Laser Isotope Separation :

a 21ST Century Technology

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TIFR: ASET colloquium

PLAN OF TALK

1. WHY are isotopes needed?
2. WHY lasers for separation?
3. WHY is it a 21st CENTURY TECHNOLOGY?

   A : The Simplicity & B: The Complexity

PART 1

1. WHY are ISOTOPES needed?

What are ISOTOPES?

- **True to their name, all Isotopes of an element occupy the same place (in Greek) in Periodic table.** Frederick Soddy in 1913 coined this word when he observed 40 different decay chains between Pb and U with only 11 slots in periodic table.
- This makes them **identical** chemically and physically too.
- So why any interest in them singly? Why separate?
- As they have distinct 'A' they differ in '**nuclear properties**'

Early Uses of isotopes

- Use of naturally occurring Radium for radiotherapy: **1930s.**
- Demonstration of nuclear pile by Enrico Fermi and Leo Szilard: **1942**.
- **Manhattan Project WW II: 1942-46.**
- **Nuclear electricity**: **1955.**
- Cobalt 60 therapy replaced X-ray radiotherapy: **1961.**

A more appropriate word "nuclide"

- Our interest lies in A, so the word "nuclide" is more appropriate.
- With 339 naturally occurring nuclides on Earth (286 primordial) and If we include artificial radioactive nuclides, we have 3,339. Out of these 905 nuclides are either stable or have half-lives longer that 60 minutes.

Nuclear physicists & engineers have a rich Menu

Some are needed in TONs (enriched or depleted): U, Pu, D…

Gd, Zr, B…

Others in smaller quantities: C, N, O…

So where is S_n ?

Early Isotope Separation Methods…

- The "Kinetic Isotope Effect" or KIE is the change in reaction rate of a chemical reaction when one atom in reactants is replaced by one of its isotopes.

$$KIE = k_L/k_H$$

L and H refer to lighter and heavier species

- Heavier isotopic species have lower mobility and higher dissociation energy resulting in lesser yields compared to lighter species.

Taking the reaction of methyl bromide with cyanide

$$CN^- + CH_3\text{-}Br \rightarrow CH_3\text{-}CN + Br^-$$

$$KIE = k_{12}/k_{13} = 1.082$$

Why is the chemical route attractive?

- Low energy consumption: typically few eV/atom. Easy scale-up by concentration/ volume. Easy instrumentation and control. No extremes.
- H_2O/D_2O. [Nuclear industry] $\Delta m/m$ = 100%
- Li_6/Li_7. [Nuclear Industry] = 17%
- B_{10}/B_{11} .[Nuclear Industry] = 10%
- C_{12}/C_{13}. [Medical] = 8.3%
- N_{14}/N_{15}. [Medical] = 7.1%
- O_{16}/O_{18}. [Climate studies] = 12.5%

All above are low Z elements where $\Delta m/m$ is high.

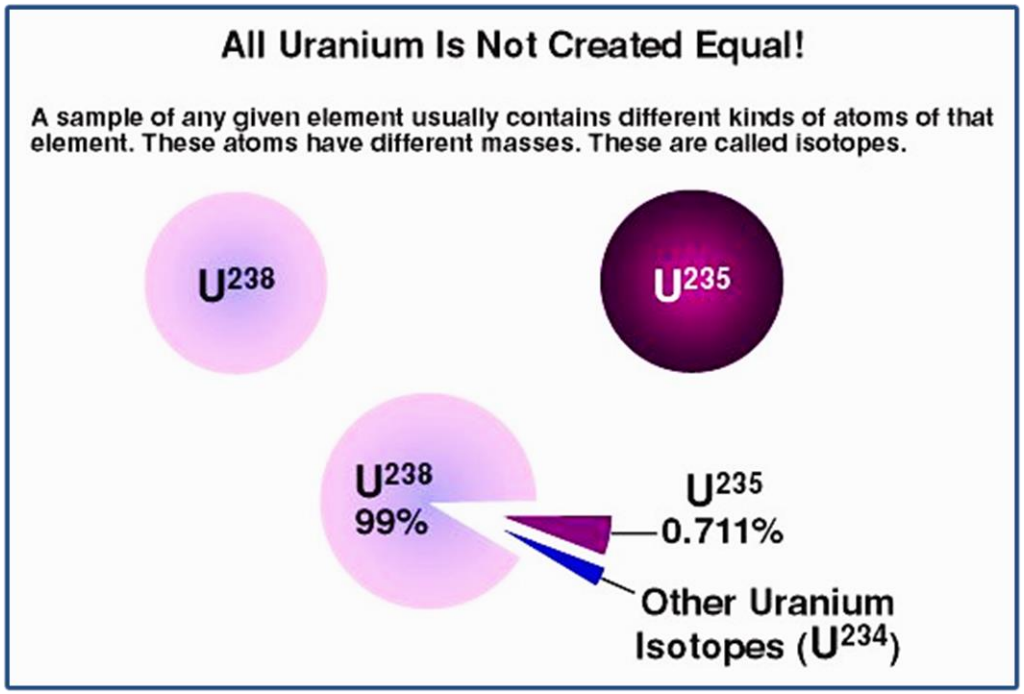
Low Z and High Z…

- For low Z elements mass effect dominates but for high Z elements it is the nuclear volume and nuclear structure effect that dominates.

- Take $_1H^1$ and $_1D^2$. The mass difference is 100%! Thus, we are likely to see comparatively large chemical/physical effects here.

High Z isotopes…

- Take $_{92}U^{235}$ and $_{92}U^{238}$. Percentage mass difference is 3/238*100 = 1.26 %. So KIE factor about 100 times less (or about 100 – 10,000 times difficult to enrich by chemical methods).



- Low abundance isotopes will behave like impurities !

For High Z we adopt physical methods

- Instead of kinetic factor in chemical dynamics, in physical methods we use differential motional effects such as diffusion and centrifugation rates.

- To enable this the atomic or molecular species have to be either in gas phase or vapor phase.

UF_6 is the wonder molecule [God's gift] which is a gas at near room temperatures.

Without this both Diffusion and Centrifugation would need **3000K**

2. WHY LASERS FOR SEPARATION?

Large Scale physical methods…

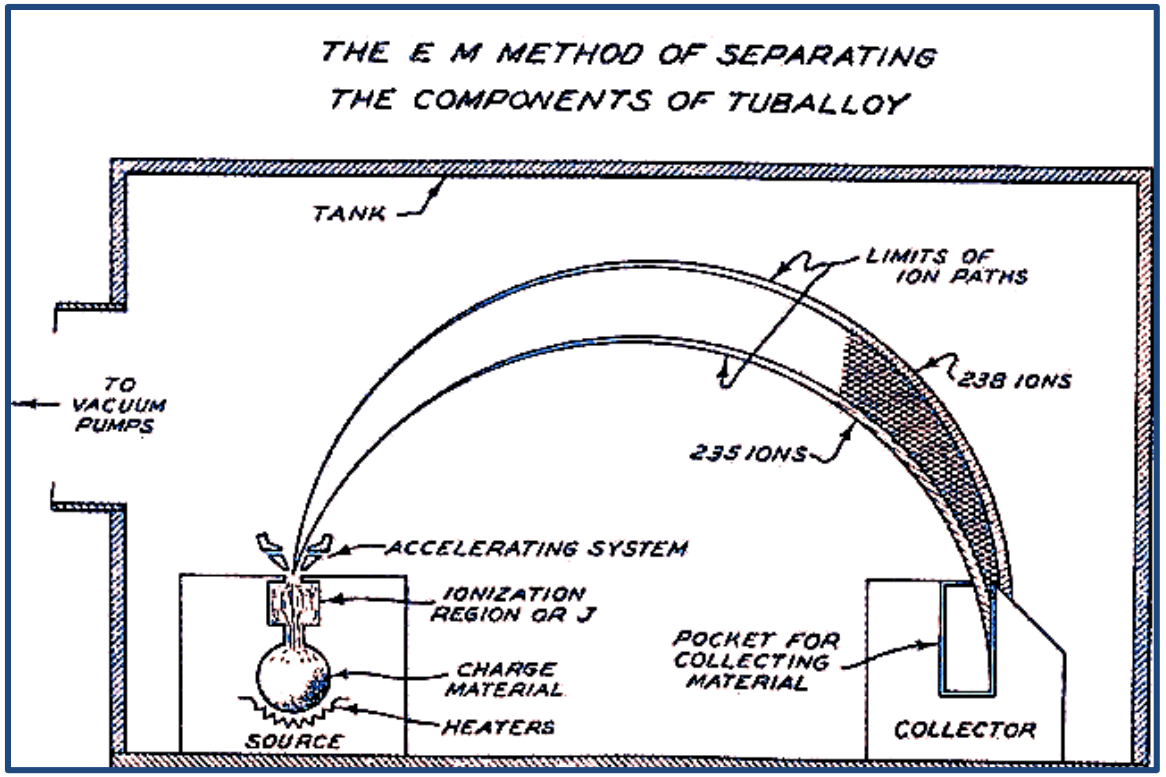
- Electromagnetic Separator (Calutron).
- **Gaseous Diffusion.**
- **Centrifugation.**
- **Laser Isotope Separation.**

The context is U^{235}/U^{238} separation to reach concentration 4.5% [from 0.725%] for use as nuclear fuel in BWRs and GCRs in large quantities – 100s tons

The nuclear industry offers business to the tune of few billion $/year to generate electricity [24,000-30,000 MWd/ton].

Electromagnetic separator

- This was used during WWII for an atomic bomb.
- Calutrons were '**slow, inefficient but effective**'.



They were nothing but 'Giant mass spectrometers'.

POST-War calutrons were phased out. Small versions still exist! Why?

- They could be used on many elements. As a method applicable to many species it is attractive.
- Spinoff: Ion sources.
- Large separation factor α in single pass:

$$\alpha = C_{out}/C_{in}$$

Like, C is the ratio of U_{235}/U_{238} by weight.

Economics decides the method…

- Engineering is called the '**handmaiden of economics**'. If this be so, Technology Decisions are even more so.

Let us see why?

This enrichment is done to fuel a **NPP to generate electricity.** We cannot spend more energy on enrichment of U^{235}/atom than its electricity worth.

$$n + U^{235} \rightarrow \text{fission products} + 2.5n + 200MeV$$

We get only **70MeV** of electricity from 200MeV of kinetic energy (at 35% efficiency).

The limits on energy cost/atom

- Upper limit: 70MeV.
- Lower limit: ??
- Lower bound of lower limit is set by thermodynamics (entropy of mixing) and is 0.001eV if we employ a reversible process.
- This is possible (very attractive!) if we employ Mr. **Maxwell Demon** to sit inside our separator and atomically move U^{235} atoms (or molecules) from feed stream to product stream. Only Demons can carry out this reversible process at this scale.

Real Processes (no Demons!)….

- These are steady state processes and governed by RATE (moles/sec of product). The higher the rate, the more the departure from equilibrium and thus from the ideal of an infinitely slow reversible process.

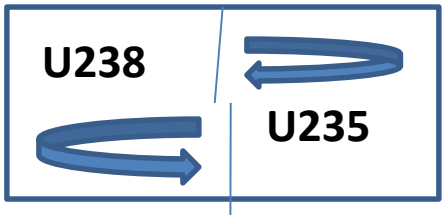
- High rates attract dissipative channels that get activated with our process of separation, and increase the energy expenditure.

We have to avoid extremes: high temperatures, pressures, speeds as these will bring in dissipative channels. **Do We?**

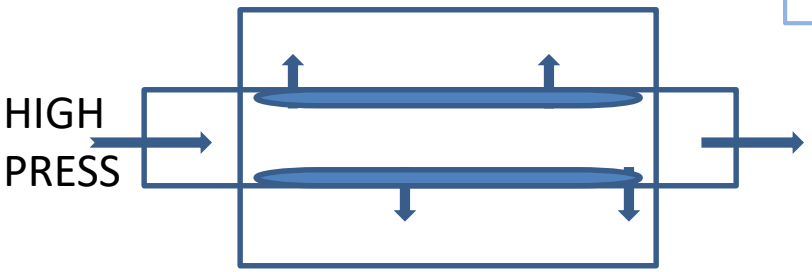
DEMON vs HUMANS

MAXWELL DEMON

0.001eV $\alpha = \infty$

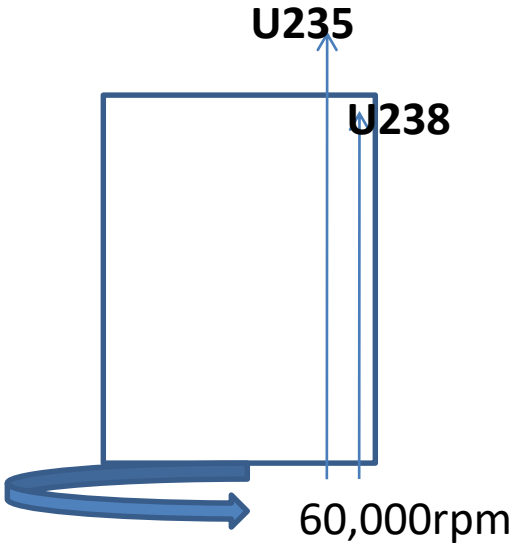


TIME ???



DIFFUSION

2.5MeV $\alpha = 1.004298$



CENTRIFUGE

200KeV $\alpha = 1.4$

PHYSICS TODAY Sept 1964, Thermodynamics in Finite Time

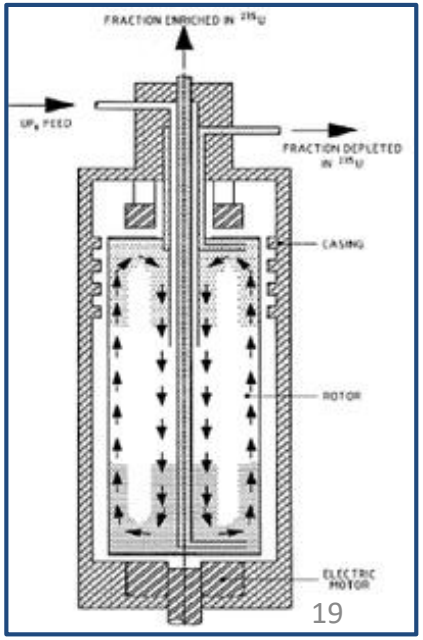
Technology and Proliferation

Diffusion

- Proliferation resistant.
- High capital cost.
- Barrier technology (high tech. and secret).
- High pressure.
- 500 stages to reach reactor grade.

