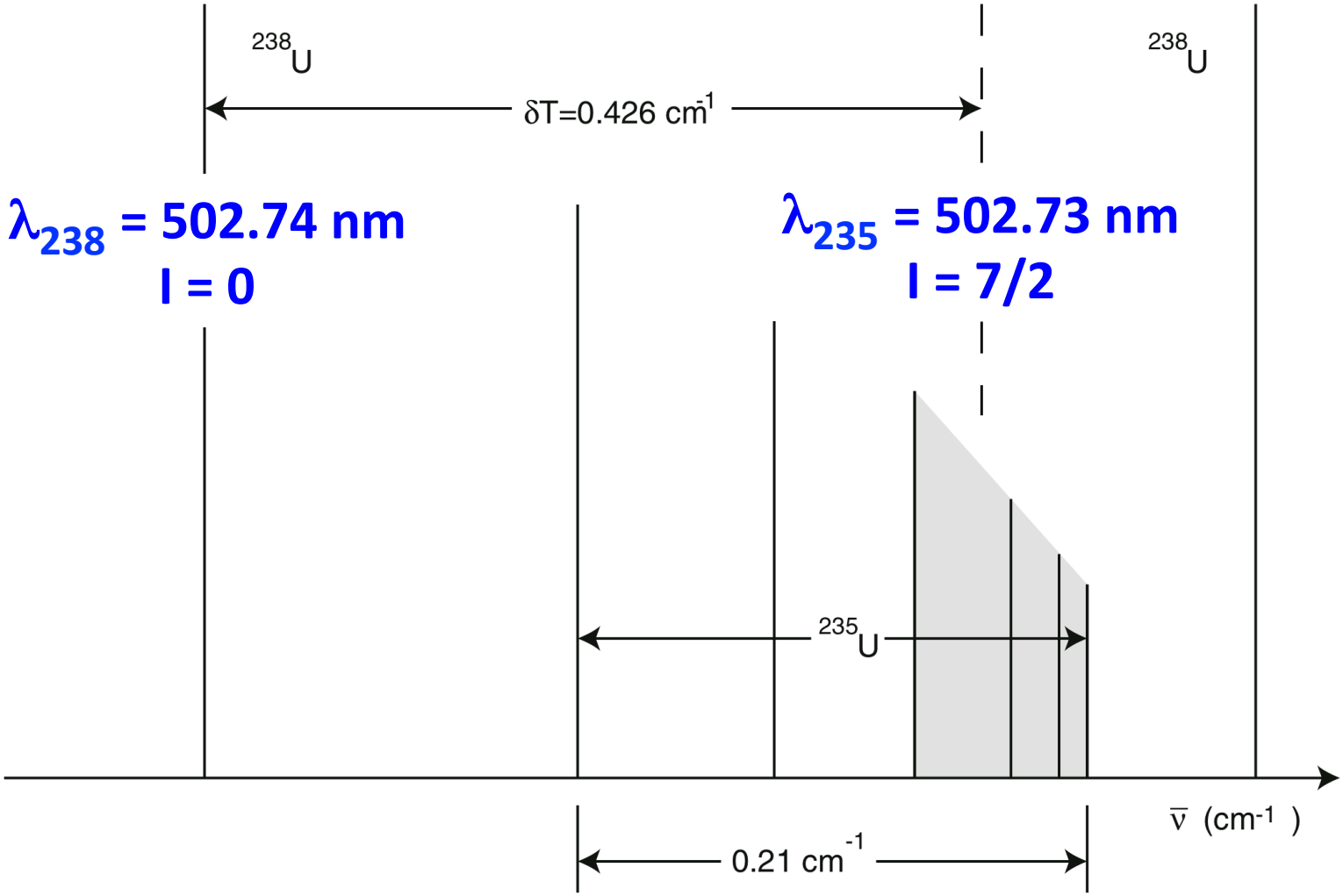
Stage No.	Tail enrichment	Feed enrichment	Head enrichment	Feed	No. of centrifuges	SWU
1	0.00405303	0.00490963	0.00594618	639.064	16	250.492
2	0.00490963	0.00594618	0.0072	1167.39	30	457.579
Feed Point → 3	0.00594618	0.0072	0.00871588	1604.64	41	628.966
4	0.0072	0.00871588	0.0105475	1325.43	34	519.526
5	0.00871588	0.0105475	0.0127591	1095.13	28	429.257
6	0.0105475	0.0127591	0.0154272	905.181	23	354.802
7	0.0127591	0.0154272	0.0186427	748.504	19	293.389
8	0.0154272	0.0186427	0.0225131	619.274	16	242.735
9	0.0186427	0.0225131	0.0271648	512.681	13	200.954
10	0.0225131	0.0271648	0.0327454	424.761	11	166.492
11	0.0271648	0.0327454	0.039426	352.241	9	138.067
12	0.0327454	0.039426	0.0474027	292.424	8	114.621
13	0.039426	0.0474027	0.0568978	243.084	7	95.2809
14	0.0474027	0.0568978	0.0681586	202.385	6	79.3282
15	0.0568978	0.0681586	0.0814557	168.812	5	66.169
16	0.0681586	0.0814557	0.0970766	141.118	4	55.3136
17	0.0814557	0.0970766	0.115317	118.271	3	46.3582
18	0.0970766	0.115317	0.136467	99.4206	3	38.9696
19	0.115317	0.136467	0.160791	83.8664	3	32.8729
20	0.136467	0.160791	0.188504	71.0293	2	27.8412
21	0.160791	0.188504	0.219742	60.4317	2	23.6873

