

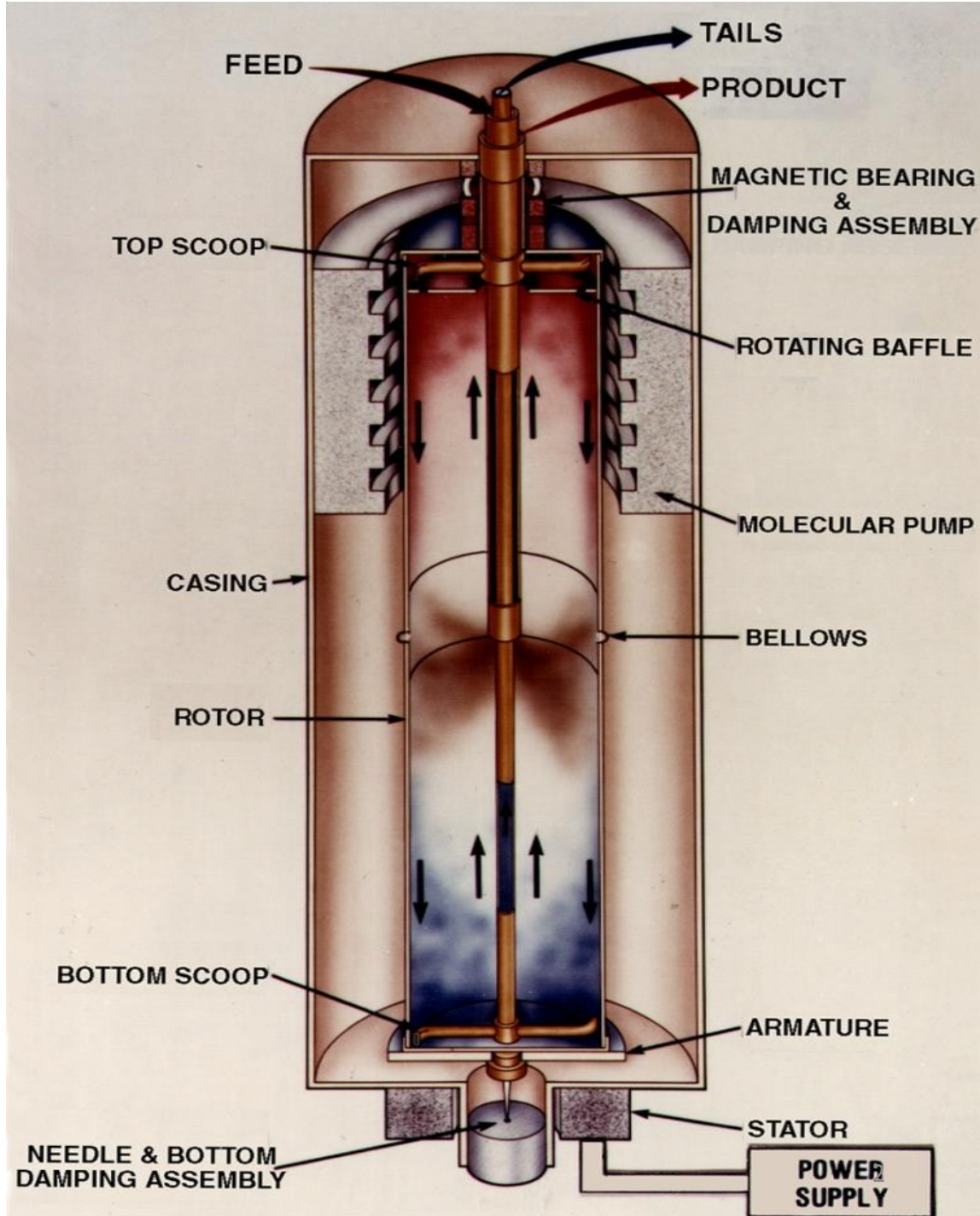
Gas Centrifuges

ISIS Course

November 6, 2014

Gas Centrifuge

- Fast spinning device to separate uranium 235
- Modern design originated in the Soviet Union following WWII and migrated from there throughout the world
- Highly successful design based on a rotor suspended by a pin, like a spinning top
- Self stabilizing
- Countercurrent flow



Separative Output (swu) of a Centrifuge

- Depends fundamentally on the speed of the outer wall, namely velocity squared, V^2
- Depends also on rotor length, L
- Not directly dependent on the rotor's diameter
- Typically operates at moderate temperatures, say
- A maximum separative output, δU , of a centrifuge can be estimated by:

$$\delta U = \frac{LV^2}{43882} (SWU/yr)$$

Rotor Material Properties Define Wall Speed

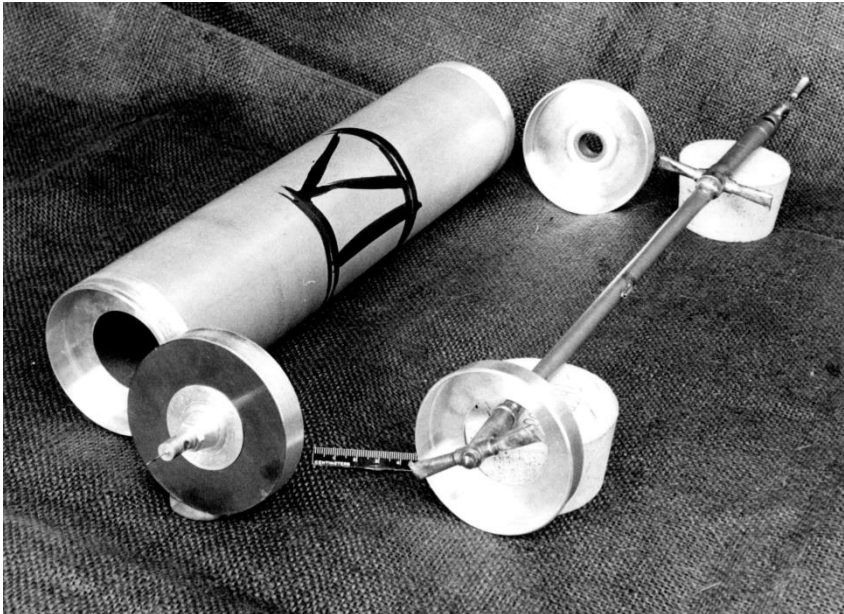
Rotor Material	Tensile Strength (M Pa)	Density (Kg/m³)	Max. Peripheral Velocity (m/sec)	Rotor Oper. Velocity (m/sec)
Aluminium Alloy	550	2800	445	~350
Titanium alloy	980	4550	464	~ 400
Maraging steel	2100	8080	510	~ 480
Glass composite	1100	2130	718	~ 550
Kevlar composite	1000	1340	865	~ 600
Carbon composite	1630	1530	1000	~700?