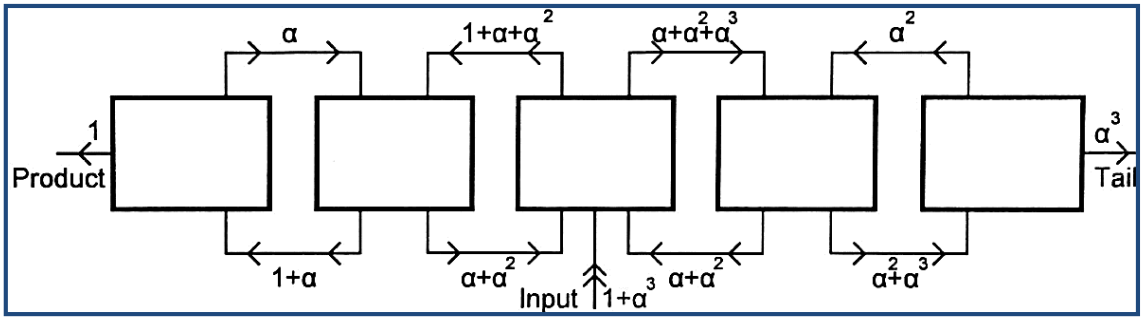
Centrifuge

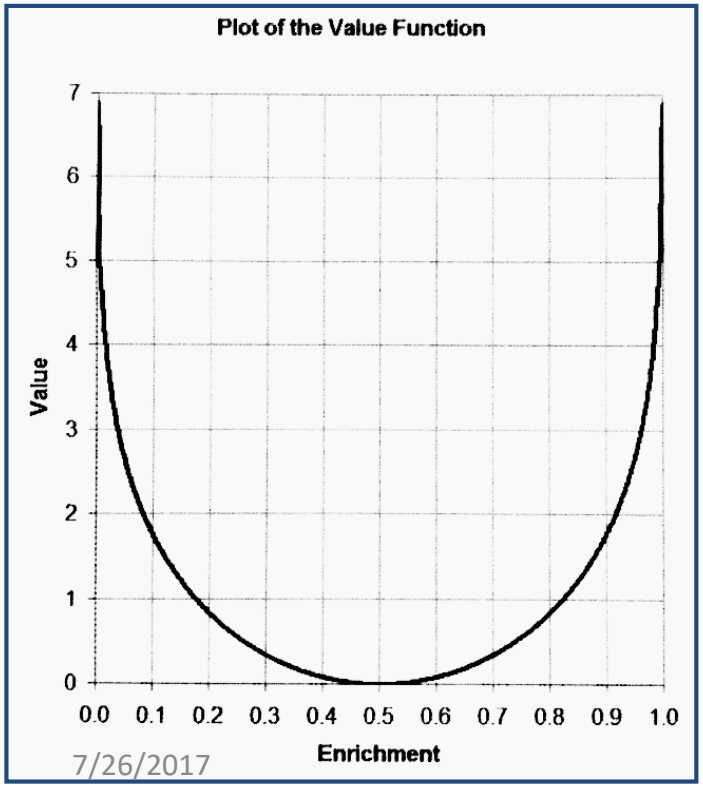
- Less proliferation resistant.
- Capital 1/10 of Diffusion.
- Rotor design & material.
- High speed.
- Stages: 300



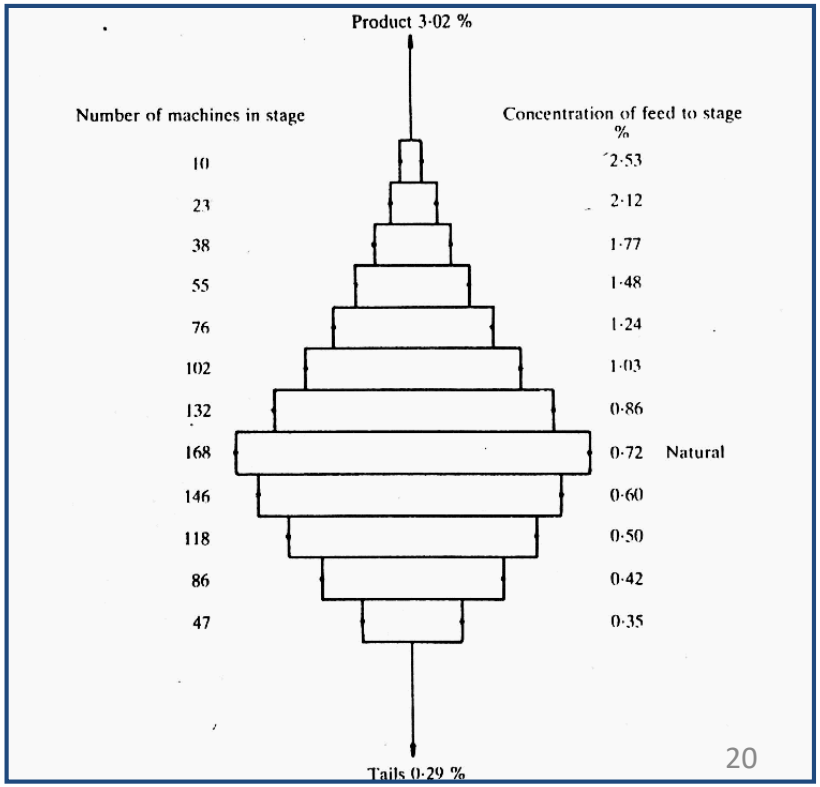
One is not enough, much more and in cascade…

P.A.M. DIRAC





Separation Capacity, SWU



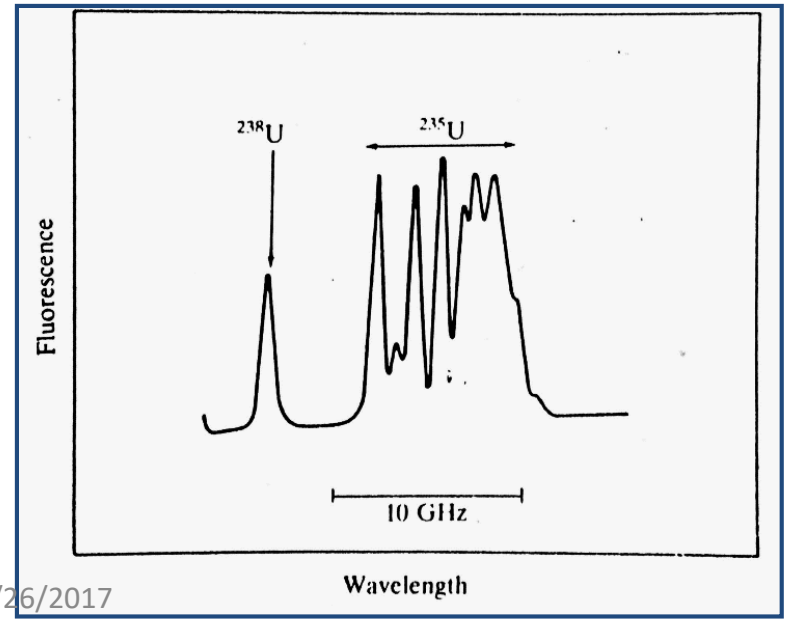
Money makes the world go round
Circa early 1970s…

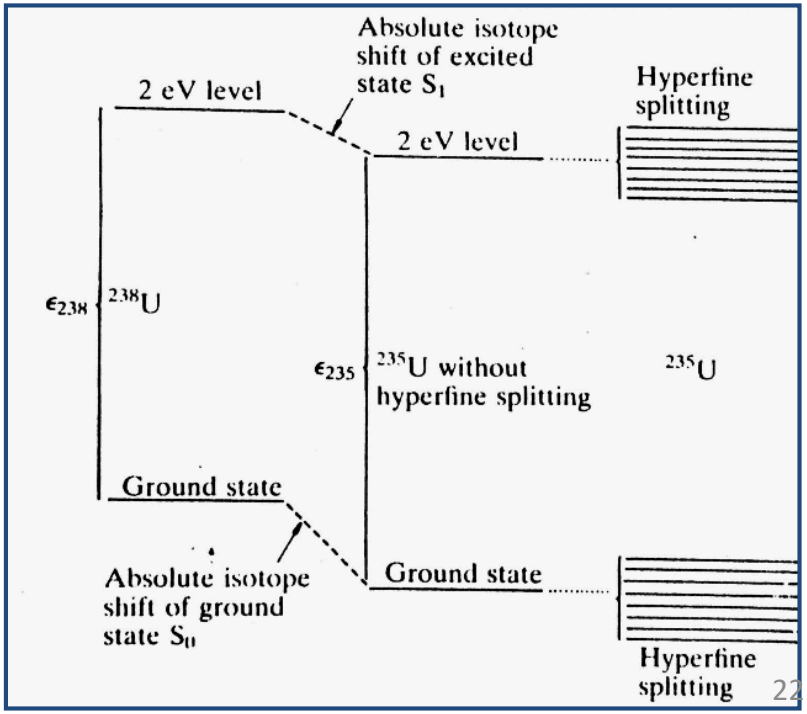
- From 1970 to 1984 there was doubling of world capacity in Nuclear Generation every 3 years! It rose from 25 to 300 GW. Except reactors in Canada/India, all others need 3% - 4.5% enriched Uranium as fuel.
- Golden chance to market reactor fuel and earn Billions
- Until 1984, Diffusion & Centrifuge plants in Europe, USA catered to 300GW installed capacity.
- Is there a process requiring less capital cost (**high α**), low running cost (**low eV/atom**) and high throughput, that can outperform Centrifuge to earn even more?

So which process?

Some light on the key question…

- Atoms and Molecules have an intimate relation to light via their emission and absorption spectra.
- **Do isotopes absorb different colors?**
- In early 1960s it was seen by many spectroscopists that indeed it is so. This was seen for uranium isotopes too.





Everything points to laser…

- Laser has unique properties due to its coherence via "stimulated emission" (Einstein 1913).

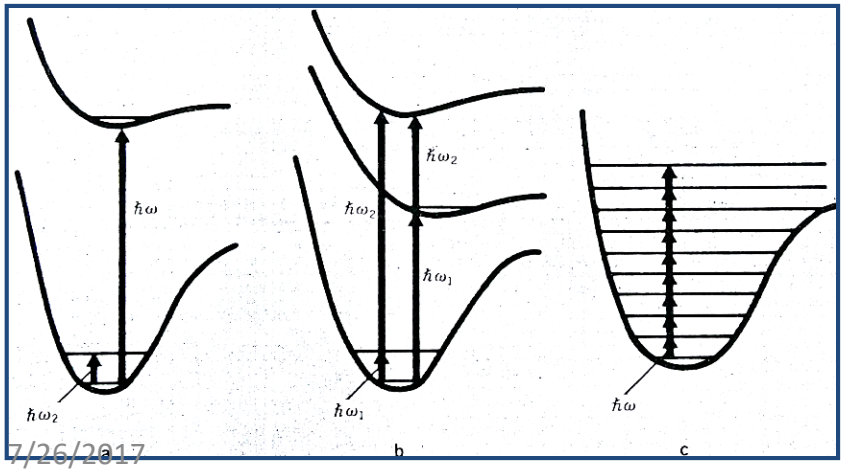
	Laser	OLS
1. Monochromaticity (Line width)	10 MHz	600GHz (SOX)
2. Directionality: Divergence	mRad	100s Rads
3. Brightness: Power Density	100s kW/cm^2	mWs/cm^2

Each of these is amply used in LIS processes. With tunable low line-width Dye Lasers the stage was ready in 1970s.

MLIS and AVLIS circa 1970s
USA, UK, France, Japan, India…

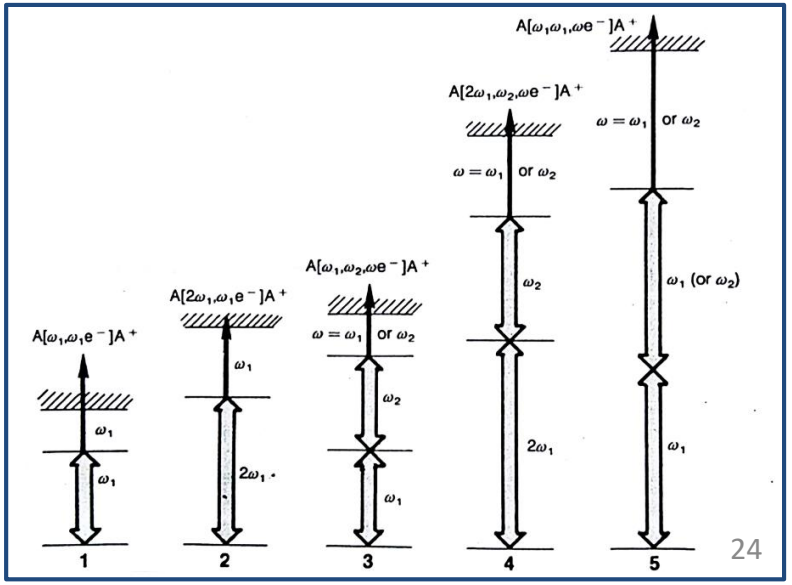
MLIS, Los Alamos

1. UF_6 (↑) Room Temp
2. Nozzle beam expansion(↓)
3. Multiphoton Dissociation MPD (↓)
4. 16μ laser (↓)
5. Selectivity (↓) **α ≥ 1.05**



AVLIS, Lawrence Livermore

1. U metal (↓) 3000K
2. Vacuum evaporation (↓)
3. Selective Photo-Ionization (↑)
4. Copper Vapor Lasers (↑)
5. Selectivity (↑↑↑…) **α ≥ 10-50**



Who wins the technology race? MLIS or AVLIS? 1984

- **Why spend $millions and ten years to discover?**

- Many a learned men think knowing the principles is enough. Not so. The Devil is in the details but so is the salvation.
- You have to learn from the mistakes of others. You won't live long enough to make them all yourself.

- Admiral Hyman G. Rickover

Multidisciplinary research …

- Not just physicists, chemists and metallurgists but also electrical/electronics/mechanical/chemical engineers.

Who will guide these young angels/devils?

Physics is love, Engineering is marriage.