The surprising logic of enrichment cascades (II)

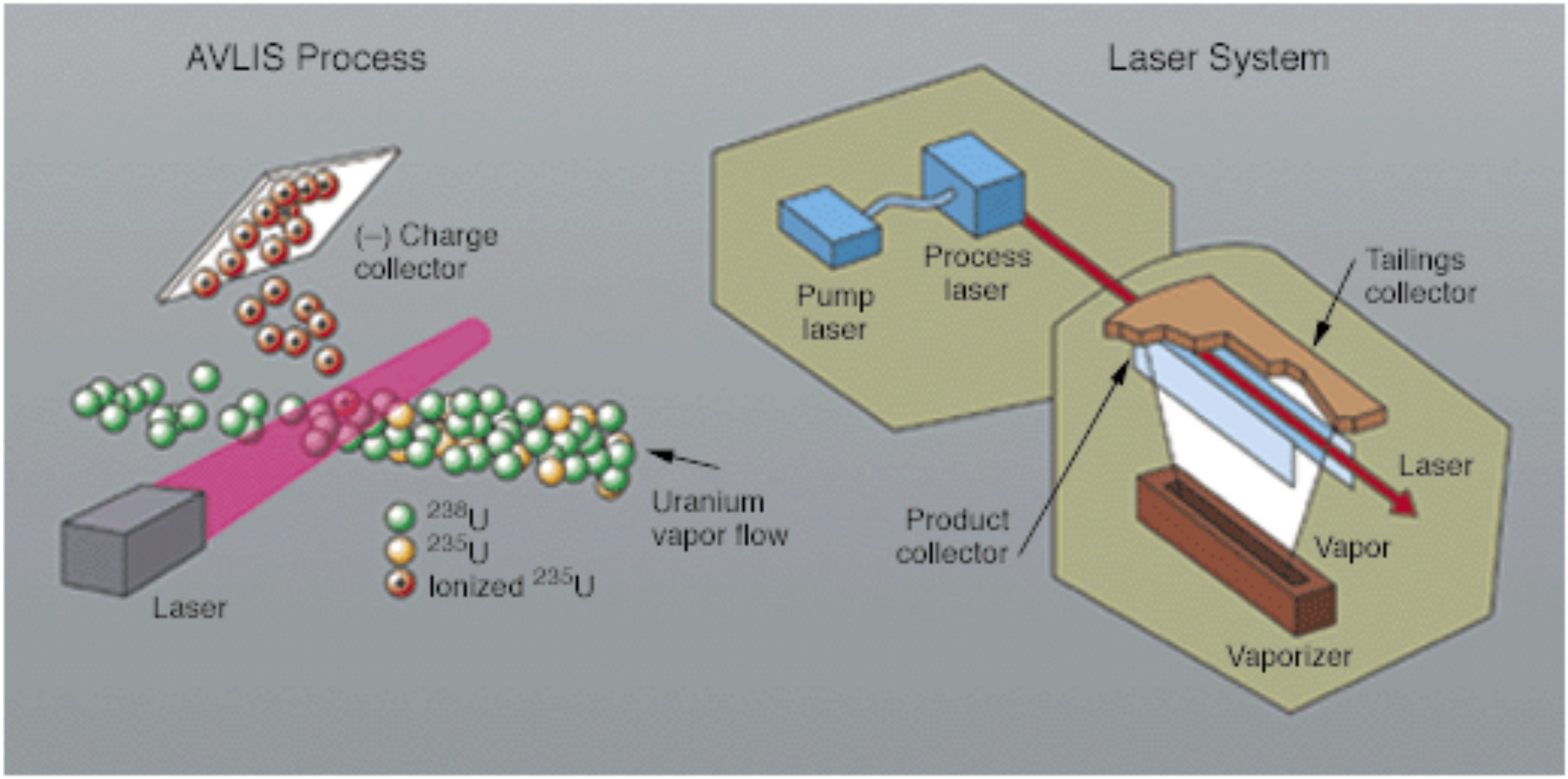
22	0.188504	0.219742	0.254534	51.6793	2	20.2566
23	0.219742	0.254534	0.292767	44.4464	2	17.4215
24	0.254534	0.292767	0.334169	38.4639	1	15.0766
25	0.292767	0.334169	0.378294	33.5092	1	13.1345
26	0.334169	0.378294	0.424531	29.398	1	11.5231
27	0.378294	0.424531	0.472127	25.9773	1	10.1823
28	0.424531	0.472127	0.520235	23.1199	1	9.06225
29	0.472127	0.520235	0.567971	20.7193	1	8.12131
30	0.520235	0.567971	0.614478	18.6864	1	7.32446
31	0.567971	0.614478	0.658983	16.9454	1	6.64205
32	0.614478	0.658983	0.700852	15.4316	1	6.04869
33	0.658983	0.700852	0.739612	14.0887	1	5.5223
34	0.700852	0.739612	0.774962	12.8666	1	5.04329
35	0.739612	0.774962	0.806767	11.7199	1	4.59384
36	0.774962	0.806767	0.835034	10.6061	1	4.15723
37	0.806767	0.835034	0.859884	9.48348	1	3.71722
38	0.835034	0.859884	0.881522	8.31044	1	3.25742
39	0.859884	0.881522	0.900206	7.0433	1	2.76075
40	0.881522	0.900206	0.916224	5.63492	1	2.2087
41	0.900206	0.916224	0.929871	4.03288	1	1.58076
42	0.916224	0.929871	0.941437	2.17758	1	0.853542
Total					306	4419.12

Laser Isotope Separation Principle

Isotope shift and hyperfine splitting in ^{235}U results in atomic lines distinctly offset from those in ^{238}U. After invention of tunable dye lasers, it became practical to selectively excited and ionize ^{235}U.