Basic Types Defined by Centrifuge Length

- **Subcritical** – a single relatively short rotor tube that is not subject to damaging resonances
- **Homogeneous Supercritical** – a single rotor tube that is long enough to experience several damaging resonances as it speeds up to its operating speed.
- **Non-Homogeneous Supercritical**- a stack of subcritical rotor tubes joined together by flexible bellows.

Early Subcritical centrifuges

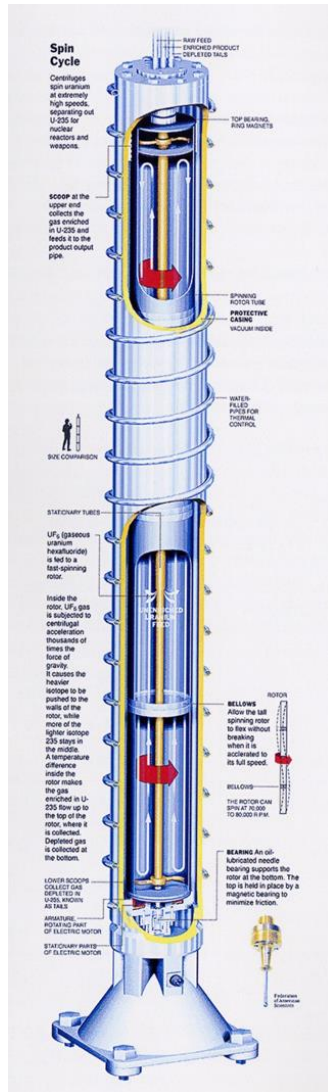
**Zippe early centrifuge, alum.
Subcritical rotor**



**Russian centrifuge plant,
subcritical centrifuges**



Iran's IR-1 Supercritical Centrifuge, Four tubes and three bellows



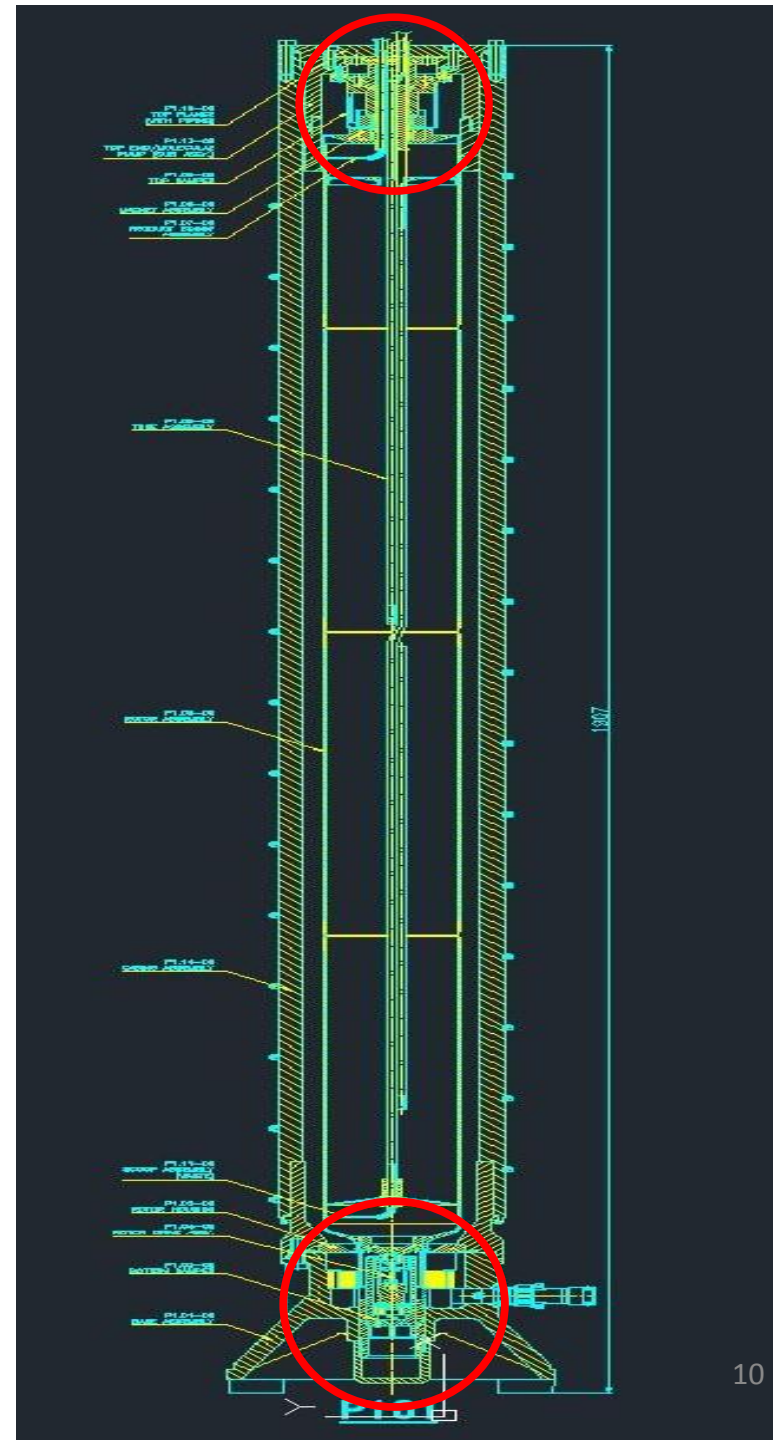


Iranian supercritical centrifuges at a recent Atomic Energy Organization of Iran exhibition in Tehran. The centrifuges on the far left and far right appear to be IR-2m centrifuges, each of which has a rotor assembly with two carbon fiber rotors (black) connected by a thin maraging steel bellow. The IR-2m bellows are believed to be made from 350 maraging steel. The tall centrifuges in the middle are IR-1 centrifuges, each of which has a rotor assembly made from four high-strength aluminum rotor tubes and three maraging steel bellows. The IR-1 bellows may be made from 300 or 350 maraging steel