-- **Norman Mailer**

"A fire on the moon"

Principles (generalities)

Trade-offs (compromises}

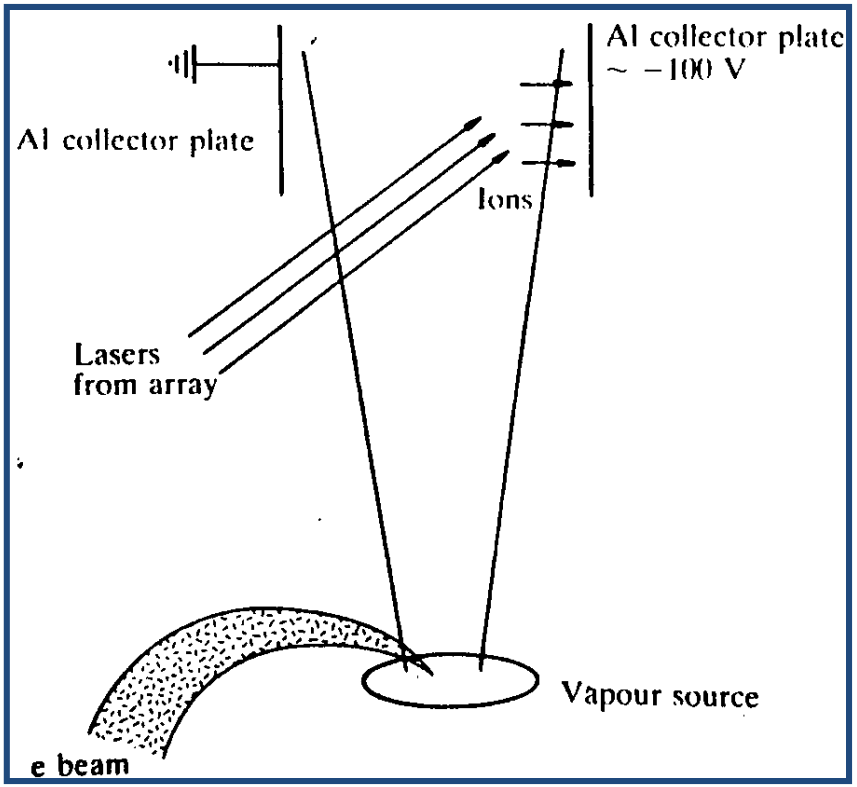
Scientists: Ok, spectrum to be seen, selectivity to be found…

Engineers: Design specifications, blueprints (auto-cad drawings). What should I optimize?..

1984: AVLIS wins the first round. Winner takes all.

So what is AVLIS?

1. Electron beam for vapor
2. Lasers for selectively converting U^{235} to ions.
3. Small field between Al plates to deflect ions: (product collector).



3 A. WHAT IS SIMPLE IN AVLIS SEPARATION?

Some estimates …

- Only two main technologies: E-beam and Laser.
- Cost of vapor generation: 0.5[1/η]eV/atom.

  If η= 2%, [ ] is 50. Hence, 25eV/atom is a safe bet. Since evaporation is non selective, we take 140.25= **3.5keV/atom.**
- Cost of laser photo-ionization: 3[2]eV[1/η]/atom.

  Here laser [ ] is 0.01% for dye laser photons. So the final figure is 60keV/atom if photon utilization is 100%. Remember, cross-section of absorption is in the range $10^{-13 \text{ to } -15}$. So realistic figure will be = **150keV/atom.**

So why AVLIS when Centrifuge cost is comparable?

Low capital cost, small size (hence small inventory)and above all wide applicability.

- Laser should exist at the desired v.

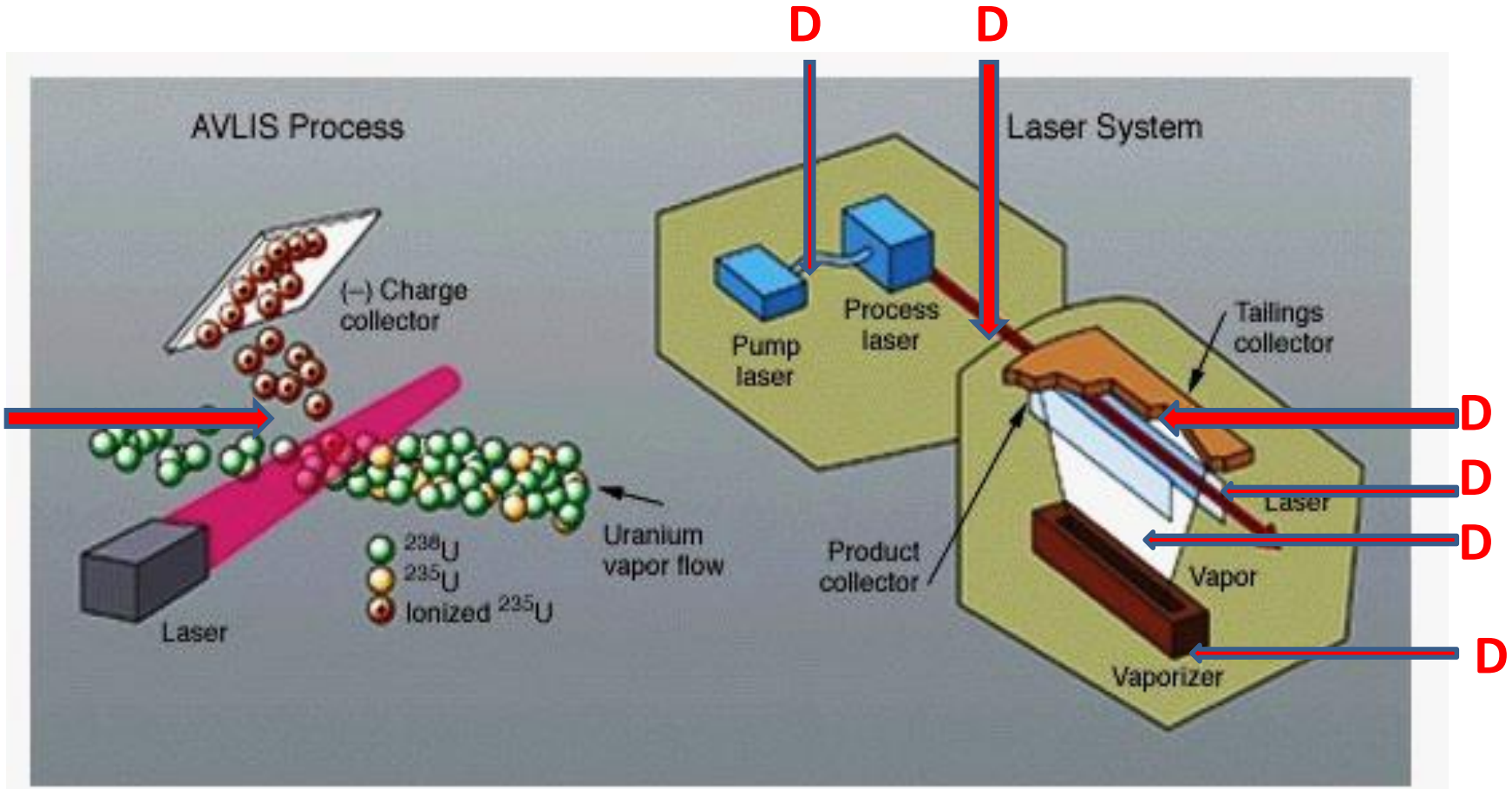
Applicability of Resonance Ionization Spectroscopy schemes

Element	Atomic number	Scheme	Element	Atomic number	Scheme	Element	Atomic number	Scheme
Hydrogen	1	5	Bromine	35	5	Thulium	69	1
Helium	2	–	Krypton	36	5	Ytterbium	70	2
Lithium	3	2	Rubidium	37	1	Lutetium	71	1
Beryllium	4	4	Strontium	38	2	Hafnium	72	3?
Boron	5	4	Yttrium	39	3	Tantalum	73	3
Carbon	6	5	Zirconium	40	3	Tungsten	74	3
Nitrogen	7	5	Niobium	41	2	Rhenium	75	2
Oxygen	8	5	Molybdenum	42	2	Osmium	76	3
Fluorine	9	5	Technetium	43	3	Iridium	77	3
Neon	10	–	Ruthenium	44	2	Platinum	78	4
Sodium	11	2	Rhodium	45	2	Gold	79	4
Magnesium	12	3	Palladium	46	4	Mercury	80	4
Aluminum	13	1	Silver	47	4	Thallium	81	1
Silicon	14	4	Cadmium	48	4	Lead	82	4
Phosphorus	15	5	Indium	49	1	Bismuth	83	4
Sulfur	16	5	Tin	50	2	Polonium	84	4
Chlorine	17	5	Antimony	51	4	Astatine	85	5?
Argon	18	5	Tellurium	52	4	Radon	86	5
Potassium	19	1	Iodine	53	5	Francium	87	1?
Calcium	20	2	Xenon	54	5	Radium	88	2
Scandium	21	2	Cesium	55	1	Actinium	89	3?
Titanium	22	2	Barium	56	2	Thorium	90	1?
Vanadium	23	2	Lanthanum	57	1	Protactinium	91	1?
Chromium	24	2	Cerium	58	1	Uranium	92	2
Manganese	25	2	Praseodymium	59	1	Neptunium	93	1
Iron	26	2	Neodymium	60	1	Plutonium	94	1
Cobalt	27	2	Promethium	61	1?	Americium	95	2
Nickel	28	2	Samarium	62	1	Curium	96	1
Copper	29	4	Europium	63	2	Berkelium	97	1
Zinc	30	4	Gadolinium	64	1	Californium	98	1?
Gallium	31	1	Terbium	65	1	Einsteinium	99	2
Germanium	32	4	Dysprosium	66	1	Fermium	100	1?
Arsenic	33	5	Holmium	67	1	Mendelevium	101	1?
Selenium	34	5	Erbium	68	1	Nobelium	102	1?
						Lawrencium	103	1?

3 B. WHAT IS COMPLEX IN AVLIS SEPARATION?

WHERE ARE THE DEVILS?

BEWARE, DEVILS EVERYWHERE…



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.

First attempt. Did it succeed? Was it a failure?

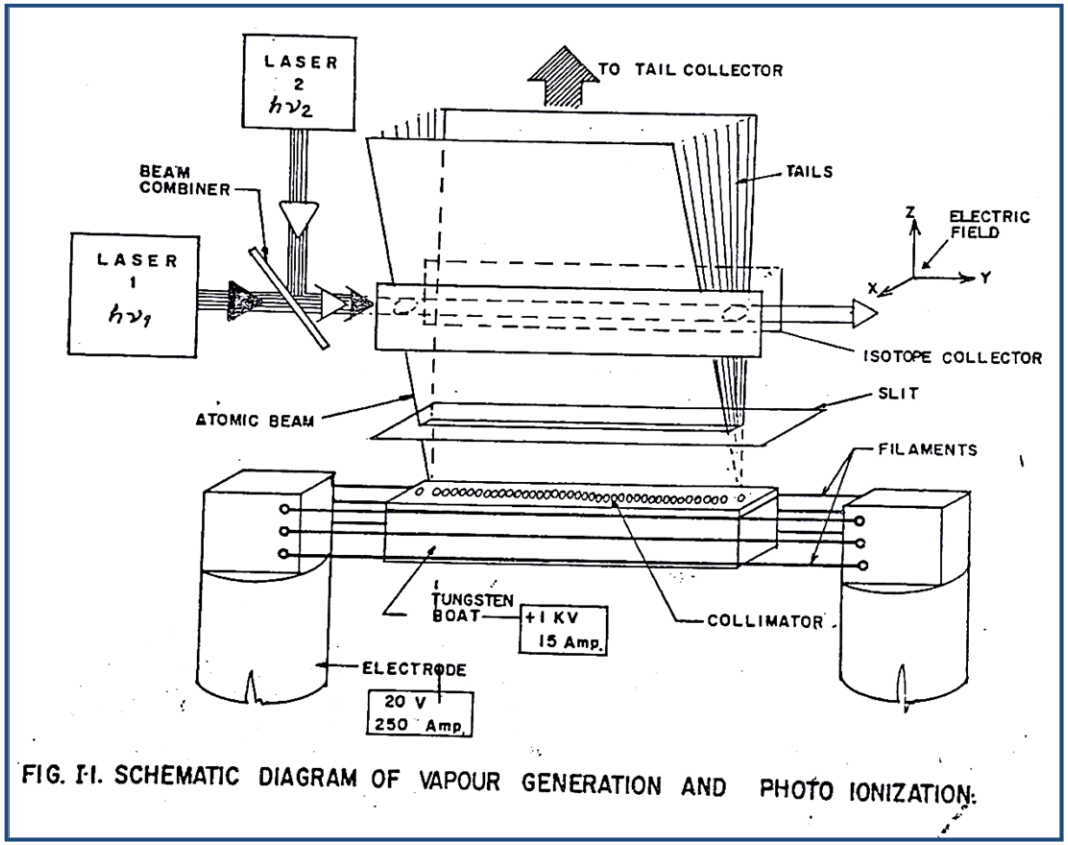


FIG. I-1. SCHEMATIC DIAGRAM OF VAPOUR GENERATION AND PHOTO IONIZATION.

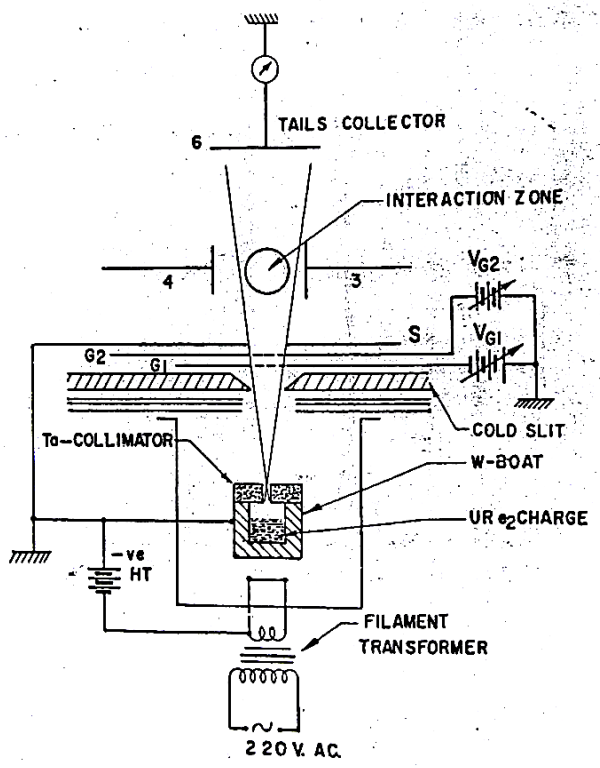


FIG. III-2 THE SCHEMATICS OF GENERATION OF ATOMIC BEAM AND THE INTERACTION ZONE.