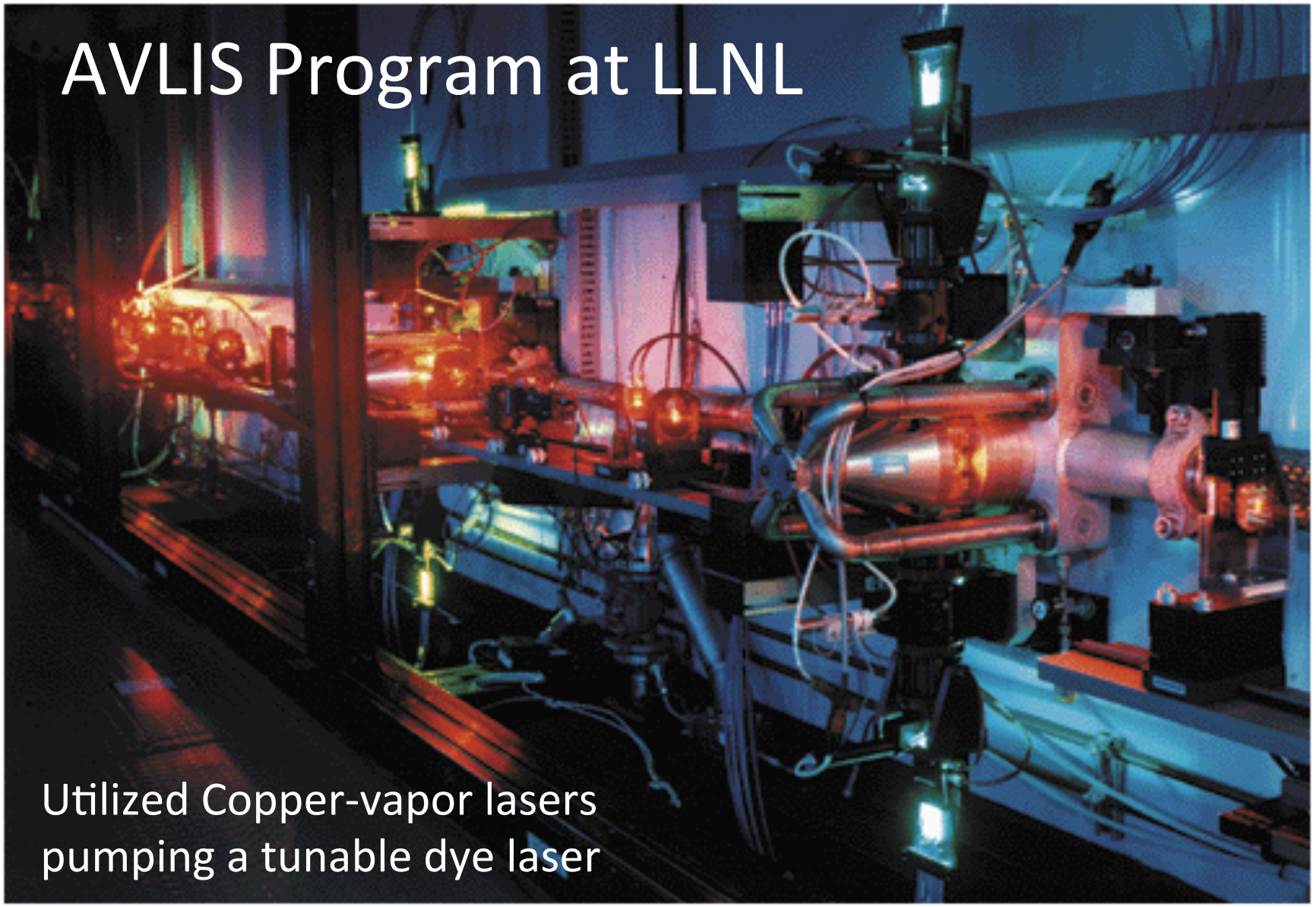


Laser Isotope Separation - Schematic



In the laser system used for the LIS uranium enrichment process (right), electrons from the ^{235}U atoms are separated (left), leaving positively charged ^{235}U ions that can be easily collected for use.

AVLIS Program at LLNL



Utilized Copper-vapor lasers pumping a tunable dye laser

LIS plant-scale dye laser chains absorb green light from solid-state lasers and reemit it at a color that can be tuned to the isotope of interest. For uranium enrichment, the green light was converted to red–orange light of three different wavelengths that are absorbed only by uranium-235.

AVLIS Summary

- Program began in 1973 at Lawrence Livermore National Lab.
- The pilot plant did successfully produce ton-quantities of ^{235}U.
- Ultimately transferred to US Enrichment Corporation (USEC).
- In 1999, USEC closed down the program, at a loss of $100M.
- This is a high-tech path to enrichment, but not beyond the means of moderately technically advanced nations nowadays, although the capital investment is significant.
- It is a proliferation challenge, as its power requirements are very low compared to gaseous diffusion or gas centrifuges.
- There was one scientific fruit of the AVLIS program however …

Laser Guide Star system for Astronomy (Claire Max, Will Happer)