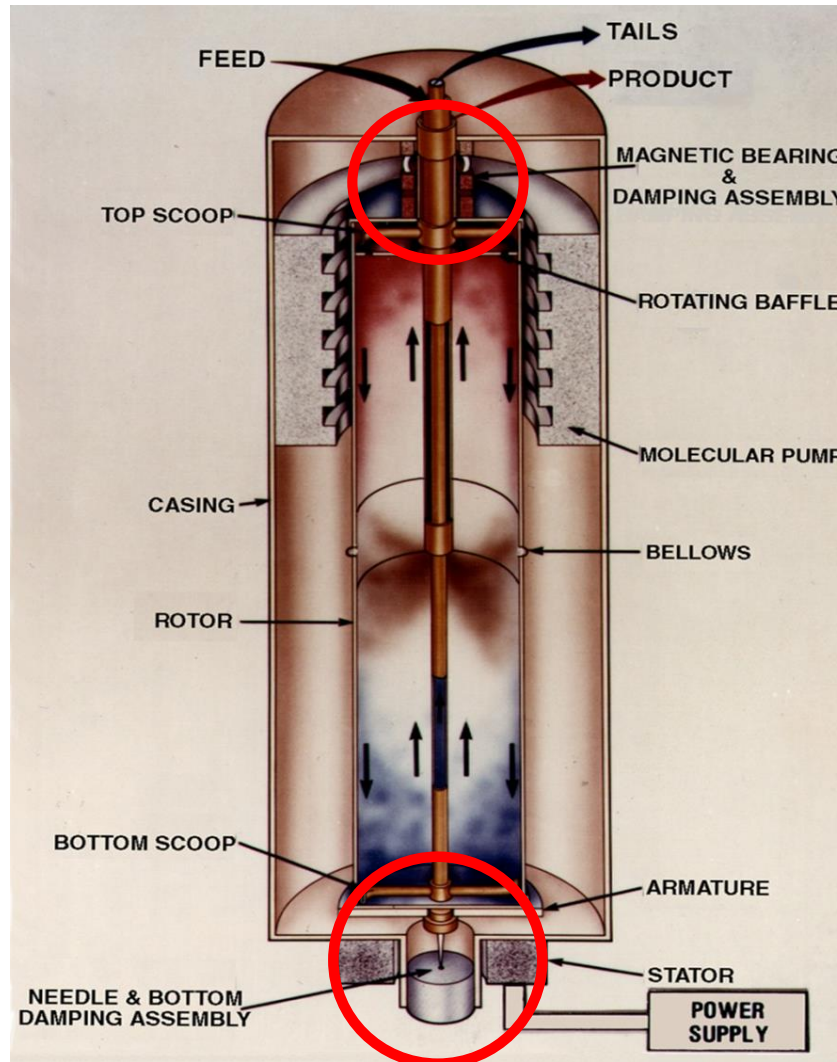
Centrifuges are Challenging to Build and Operate

- The principal engineering challenge is posed by the high speed of the spinning rotors. Imbalances can cause rotor to crash (worsened by the impossibility of aligning the mass and geometric axis).
- For thin walled rotor minor eccentricity between internal and external diameter magnifies unbalance, emphasizing the need for high precision manufacturing.
- Successful operation requires flexible rotor-bearing systems, for example the top and bottom bearings must allow the rotor to move sideways and absorb vibrations in the rotor. The bearings illustrate the complexity of gas centrifuges and the typical need for foreign procurements.

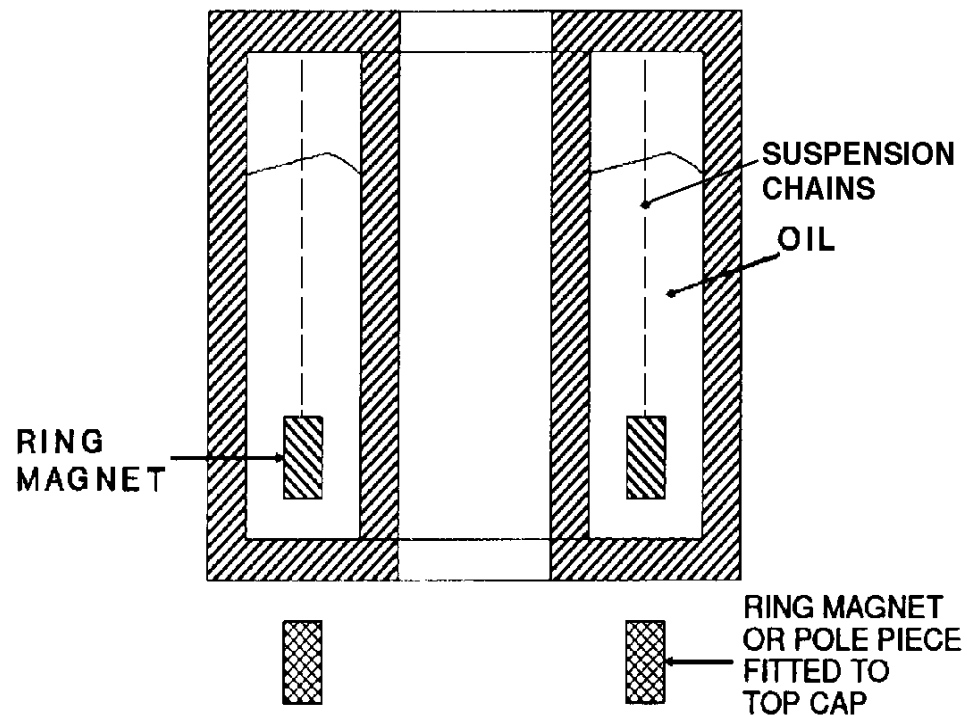
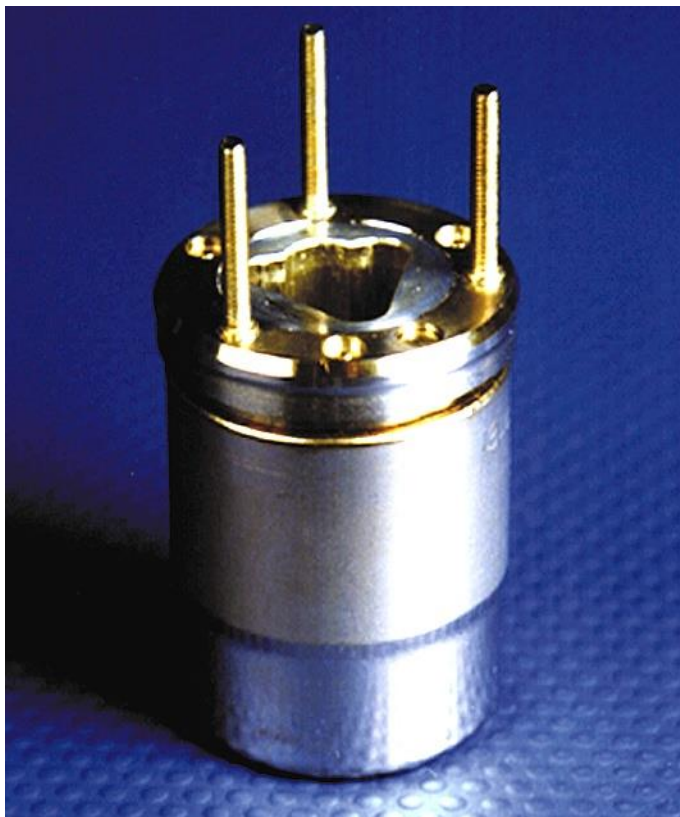
- Pakistani P-1 centrifuge which is nearly identical to IR-1 centrifuge in Iran
- Top and bottom bearings are circled in red