Our aim. To collect enough to mass-spectrometric analysis (200picomoles) **100 ngm.**

Vacuum surprises…

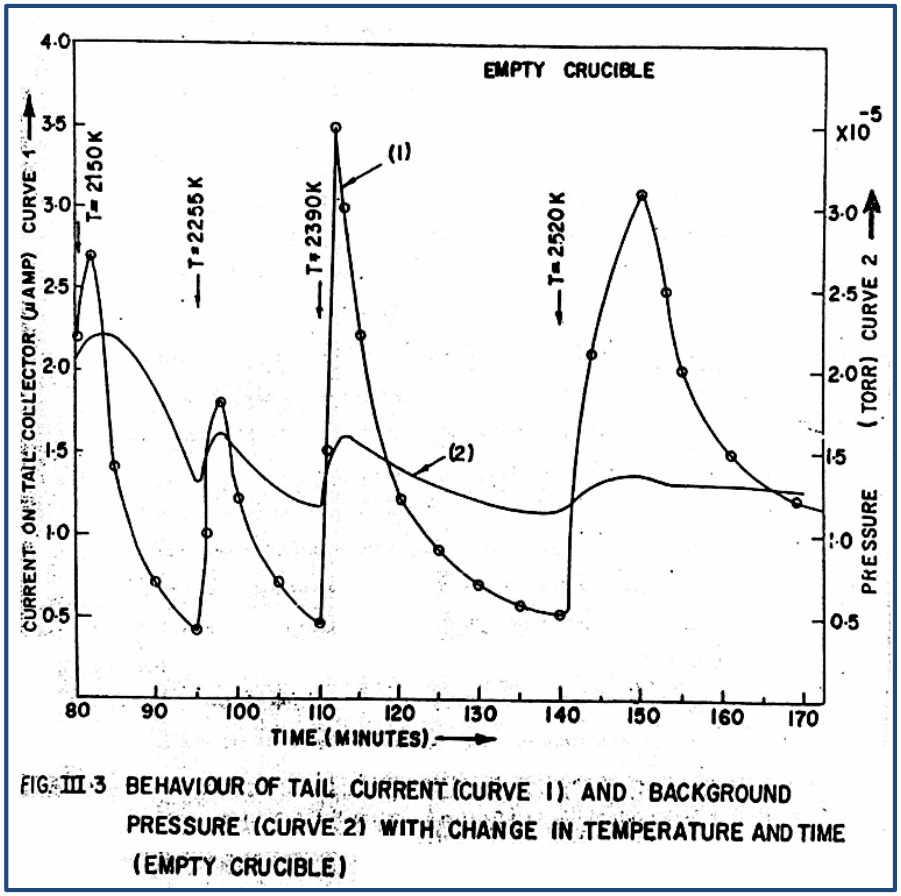


FIG. III·3 BEHAVIOUR OF TAIL CURRENT (CURVE 1) AND BACKGROUND PRESSURE (CURVE 2) WITH CHANGE IN TEMPERATURE AND TIME (EMPTY CRUCIBLE)

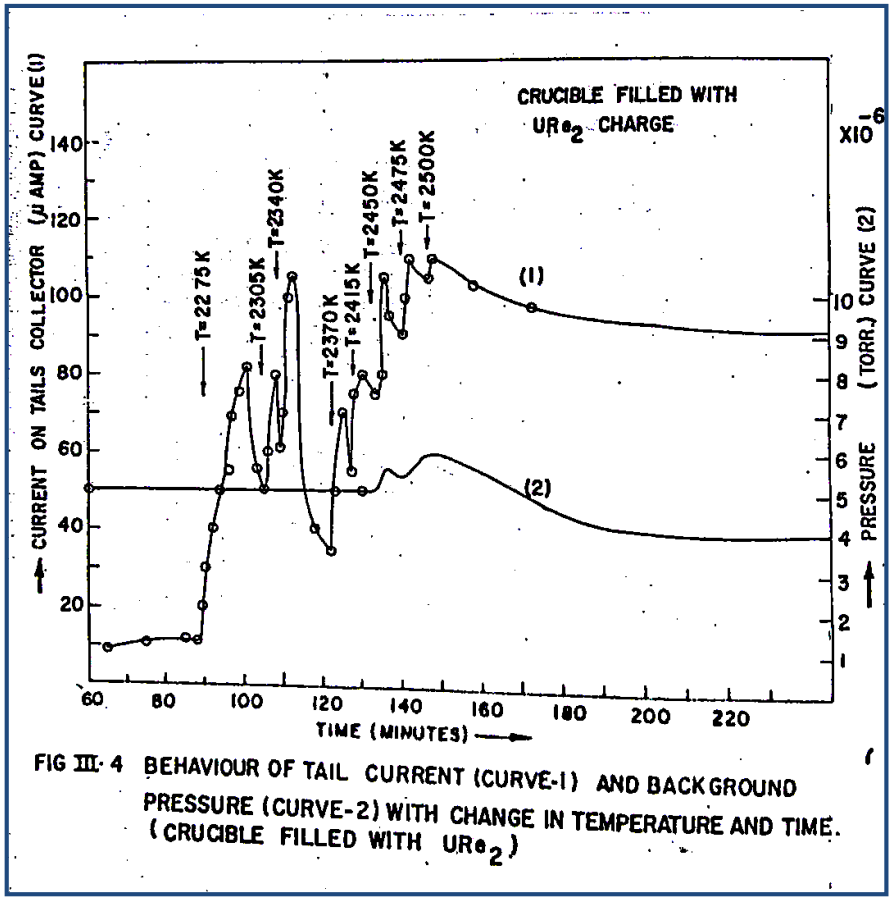


FIG III·4 BEHAVIOUR OF TAIL CURRENT (CURVE-1) AND BACKGROUND PRESSURE (CURVE-2) WITH CHANGE IN TEMPERATURE AND TIME. (CRUCIBLE FILLED WITH UR_2)

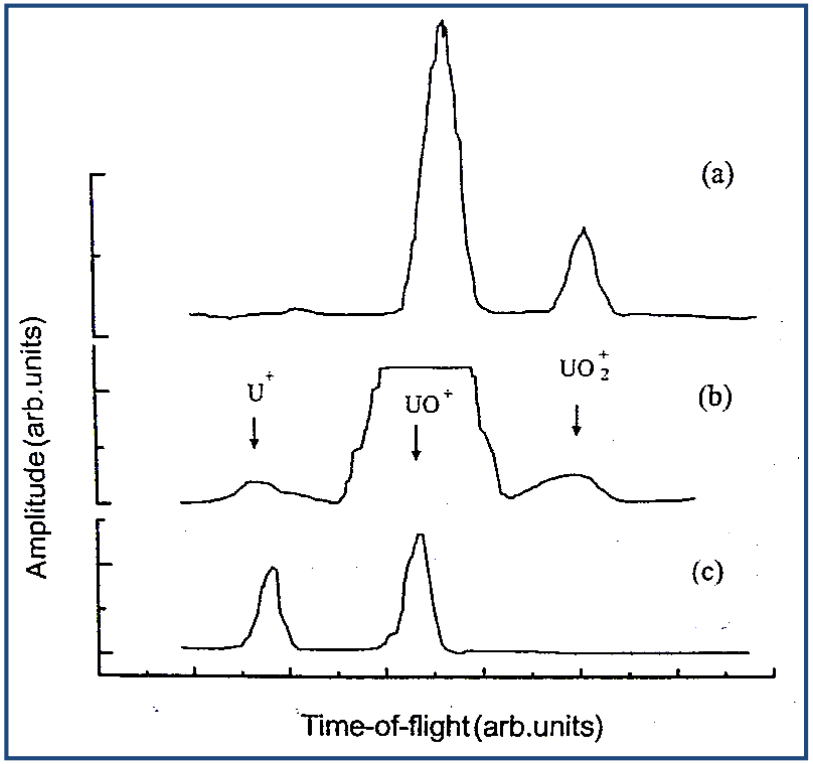
Devil is helping in vacuum.!!! At what price?

Reducing operation time to 1/10 and making signals 40 times difficult to detect. Please notice the large current on tails (30-40 times).

Something not planned. Devilish?

We investigated the species by installing a TOF mass spectrometer with 2 step laser photoionization.

- (a) 5 min of heating 2130K
- (b) 15 min at 2190K
- (c) 1 hr at 2250K.
- Oxide peak is still more than U peak (not a good sign!).



Compromises with vacuum….

(1) 5 hrs heating
(2) Brief exposure to air.

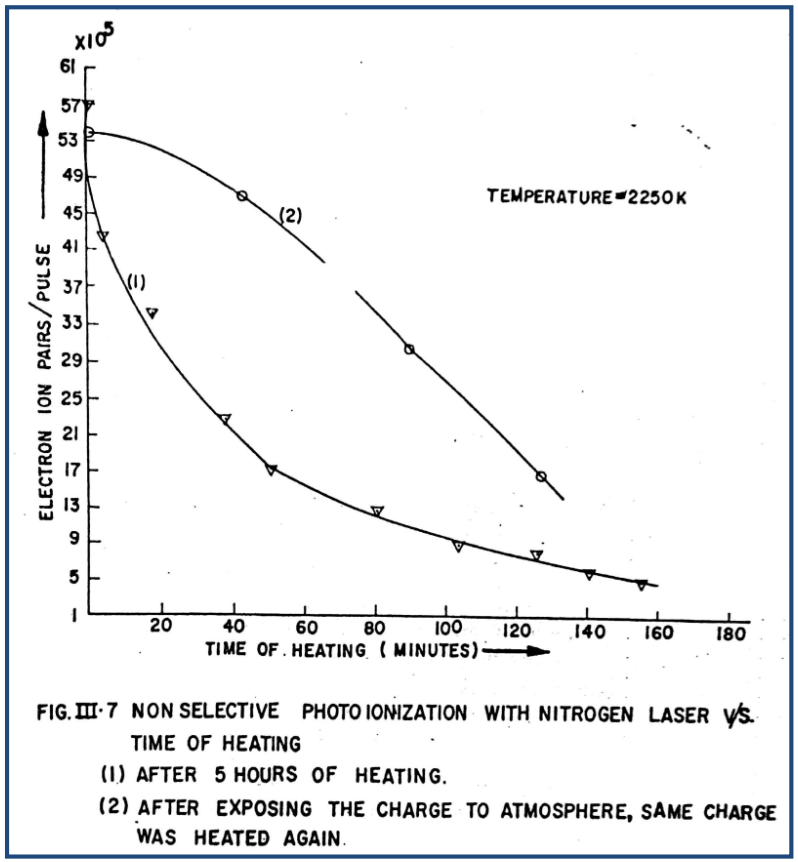


FIG. III·7 NON SELECTIVE PHOTO IONIZATION WITH NITROGEN LASER VS. TIME OF HEATING
(1) AFTER 5 HOURS OF HEATING.
(2) AFTER EXPOSING THE CHARGE TO ATMOSPHERE, SAME CHARGE WAS HEATED AGAIN.

(1) Overnight closure
(2) After 12 days

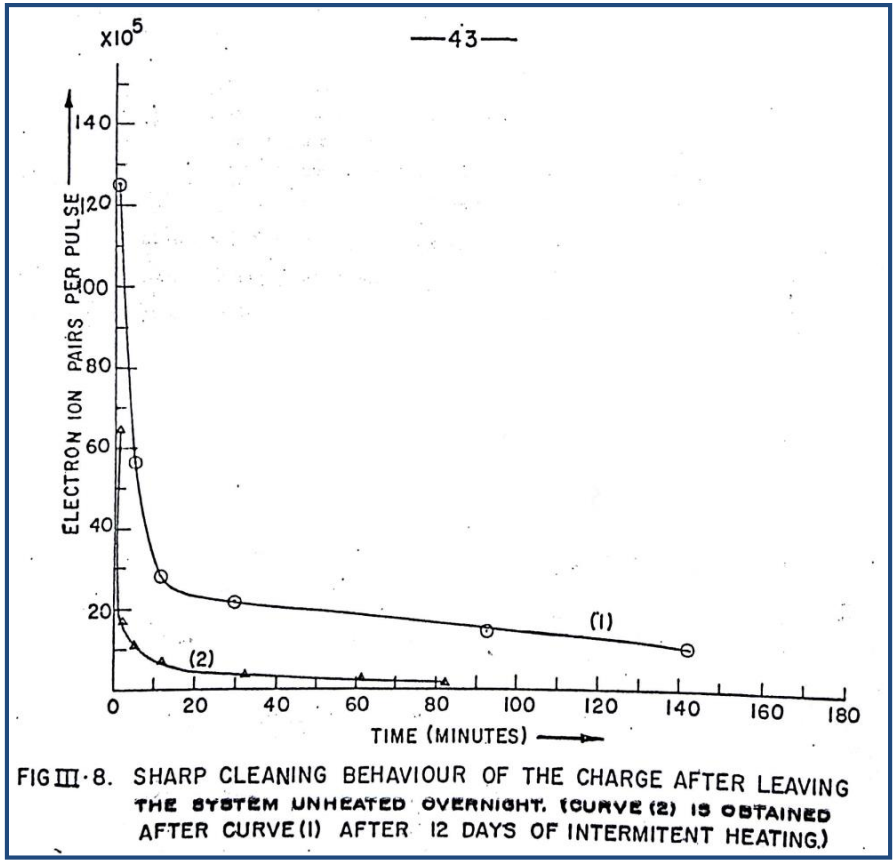


FIG III·8. SHARP CLEANING BEHAVIOUR OF THE CHARGE AFTER LEAVING THE SYSTEM UNHEATED OVERNIGHT. (CURVE (2) IS OBTAINED AFTER CURVE (1) AFTER 12 DAYS OF INTERMITENT HEATING.)

Started working two shifts with pumps running all the time to minimise Oxide menace!

We hit a wall. No increase beyond 2500K. Only a (BANG).

- Impedance of the load falls and very fast. Can we make it slower and stabilize to study what is happening?
- The bank of bulbs slowed down and stabilized the operation if we lower the voltage manually.
- **Then we discovered that filament can be turned off completely!**
- Who on earth is giving this HIGH CURRENT?