Top and Bottom Bearings



Top Magnetic Bearing Housing and ring magnet, with oil

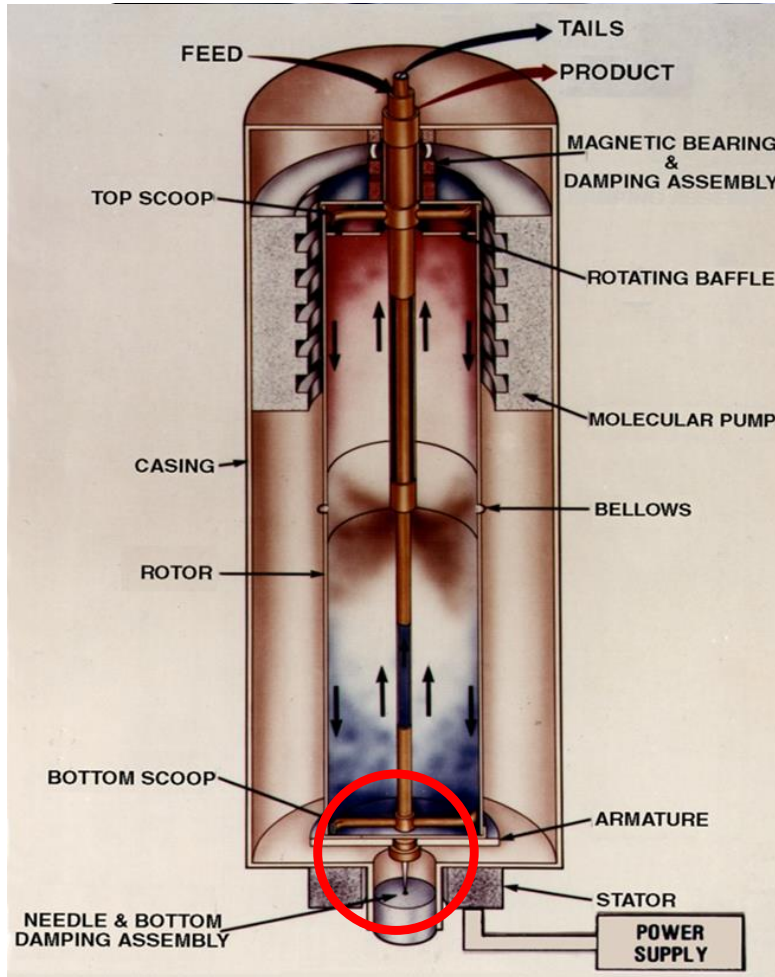


SCHEMATIC CROSS SECTION

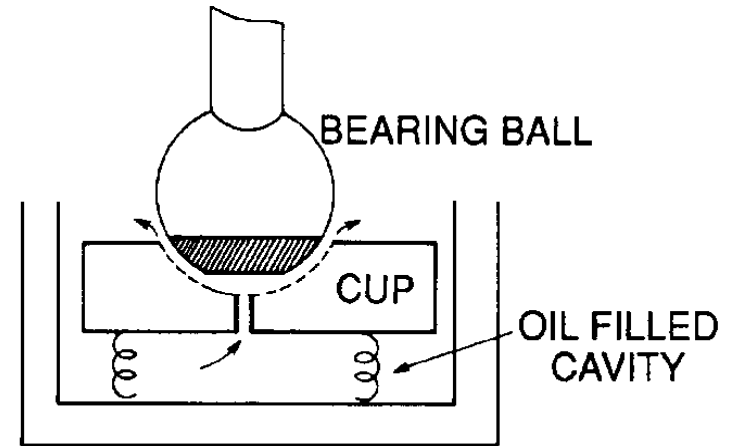
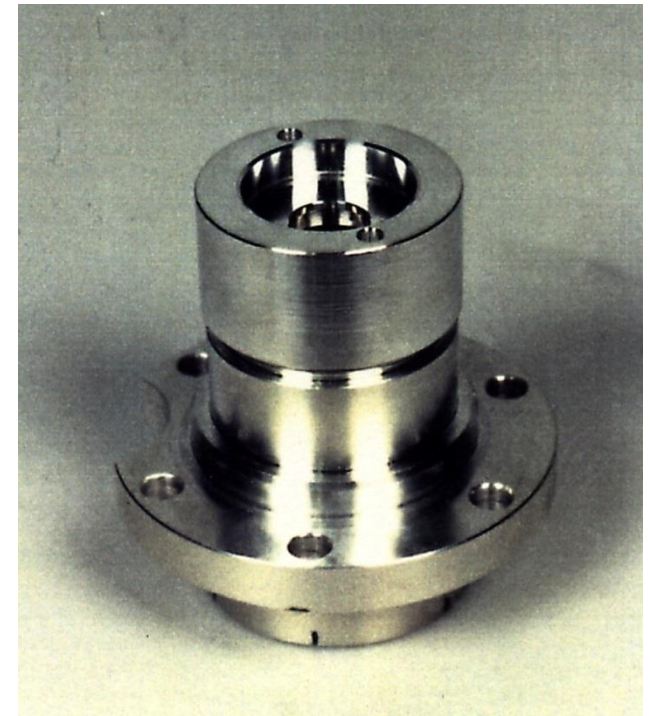
P-1 Ring Magnet