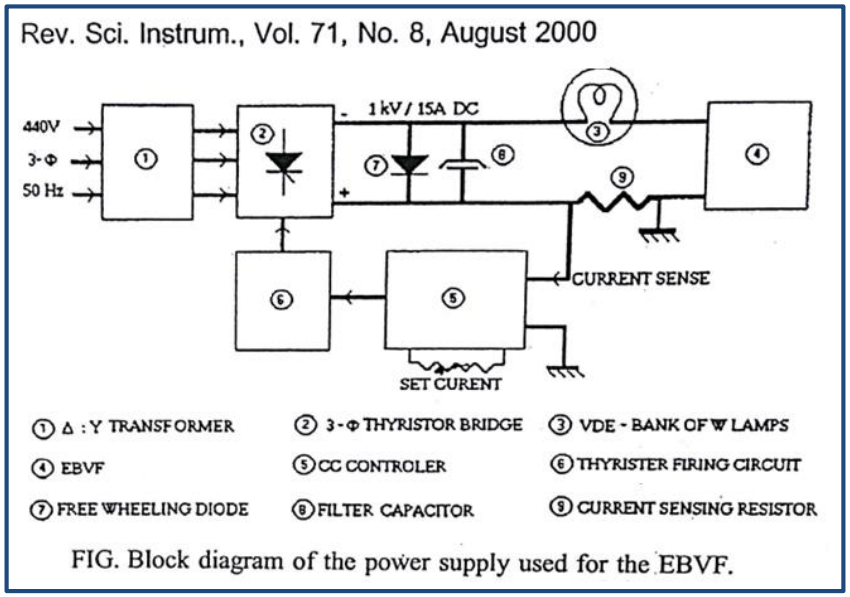


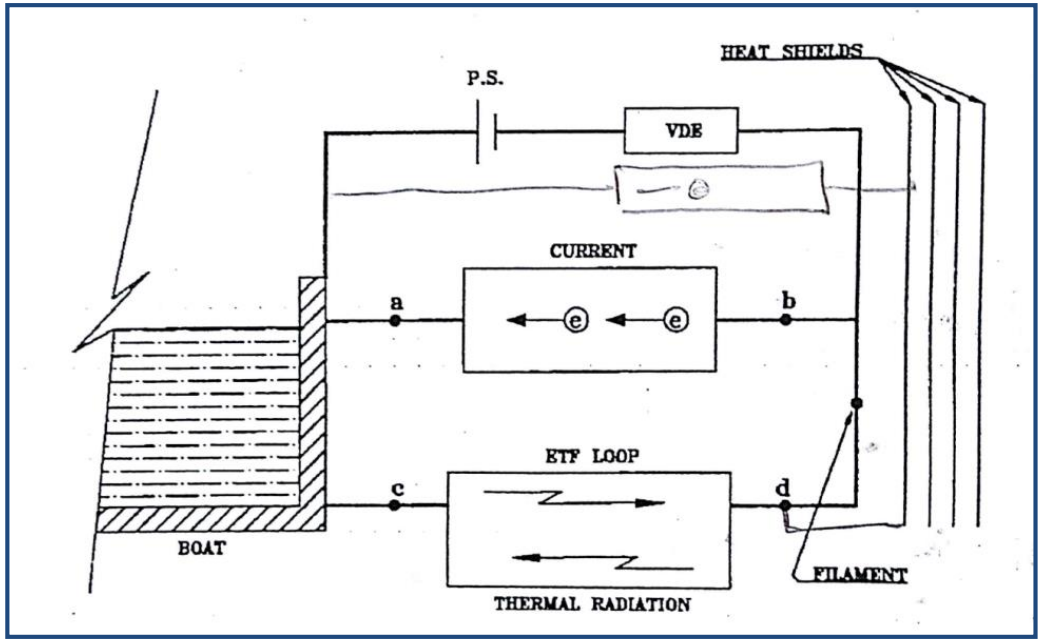
FIG. Block diagram of the power supply used for the EBVF.

We were asked to bury this find and move on to the solution…..

Devil for Sure!

THE ANSWER AFTER 20 YEARS!

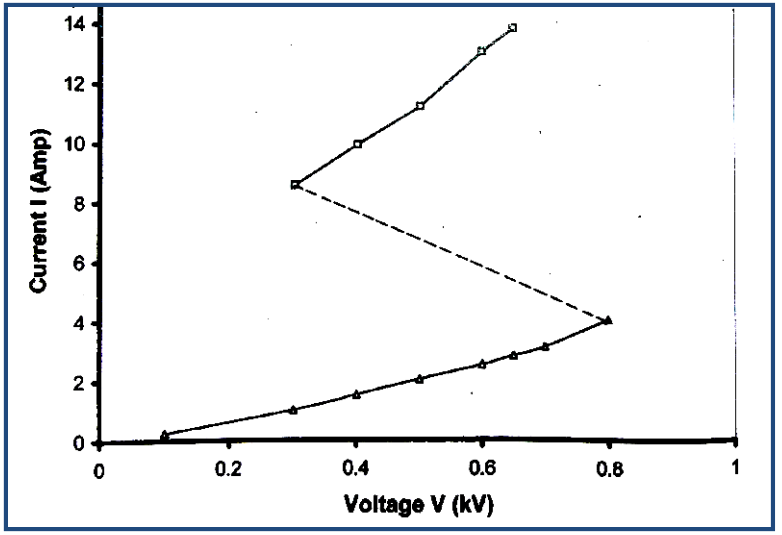
ANALYSIS



Two paths: filament and innermost shield.
M.S. Bhatia et al, RSI, 2000.

PHYSICAL EVIDENCE

7. Transverse section of rectangular used boat heated to 2765 K with Ta-Collimator W-Density 98%.



Contain liquid Uranium…

- **Who can save us from the fury of liquid uranium?**

  I am reminded of a dialog

  "Gabbar ke taap se sirf ek hi aadmi bacha sakta hai, khud Gabbar"!

- **The answer: Only cold Uranium**

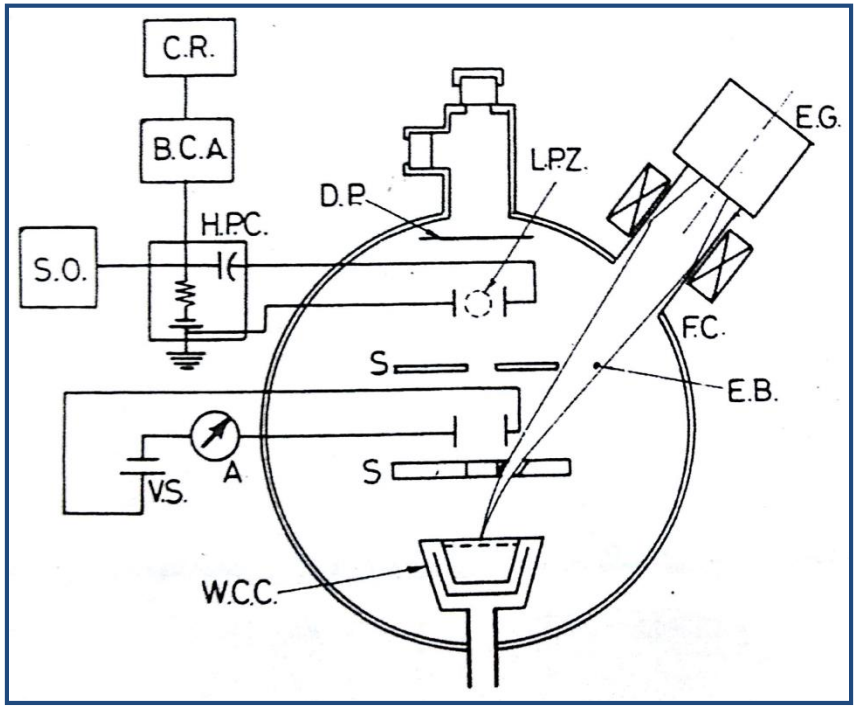
Although its vapour is relatively innocuous, liquid uranium is that cynosure of the Alchemists, the alkahest, the universal solvent of Paracelsus.

P.T. Greenland, Contemp. Phys, 1990

Switch to Self Accelerated e-Guns- High Voltage

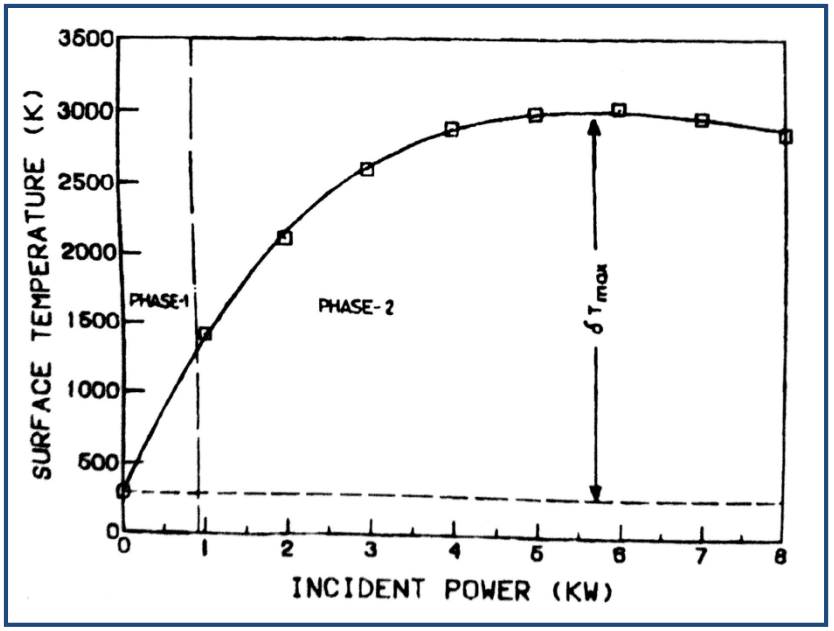
3000K. Oxide problem solved for free!

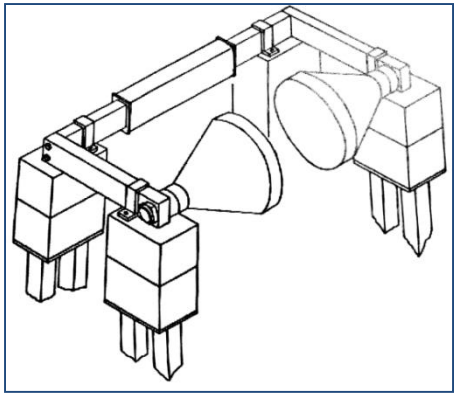
Power density 100kW/cm²



M.S. Bhatia et al, JAP 1989.

Some more devils…





Enrichment but very low. Reason?

Very poor duty cycle of laser.

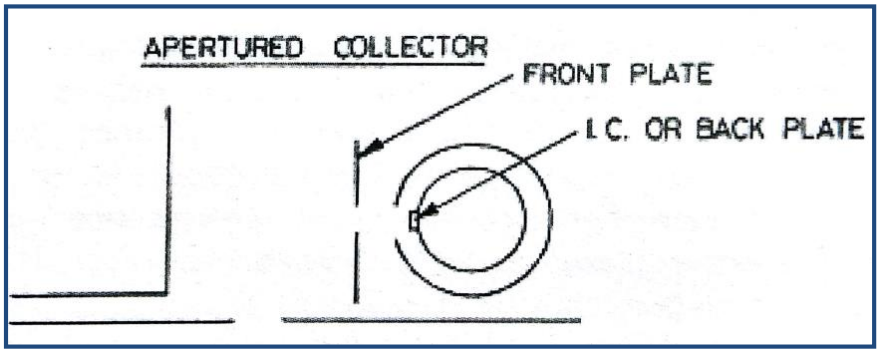
- **Good ideas are not adopted automatically. They must be driven into practice with courageous patience.**
- **If you're going to sin, sin against God not the bureaucracy; God will forgive you but the bureaucracy won't.**

- Admiral Hyman G. Rickover

- So I sinned….

MY sin was the greatest boon!

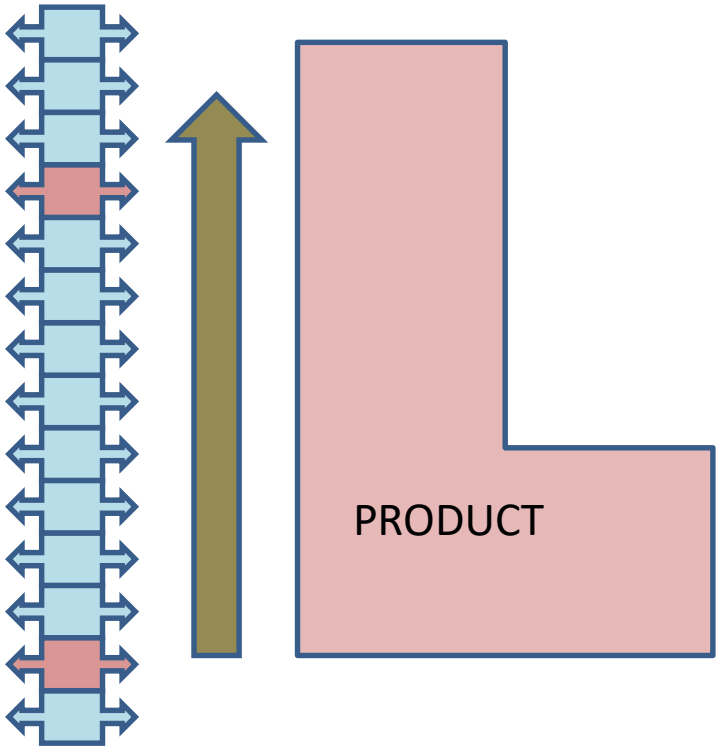
Relative freq. of Non selective vs Selective



Low selectivity. Low intensity. High background.

Increase the laser freq. must.

- We had to wait for CVLs.



With a great result, What next? Gear up for scaling…

- Big plans. Big budget and more people & space.
- All given.
- We were still a younger lot. Success creates opportunities. **So big people with big plans took over.**
- In hindsight, it can be said that old/usual methods of managing in a 21st century technology fail no matter how long and hard you try.
- Managing human aspect is not easy, especially when you are up against talented people.