Needle and pin assembly attached to bottom of rotor endcap



Bottom Bearing Components



SCHEMATIC CROSS SECTION

Example of a March 2013 Enquiry from a Pakistani Trading Company for Steel Balls of Type Used in Bottom Bearing

02.		Chrome steel bearing balls Dia: 4.000 mm	Nos	5000	VXB.com Ball Bearings, USA.
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Centrifuge Cascading and Inefficiencies in Centrifuge Enrichment Output

Inefficiencies Reduce Separative Output of Centrifuge

- δU , or separative output (swu), is reduced in practice from theoretical or maximum values, such as those derived from the equation on slide 3.
- Actual separative output can be even lower when centrifuges operate in production-scale cascades

Examples of Centrifuge Types

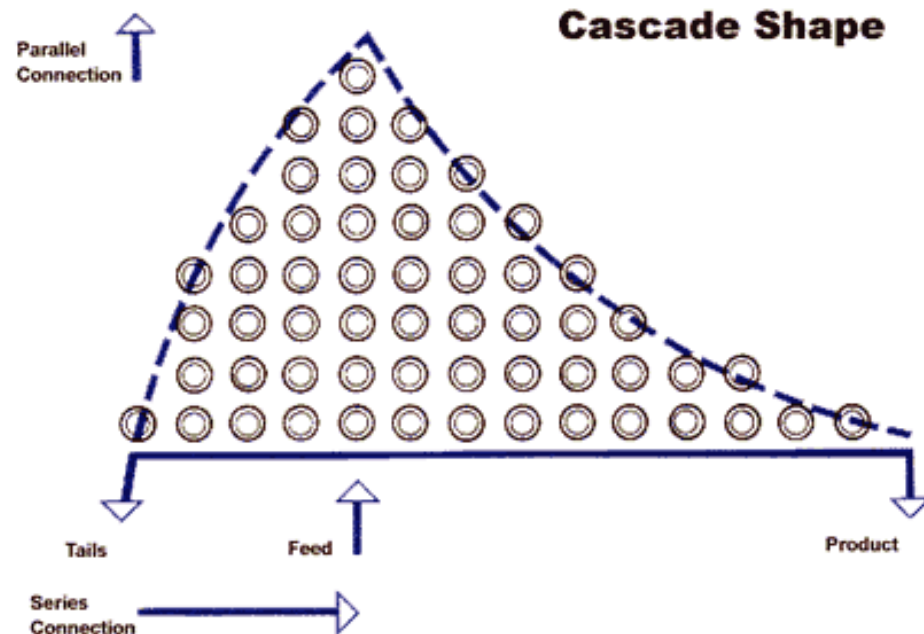
Type	Design Basis	Rotor Material	Diameter (mm)	Length (cm)	Single Centrifuge SWU/yr
P-1	Dutch	Aluminum	100	180	2
IR-1	Dutch, Pakistani	Aluminum	100	180	1.4 (0.9 in prod. cascade)
P-2	German	Mar. Steel	145	100	5 (4 in prod. cascade)
IR-2m	German/ Iran	Carbon Fiber	145	100	6? (3-5 in prod. cascade)
P-3	Dutch or German	Mar. Steel	145	180	9-10

Combining Centrifuges Into Cascades

- A single centrifuge cannot enrich significantly or produce the necessary quantity of enriched uranium.
- As a result,
 - Centrifuges are arranged in series to reach the desired enrichment level.
 - Centrifuges are arranged in parallel to give the desired output.
- Such an arrangement is called a cascade, as we discussed last week.

Cascades: A Network of Connected Separators

- Centrifuges are combined in order to produce large quantities of enriched uranium.
- A cascade is the network of centrifuges connected by piping.
- A stage is comprised of centrifuges in parallel to increase the quantity of product
- Stages are arranged in series to increase the quantity of product.
- An ideal cascade is shaped as in the adjacent figure



Ideal Cascade

- **Definition:** An ideal cascade is defined as a cascade for which the separation factor is constant in every stage – an idealization never achieved in practice – and for which the internal flow rates are chosen to prevent mixing between streams with unequal isotopic concentrations.
- An ideal cascade is the most efficient arrangement of centrifuges in a cascade and requires the least number of centrifuges to achieve the required total separative output.
- An ideal cascade allows for much simpler mathematical calculations
- But I need to emphasize, an ideal cascade is an idealized model and cannot be achieved in practice. Actual cascades will be less efficient.

IR-1 Centrifuge Cascade – Iran



IR-1 Machines in Two Cascades



A P-2 Cascade in Kahuta Plant in Pakistan and Yongbyon Plant in North Korea that makes 4-5% enriched uranium

Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Cent. per stage	2	6	8	12	16	20	24	30	38	46	42	36	30	22	12	344

IR-1 Cascade, non-ideal

Table 3: Sequence C Array and FEP IR-1 Centrifuge Cascade

Cluster	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Stage	10E	9E	8E	7E	6E	5E	4E	3E	2E	1E	5S	4S	3S	2S	1S
No. of Centrifuges	2 (1+1)	2	4	6	8	10	12	16	20	24	20	16	12	8	4
	Product Stage									Feed Stage					Tails Stage

3.5% U 235

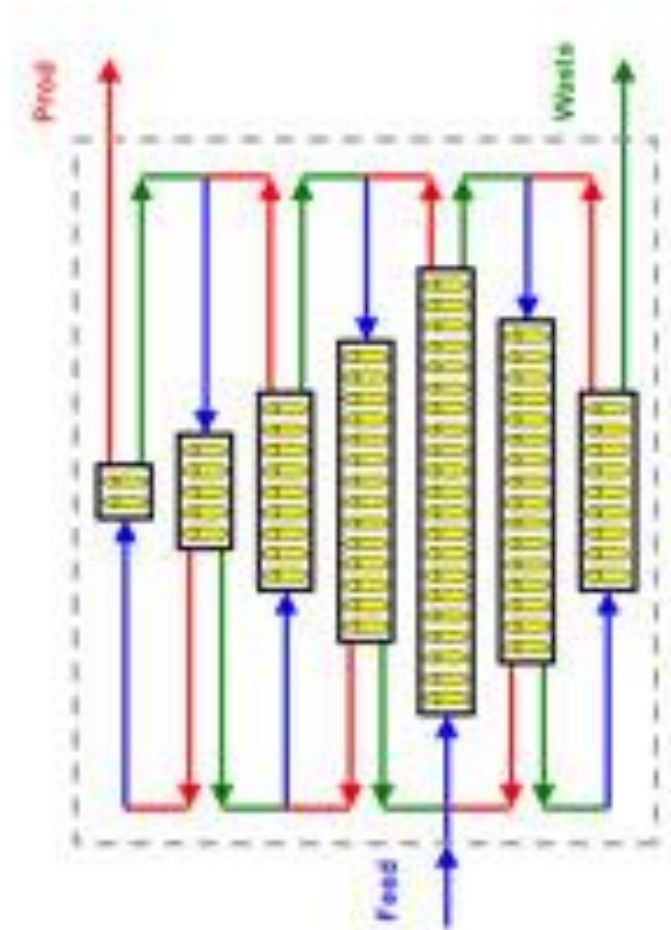
0.71% U 235

0.4% U 235

Notes and Comments:

- 1) Stage 10E, which is where the highest enrichment level is achieved, involves two centrifuges but this stage acts to all intents as ‘one plus a spare.’
- 2) The cascade shape is far from ideal.
- 3) The number of stages is set by the required enrichment and depletion factors. They would be similar for any centrifuge that has an enrichment factor equal to the depletion factor. Thus, this cascade design is not unique to an IR-1 design but it is the basis for what Iran showed the IAEA in the Pilot Plant at Natanz in August 2003 and what Iran has installed underground in the FEP.

Cascade Schematic, showing flows of uranium hexafluoride in stages



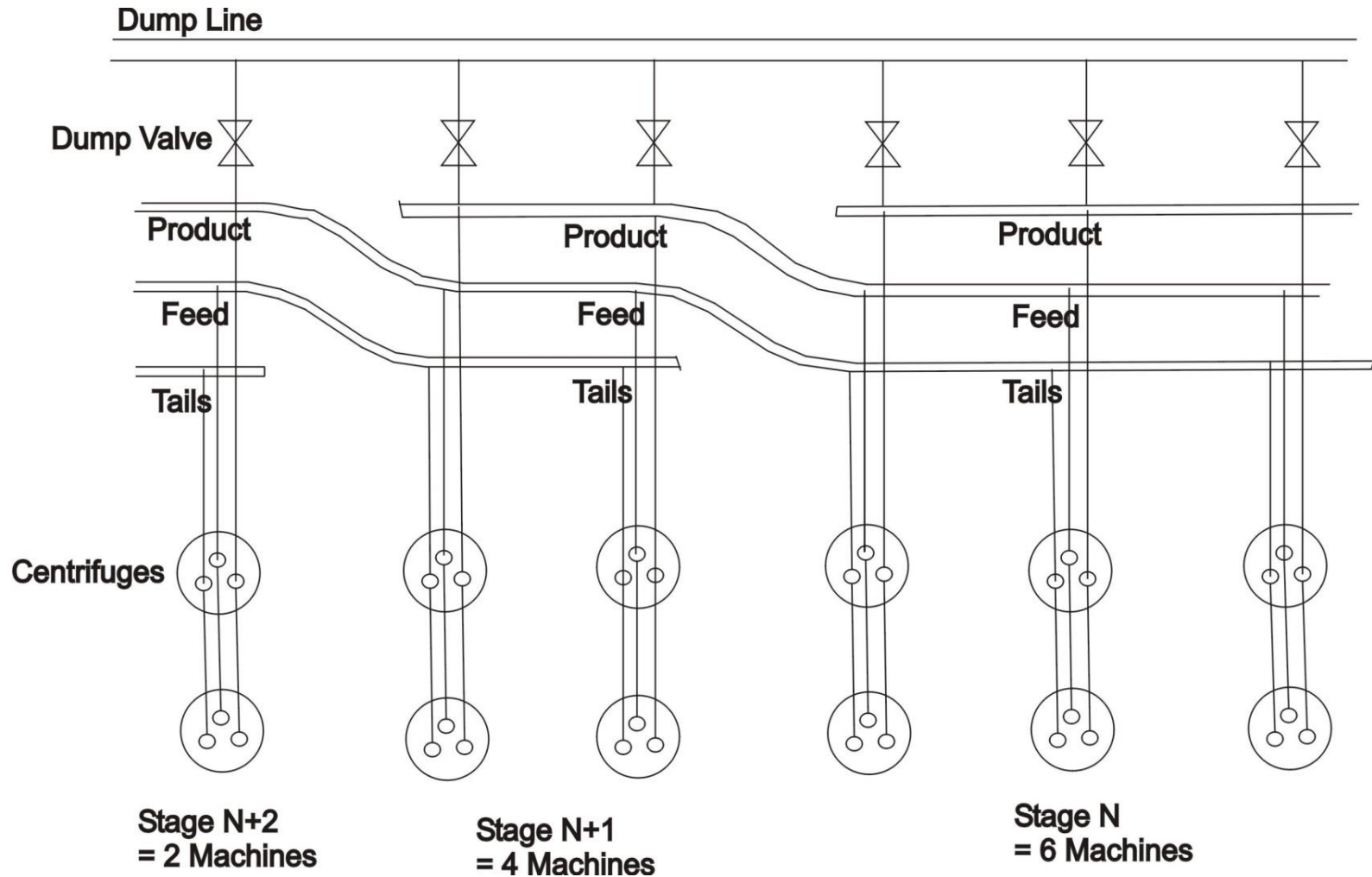
Source: Oak Ridge National Laboratory

<http://www.ornl.gov/science-discovery/supercomputing-and-computation/projects/gas-centrifuge-cascade-design>