My Research, Publications…

01. 'Study of G-factor of a Split-coil System'
M.S. Bhatia,
J. Phys. E. Sci. Instrum., **22(1)**, Jan. 1989, 23.
02. 'A simple Technique for Modulating the Output of A CW E-Beam Evaporator',
M.S. Bhatia, A. Joshi, K. Patel and U.K. Chatterjee,
Rev. Sci. Instrum. **60(3)**, Mar. 1989, 505.
03. 'Observation of Non-linearity in E-beam Evaporation from Water Cooled Crucible',
M.S. Bhatia, A. Joshi, K. Patel and U.K. Chatterjee,
J. Appl. Phys. **66(3)**, Aug. 1989, 1159.
04. 'Control of Ionisation in E-beam Evaporators via Optimum Choice of Focal Coil Current',
M.S. Bhatia, K. Patel, A. Joshi and U.K. Chatterjee,
Rev. Sci. Instrum. **60(8)**, Aug. 1989, 2794.
05. 'Pulsed Laser Photo-ionisation Technique for Recording Atomic Flux Variations during Deposition',
M.S. Bhatia, B.A. Dasannacharya and G.L. Sharma,
Rev. Sci. Instrum. **64(7)**, July 1993. 2003.
06. 'Simple Temperature Sensor for Diagnostic Use in E-Beam Evaporators',
M.S. Bhatia, U.K. Chatterjee and G.L. Sharma,
Rev. Sci. Instrum. **64(8)**, Aug. 1993, 2371.
07. 'Novel In-situ Method for Locating the Virtual Source Position in High Rate E-Beam evaporation',
M.S. Bhatia,
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BARC Newsletter, **Issue 135**, May 1995.
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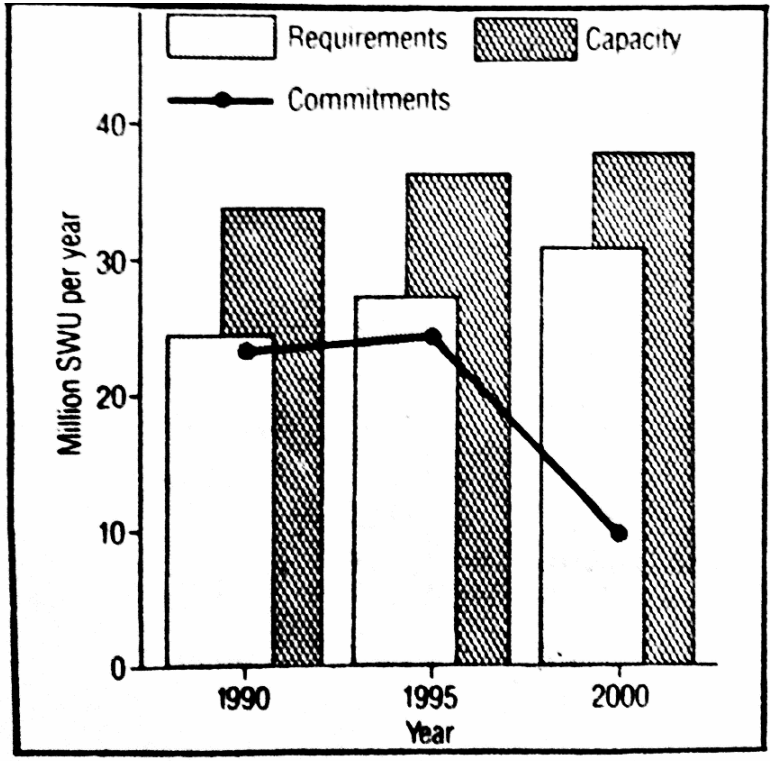
10. 'Interference due to Degassing and Metal-oxide in an E-Bombardment Furnace while Conducting RIS and RIMS Investigations',
M.S. Bhatia, and V.K. Mago,
Vacuum **67(2)**, Sept. 2002, 199.
11. 'Electron Beam Evaporation of Aluminum with a Porous Tantalum Rod in Melt Pool',
B. Dikshit, G.R. Zende, **M.S. Bhatia** and B.M. Suri,
J. Phys. D: Appl. Phys. **38**, July 2005, 2484.
12. 'Hysteresis in Electron Emission Current of an Axial Electron Gun used for Evaporation of Metals',
B. Dikshit and **M.S. Bhatia,**
IEEE Transactions on Plasma Science, **35(2)**, April 2007, 396.
13. 'Effect of Periscope Reflecting Mirror on Uncertainty of Measured Temperature of an Electron Beam Heated Metal Vapor Source',
B. Dikshit, G.R. Zende, **M.S. Bhatia** and B.M. Suri,
Meas. Sci. & Technol. **19(2)**, Feb. 2008, 511.
14. 'Numerical Methods for Bio-electromagnetic Computation: A General Perspective',
L.K. Ragha and **M.S. Bhatia,**
Proceedings of SPIT-IEEE Colloqium and International Conference, Mumbai, **Vol. 2**, 94-99.
15. 'Collisional Effects on Metastable Atom Population in Vapour Generated by Electron Beam Heating',
B. Dikshit, A. Mazumdar, **M.S. Bhatia** and V.K. Mago,
J. Phys D: Appl. Phys. **41(6)**, Mar. 2008, 065204.
16. 'Ideal Distortion-less Bending of a Focussed Non-Para-axial Electron Beam',
B. Dikshit and **M.S. Bhatia,**
Nucl. Instrum and Methods in Phys. Res. A **596(3)**, Sept. 2008, 300.
17. 'Use of Langmair Probe for Analysis of Charged Particles in Metal Vapour Generated by Electron Beam Heating',
B. Dikshit and **M.S. Bhatia,**
J. of Phys.: Conference Series **114(1)**, May 2008, 012030.
18. 'Use of Multi-wavelength Emission from Hollow Cathode Lamp for Measurement of State Resolved Atom Density of Metal Vapor Produced by Electron Beam Evaporation',
A. Majumdar, B. Dikshit, **M.S. Bhatia** and V.K. Mago,
Rev. Sci. Instrum., **79(9)**, Sept. 2008, 093305.

30. 'Novel 270 Bent Axial Electron-gun and Positioning of its Electron Beam on Target',
B. Dikshit and **M.S. Bhatia,**
IEEE Trans. on Electron Devices, **57(4)**, April 2010, 939-945.
31. 'Numerical Assessment of UWB Patch Antenna for Breast Tumor Detection',
L.K. Ragha and **M.S. Bhatia,**
Int J. for Recent Trends in Engineering, **Vol. 3(3)**, May 2010, 51-55.
32. 'Studies on Electron Beam Vapour Generation in PVD Processes',
B. Dikshit and **M.S. Bhatia,**
BARC Newsletter, **Issue 314**, May-June 2010, 10-19.
33. 'Effect of Oxygen Flow Rate on Microstructure and Optical Properties of Aluminum Oxide Films Deposited by E-Beam Evapo. Tech.'
N. Maiti, A. Biswas, R.B. Tokas, D. Bhattacharya, S.N. Jha, U.P. Deshpande, U.D. Barve, **M.S. Bhatia** and A.K. Das,
Vacuum, **Vol. 85**, No 8, August 2010, 214-220.
34. 'Analysis and Design of Higher Order T-type Resonant Convertor as a Constant Current Transformer'
M. Borage, K.V. Nagesh, **M.S. Bhatia** and S. Tiwari,
IET Transactions on Power Electronics, **Vol. 4**, No. 1, Jan. 2011, 72-80.
35. 'Resonant Immittance Convertor Technologies',
M. Borage, K.V. Nagesh, **M.S. Bhatia** and S. Tiwari,
IEEE Transactions on Industrial Electronics, **Vol. 58**, No. 3, March 2011, 971-978.
36. 'Design of Transverse Electron Gun for Electron Beam based Reactive Evaporation',
N. Maiti, U.D. Barve, **M.S. Bhatia** and A.K. Das,
Rev. Sci. Instrum, **Vol. 82(5)**, May 2011.
37. 'Effect of Low Power Microwave Fields on Seed Germination and Growth Rates',
L. Ragha, S. Mishra, V. Ramchandran and **M.S. Bhatia,**
J. Electromag. Analysis & Applications, **Vol. 3**, No. 5, May 2011, 165-171.
38. 'Approximate Equivalent Circuit Modeling and Analysis of Type-II Resonant Immittance Convertors',
M. Borage, K.V. Nagesh, **M.S. Bhatia** and S. Tiwari,
J. of Power Electronics, **Vol. 12(2)**, March 2012, 317-325.

P. R. K. Rao, Current Science, Vol. 85, no.5, 10 September 2003.

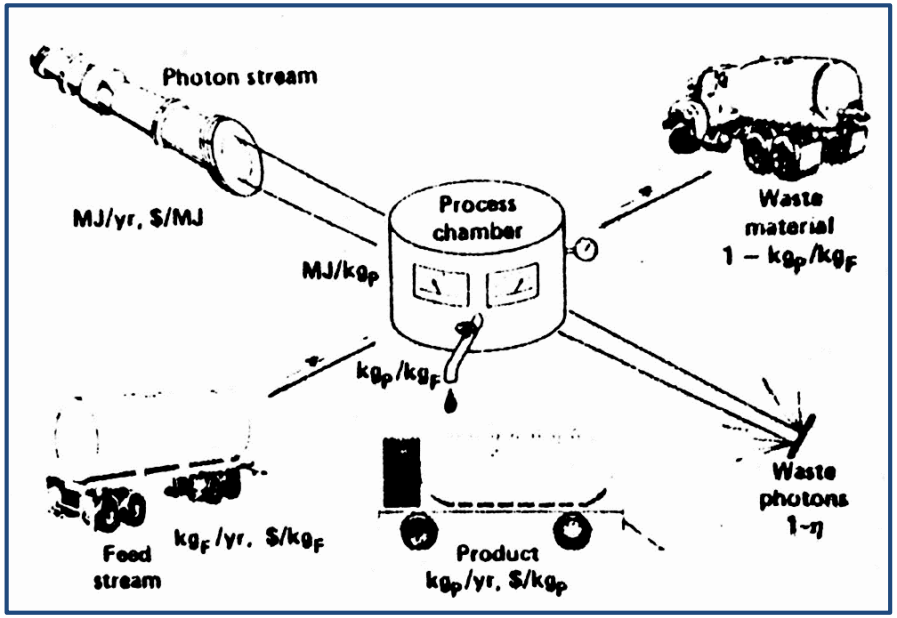
1990, AVLIS succeeds in US/France/Japan at pilot plant level. Plant?

Supply exceeds demand for U



Enrichment supply demand and commitment.

For other elements



$$\left[\frac{\$}{\text{unit}}\right]_{\text{Product}} = \left\{\left[\frac{\$}{\text{MJ}}\right] \cdot \left[\frac{\text{MJ}}{\text{unit}}\right]\right\}_{\text{Laser}} + \left[\frac{\$}{\text{KG}}\right]_{\text{HANDLING}}$$

S. Hargrove, Lawrence Liv. Lab, May 2000.

Science goes on. Occasional surprises! I found it!

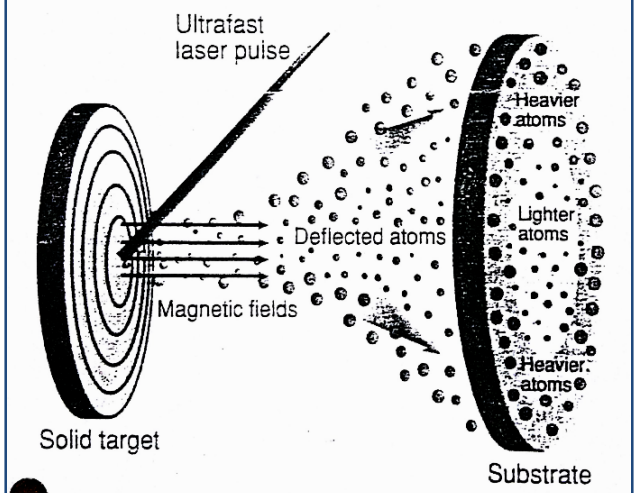
- **Isotopic Expansion of Boron,** L. Chkhartishvili, O. Tsagareishvili & D. Gabunia; J. Metallurgical Engg (ME) Vol. 3, Issue 3, July 2014.
-

CHEMISTRY

A Cheaper Way to Separate Isotopes?

For Manhattan Project scientists racing to build the first atomic bomb during World War II, one of the biggest challenges had nothing to do with learning how to set off a nuclear explosion. They also had to devise a way to separate the fuel for the reaction, ura-n-235, from its slightly heavier but far more abundant cousin, U-238. Ultimately,

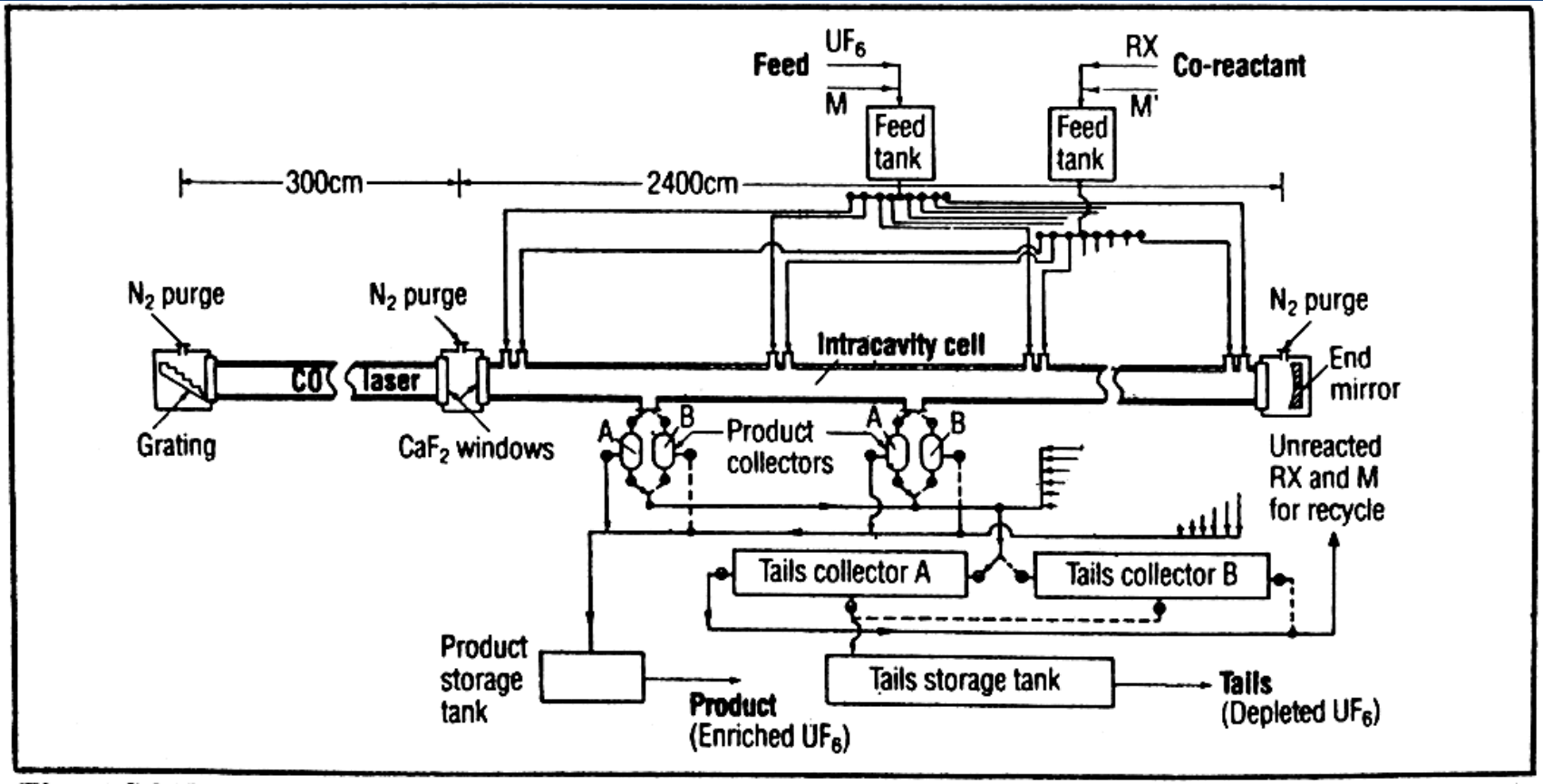
were initially trying t
boron-nitride, a supe
searchers commonly m
are used for high-tech
devices, by aiming a las
porizing it, and deposit
Pronko and his collea
trying out an unusual l
up to 1 quadrillion watt
centimeter in extremel
just 150 femtoseconds,
second. Trained on a sc
tride, the laser deposite



Moving out. When vaporized by an ultrafast laser, heavier isotopes tend to concentrate at the edges of the target.

SCIENCE 2014
Small scale

MLIS scientists. What are they up to?



The CRISLA pilot unit for 1000SWU/y. Collector A is used whilst material in tank B is transferred to storage, and vice-versa.

We are more economic. So it is us!

Table 1. Uranium enrichment processes compared

Process name	Key separation mechanism	Energy used for separation	kWh per SWU	Per cent of world market
Mass action processes				
Jet process – UCOR (Becker-S. Africa)	Radial pressure gradients in jets	Mechanical	3000	–
Diffusion	Differential diffusion through porous walls	Mechanical	2500	90
Ultracentrifuge	Differential centrifugation	Mechanical	50	10
Quantum processes				
AVLIS	Laser-driven ionization	Photonic	40	–
MLIS	Laser-driven	Photonic	30	–
CRISLA	Laser-catalyzed chemical reaction	Chemical	10	–

The latest…SILEX

- One can make guesses, informed or hazardous ! This approach is molecular and it involves infra-red lasers. Like Isotope Kinetic Effects discussed earlier, it exploits Δm/m effects in some way. If true, this is likely to be more economical than AVLIS.

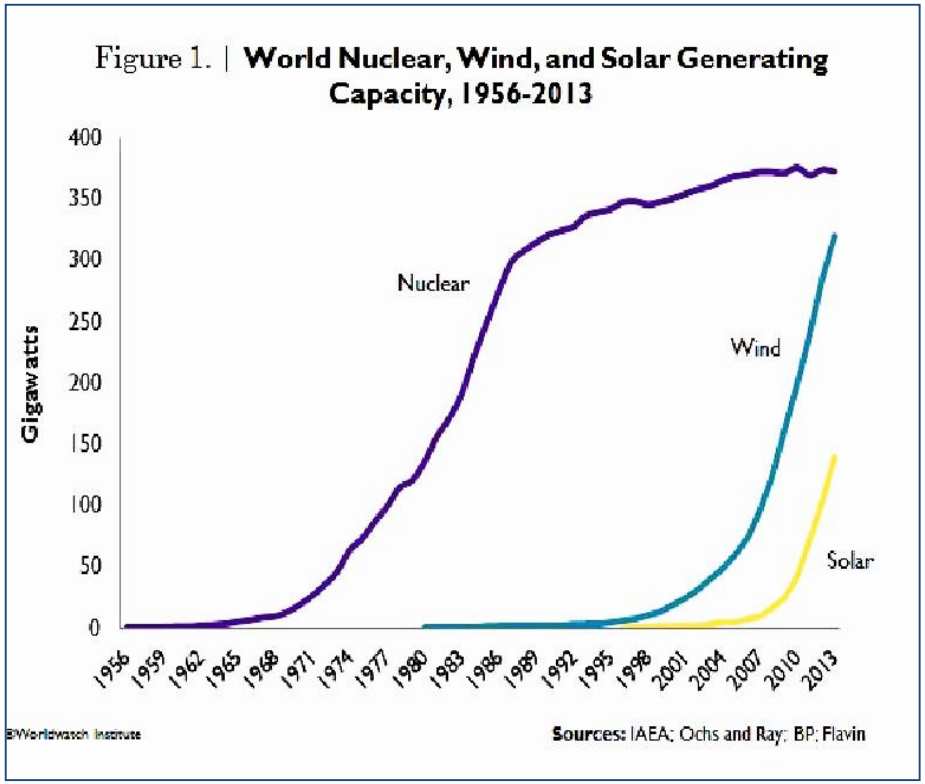
- The R&D and technology investigations continue and the matter is not settled one way or the other **till demand picks up.**

- The big question is **Will it?**

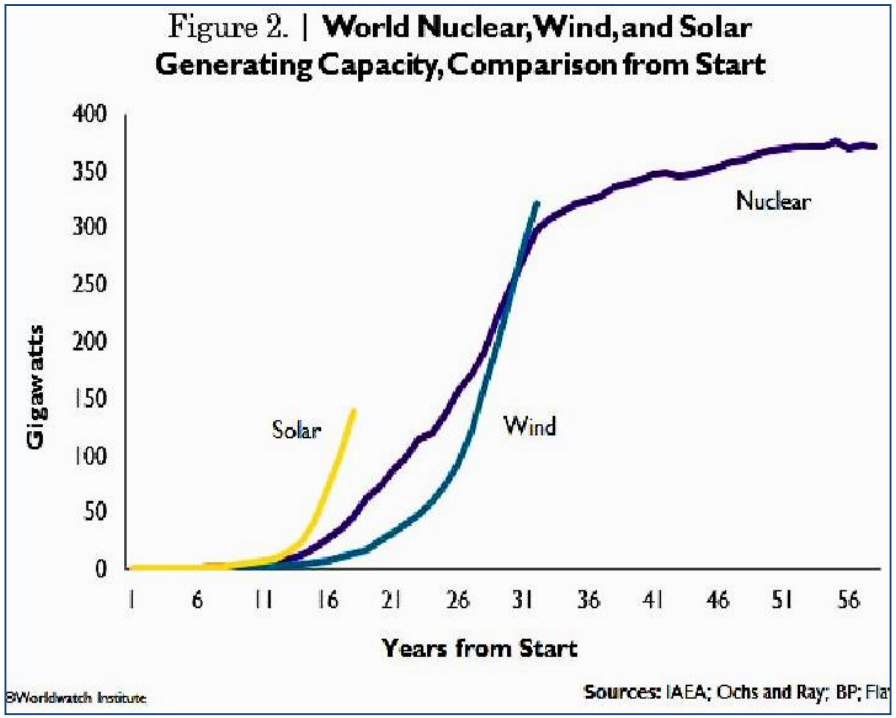
J. Kim et al, Trans. Korean Nucl. Soc., May 2009.

Nuclear energy losing lustre…

Growth stunted in comparison to Solar and Wind.



Wind overtakes Solar



Energy scene is now multiplayer…

INVESTMENTS

R & D

Figure 4. | **Average Annual Investments in Power Generation, 2000-2013**

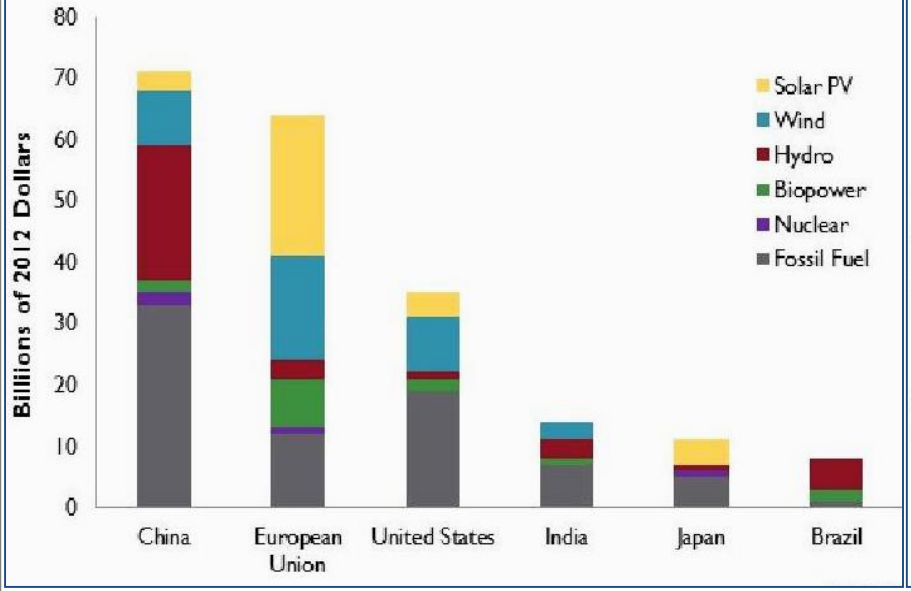
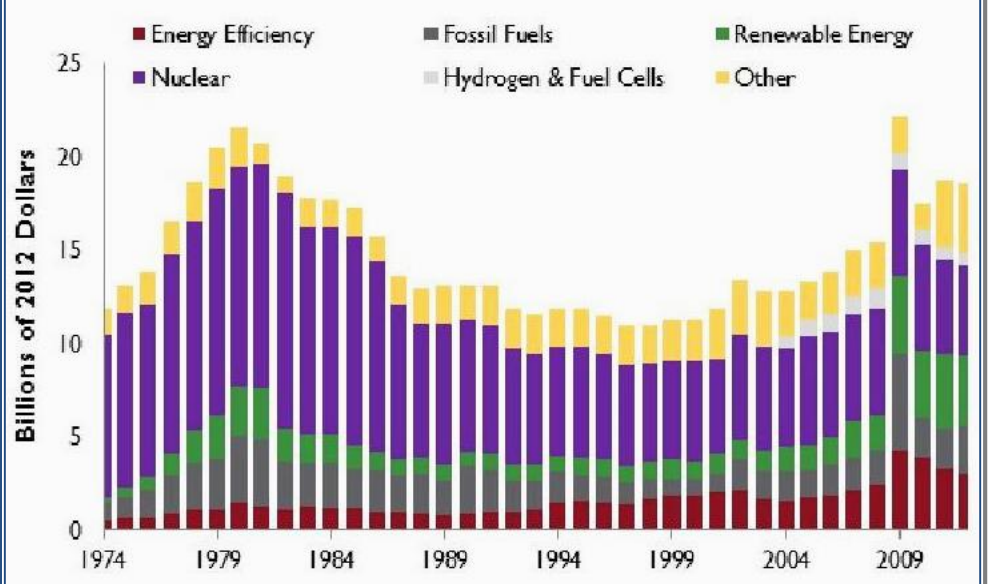


Figure 5. | **IEA Members' Energy R&D Budgets, 1974-2012**



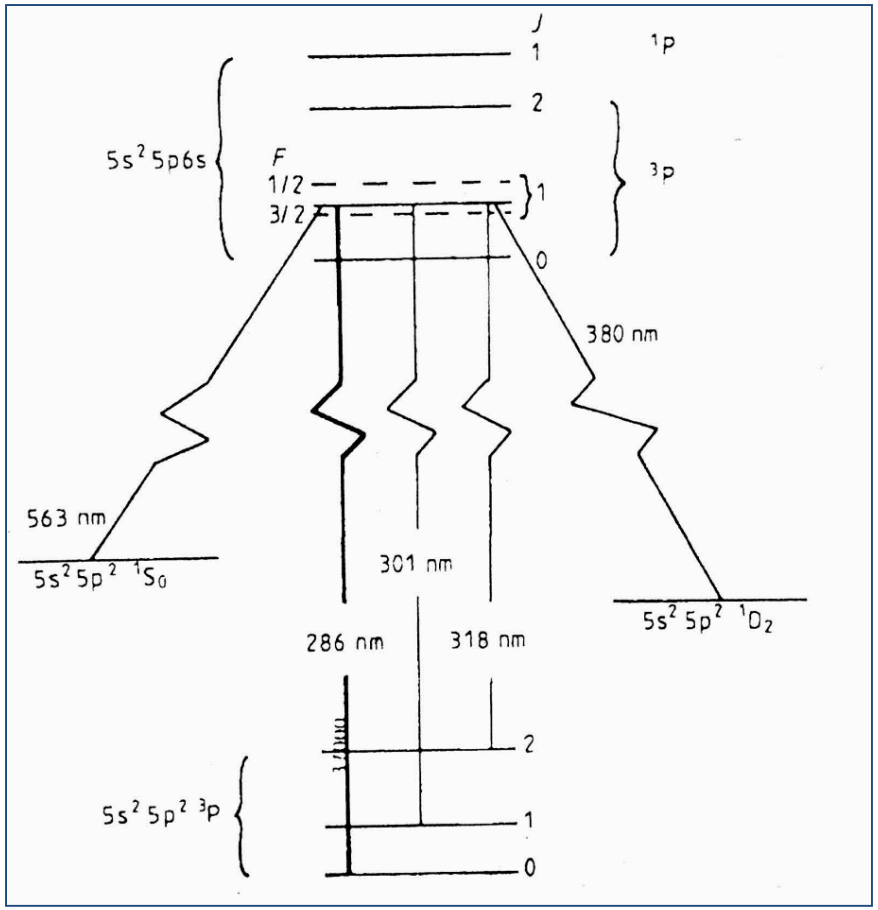
Sn^{124} Separation…

- Z = 50. KIE, MLIS or AVLIS?
- Tin compounds vs Tin metal.
- Required α = 96/6 = 16.