Urenco Cascade Piping System



Cascade Subheader System



Ideal vs Step Cascades

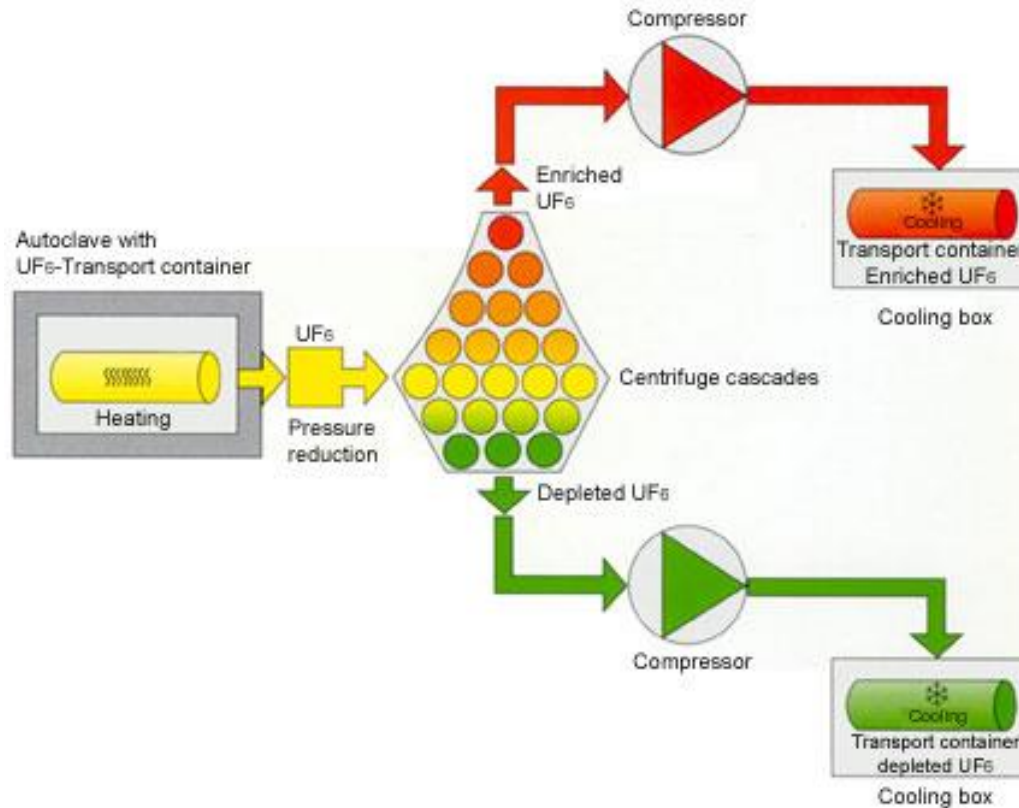
- To make low enriched uranium, large cascades are more efficient since their shape can be made closer to the ideal.
- To produce weapon-grade uranium a very large single cascade could be used. But large, or “long,” cascades can be risky to operate.
- Instead, another design has emerged to make weapon-grade uranium--the “step cascade.”
- A step cascade design is relatively expensive but it can more easily be manipulated to make weapon-grade uranium.
- Step cascades basically divide up the process of enriching uranium up to weapon-grade into several steps, achieving weapon-grade uranium (90% enriched) in increments. Each step is composed of a number of cascades of identical type, and each step has its own feed and withdrawal stations. A step cascade system is not an ideal cascade system and cannot achieve the separative output of an equivalent ideal cascade making weapon-grade uranium.

Example of a Step Cascade Design

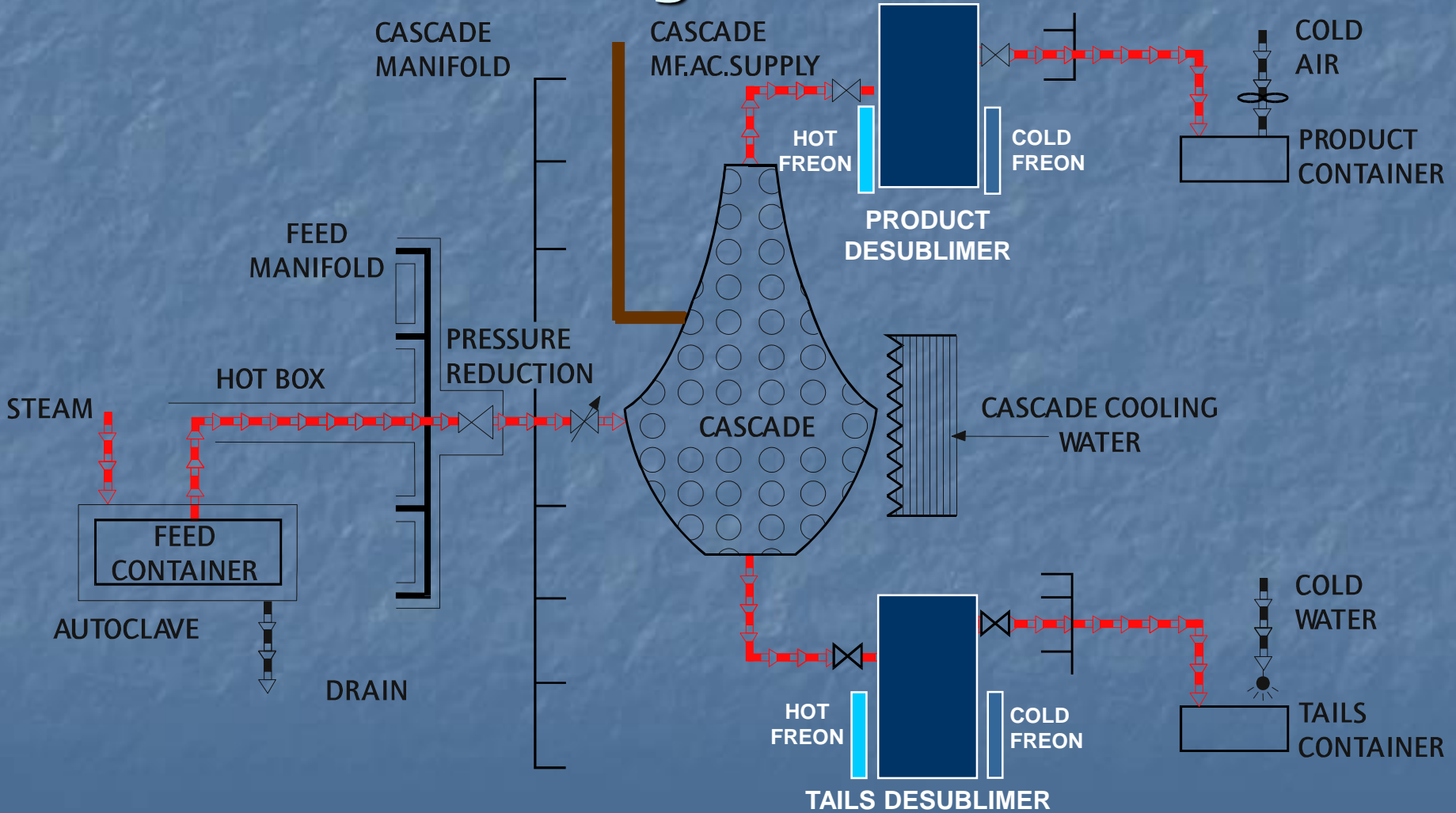
Cascade Step	No. of Cascades	No. of Machines per cascade	Cascade Feed Concentration	Cascade Product Concentration
1	32	164	0.71 %	3.0%
2	8	164	3.0%	20%
3	3	114	20%	60%
4	3	60	60%	90%
	46	Total 7094		