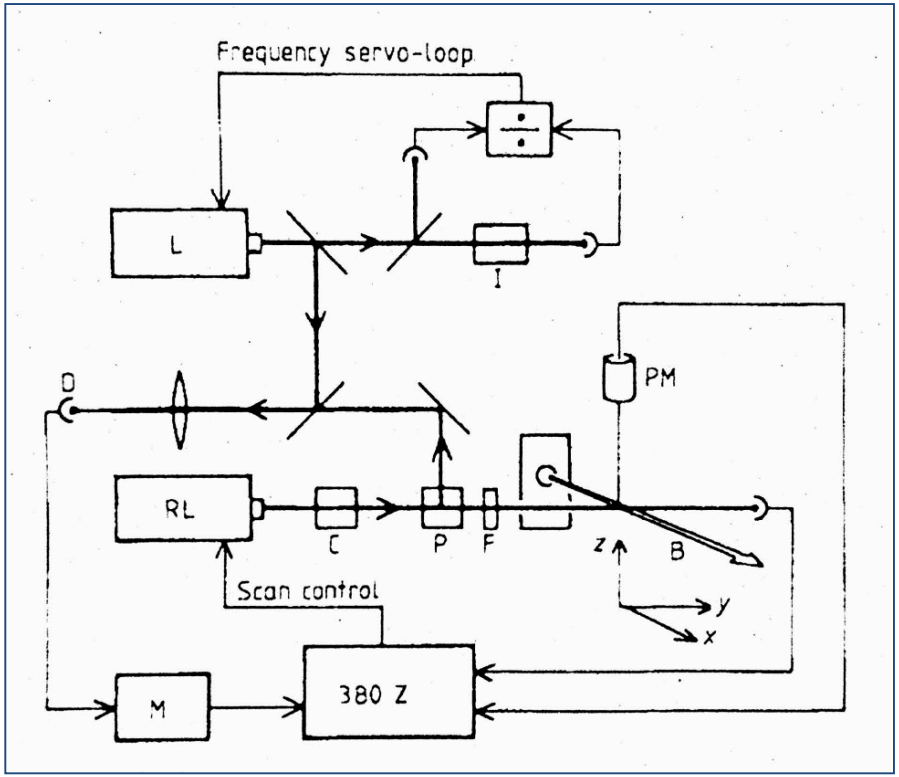
  This is easily within reach of AVLIS in a step.
- Spectroscopy and then Laser system.
- Isotope shift: 200Mhz.
- Volatility and toxicity: Benign.

Narrow line-width frequency doubled…

Spectroscopy



Laser system



A race that we can run…

- First attempt: mg/hr (+95% Sn^{124}).
- Chamber/accessories: 20 lacs.
- Lasers: 2-3 cr. (Oscillator amplifier).
- Optimization and multiplication to produce 10-20Kg/year.

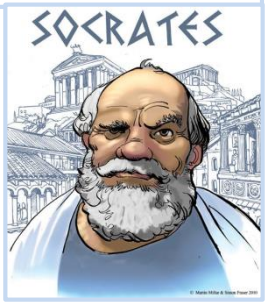
THANK YOU

Meanwhile LIS Science and Technology

Plays to the tune of FORCES

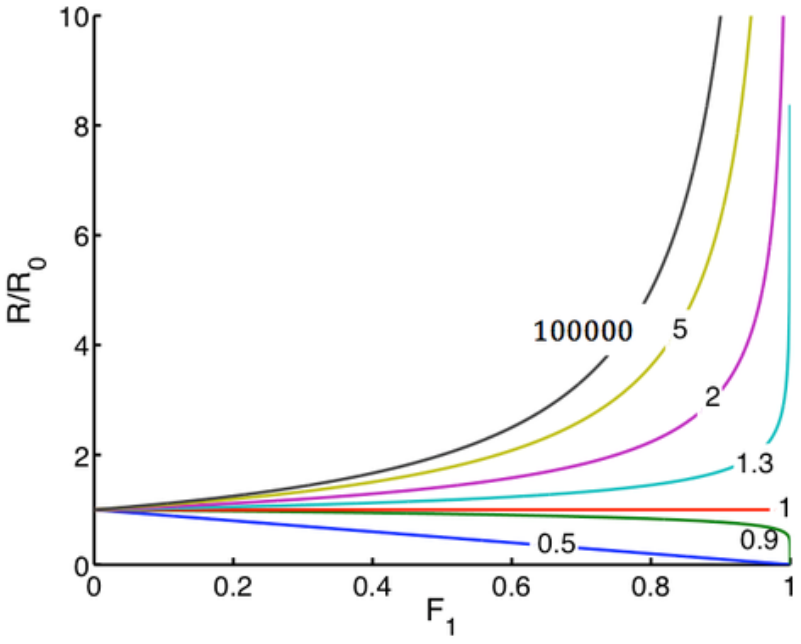
Some physical and some fiscal…

"True wisdom comes to each of us when we realize how little we understand about life, ourselves, and the world around us."



Enrichment thru KIE

Let F_1 be the isotopic specie who's fraction is to increased thru KIE from R_0 to R_1. Let the KIE vary from say 0.5 to100000. The result is shown below



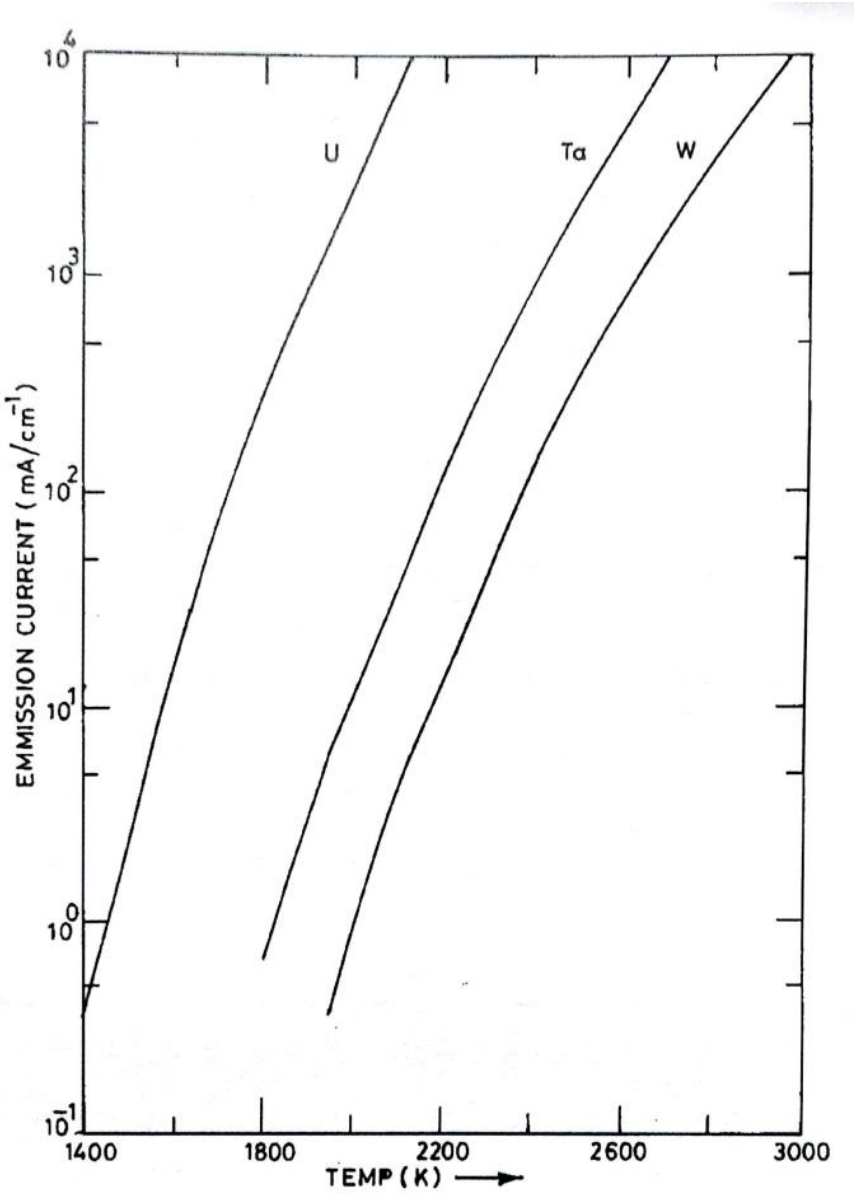
Wide applicability of Calutron…

TABLE I. Isotopes processed and isotopic enrichments attained in the calutron.

Element	Isotope mass	Natural abundance percent	Enriched abundance percent
Lithium	6	7.52	99.40
	7	92.48	99.97
Boron	10	18.98	86.78
	11	81.02	*
Carbon	12	98.892	99.99
	13	1.108	7.52
Nitrogen	14	99.635	*
	15	0.365	
Oxygen	16	99.759	*
	17	0.0374	*
	18	0.2039	*
Magnesium	24	78.60	99.52
	25	10.11	92.33
	26	11.29	98.12
Silicon	28	92.27	99.4
	29	4.68	68.6
	30	3.05	64.0
Sulfur	32	95.06	98.45
	33	0.74	9.8
	34	4.18	20.65
	36	0.016	0.88
Chlorine	35	75.4	92.4
	37	24.6	65.6
Potassium	39	93.08	99.96
	40	0.0119	7.75
	41	6.91	99.21
Calcium	40	96.97	99.97
	42	0.64	82.52
	43	0.145	72.13
	44	2.06	97.99
	46	0.0033	10.16
	48	0.185	84.28
Titanium	46	7.95	84.26
	47	7.75	82.05
	48	73.45	99.23
	49	5.51	77.62
	50	5.34	84.69
Vanadium	50	0.24	22.93
	51	99.76	99.98
Chromium	50	4.31	88.3
	52	83.76	99.14
	53	9.55	92.1
	54	2.38	88.95
Iron	54	5.84	93.27
	56	91.68	99.84
	57	2.17	87.29
	58	0.31	86.0
Nickel	58	67.76	99.3
	60	26.16	97.7
	61	1.25	80.9
	62	3.66	94.7
	64	1.16	97.4
Copper	63	69.1	99.70
	65	30.9	98.16
Zinc	64	48.89	93.4
	66	27.82	93.79
	67	4.14	62.6
	68	18.54	95.47
	70	0.617	48.4
Gallium	69	60.2	98.42
	71	39.8	98.08
Germanium	70	20.55	88.1
	72	27.37	89.2
	73	7.61	68.9
	74	36.74	95.2
	76	7.67	79.3
Selenium	74	0.87	33.06
	76	9.02	88.51
	77	7.58	91.73
	78	23.52	96.55
Selenium	80	49.82	98.39
	82	9.19	89.87
Bromine	79	50.52	90.54
	81	49.48	96.81
Rubidium	85	72.15	95.97
	87	27.85	89.62
Strontium	84	0.56	63.68
	86	9.86	89.02
	87	7.02	73.1
	88	82.56	99.67
Zirconium	90	51.46	98.66
	91	11.23	86.89
	92	17.11	95.38
	94	17.40	97.92
	96	2.80	89.48
Molybdenum	92	15.86	95.5
	94	9.12	79.1
	95	15.70	91.27
	96	16.50	92.0
	97	9.45	89.63
	98	23.75	96.3
	100	9.62	93.0
Silver	107	51.35	96.10
	109	46.85	99.54
Cadmium	106	1.215	32.9
	108	0.875	24.8
	110	12.39	70.0
	111	12.75	64.5
	112	24.07	83.5
	113	12.26	54.1
	114	28.86	94.2
	116	7.58	71.2
Indium	113	4.23	65.4
	115	95.77	99.94
Tin	112	0.95	72.49
	114	0.65	50.03
	115	0.34	17.64
	116	14.24	92.64
	117	7.57	77.07
	118	24.01	94.91
	119	8.58	79.82
	120	32.97	98.21
	122	4.71	88.92
	124	5.98	95.04
Antimony	121	57.25	99.4
	123	42.75	96.7
Tellurium	120	0.089	22.3
	122	2.46	86.24
	123	0.87	60.91
	124	4.61	83.9
	125	6.99	87.9
	126	18.71	95.4
	128	31.79	96.47
	130	34.49	97.78
Barium	130	0.101	27.50
	132	0.097	12.01
	134	2.42	51.39
	135	6.59	67.32
	136	7.81	50.02
	137	11.32	38.98
	138	71.66	98.04
Lanthanum	138	0.089	0.597
	139	99.911	99.96
Cerium	136	0.193	29.97
	138	0.250	13.10
	140	88.48	99.65
	142	11.07	90.06
Neodymium	142	27.13	93.00
	143	12.20	83.93
	144	23.87	93.45

* No mass analysis performed.

Element	Isotope mass	Natural abundance percent	Enriched abundance percent
Neodymium	145	8.30	78.60
	146	17.18	95.60
	148	5.72	89.85
	150	5.60	94.76
Samarium	144	3.16	72.13
	147	15.07	81.63
	148	11.27	76.01
	149	13.84	73.01
	150	7.47	74.09
	152	26.63	93.92
	154	22.53	96.05
Hafnium	174	0.18	7.85
	176	5.15	48.46
	177	18.39	61.71
	178	27.08	80.91
	179	13.78	46.57
	180	35.44	93.96
Tungsten	180	0.135	9.0
	182	26.4	94.25
	183	14.4	86.21
	184	30.6	95.72
	186	28.4	97.94
Rhenium	185	37.07	85.38
	187	62.93	98.22
Mercury	196	0.146	8.44
	198	10.02	79.11
	199	16.84	73.09
	200	23.13	91.3
	201	13.22	71.9
	202	29.80	98.3
	204	6.85	89.17
Thallium	203	29.50	86.0
	205	70.50	98.7
Lead	204	1.48	27.0
	206	23.6	81.0
	207	22.6	66.8
	208	52.3	96.6


U
Ta
W
EMMISSION CURRENT (mA/cm^{-1})
10^4
10^3
10^2
10^1
10^0
10^{-1}
1400
1800
2200
2600
3000
TEMP (K) ⟶