Centrifuge Plant Schematic,

With a single ideal cascade and a compressor system for withdrawal



Process Flow Sheet for a Centrifuge Plant using Desublimers



Gas Centrifuge Plant Equipment

- **Feed System**
 - Autoclave or steam chest, UF_6 leakage detection system, emergency isolation valves, pressure and temperature measurement systems pipework.
- **Cascade Marshalling Console**
 - Manual and electrical driven valves, bellows sealed valves for feed pressure reduction,
- **Desublimer Systems (product and tails)**
 - UF_6 collection traps, UF_6 capacity measuring system, UF_6 flow and pressure measurement devices, freon cooling/heating system, bellows sealed isolation valves.

Centrifuge Plant Equipment (cont.)

- **Cascade Header Piping System**
 - UF₆ main headers, bellows sealed needle valves for cascade feed, product and tails flow control, cascade header piping, dump header, machine failure accelerometers (vibration detectors), fast-acting centrifuge isolation valves.
- **Product and Tails collection system**
 - UF₆ pressure boosting pumps, UF₆ container stations, pumps, chilled air or water system, roots and rotary vacuum pumps, chemical backing traps, gas discharge scrubbing and monitoring equipment.

Equipment (cont.)

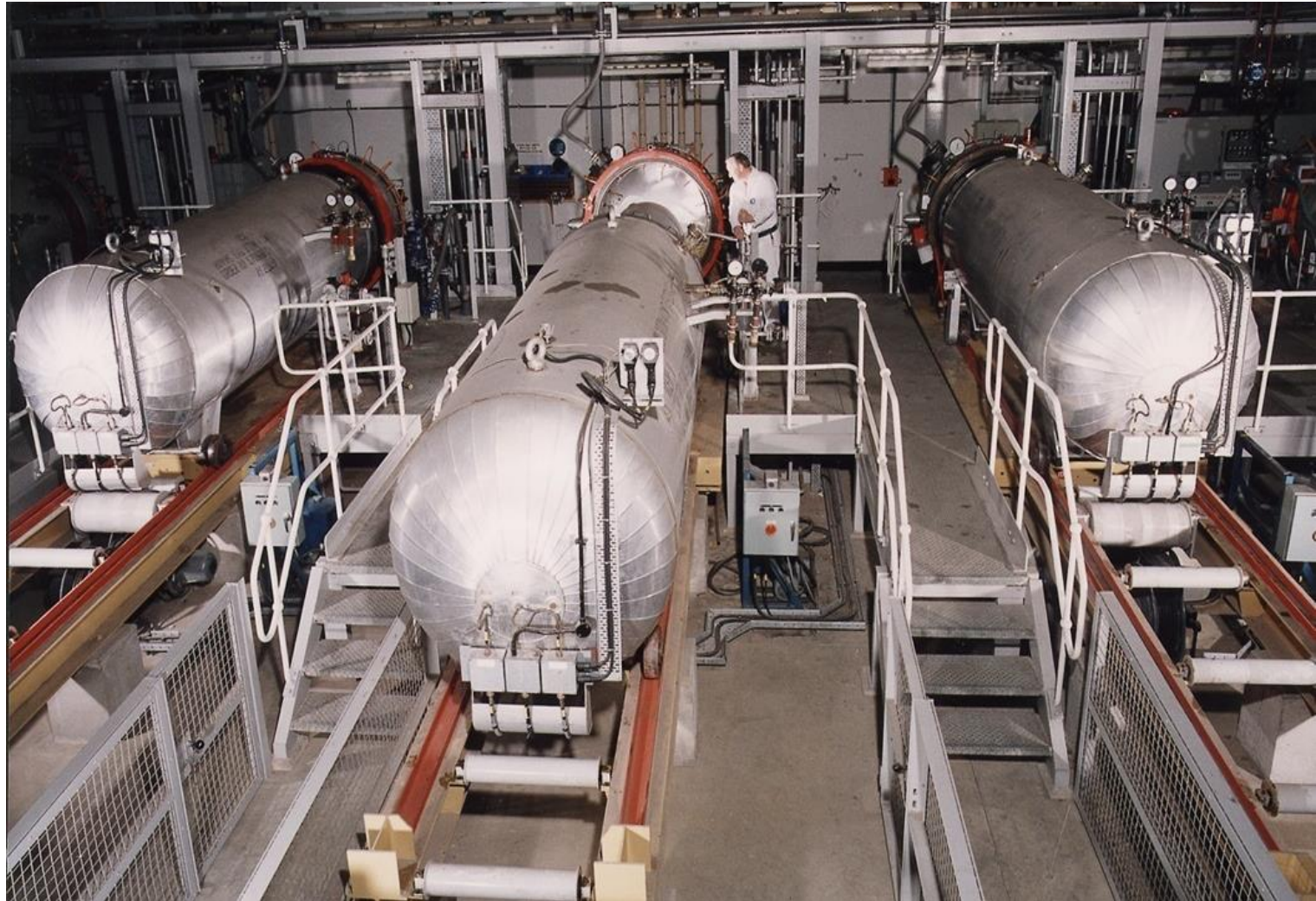
- **Electrical/Instrument Systems**

- Incoming high voltage (HV) power, HV/medium voltage (MV) transformer pens, 3-phase voltage distribution system, building lighting/power distribution, frequency conversion equipment (run-up and run converters), machine frequency distribution, control room equipment (cascade monitoring and control), machine failure recording system, on-line UF₆ mass spectrometers.

- **General Services**

- Cooling water plant, de-mineralised water plant, compressed air plant, stand-by diesel generators, battery-backed system for critical valves and lighting.

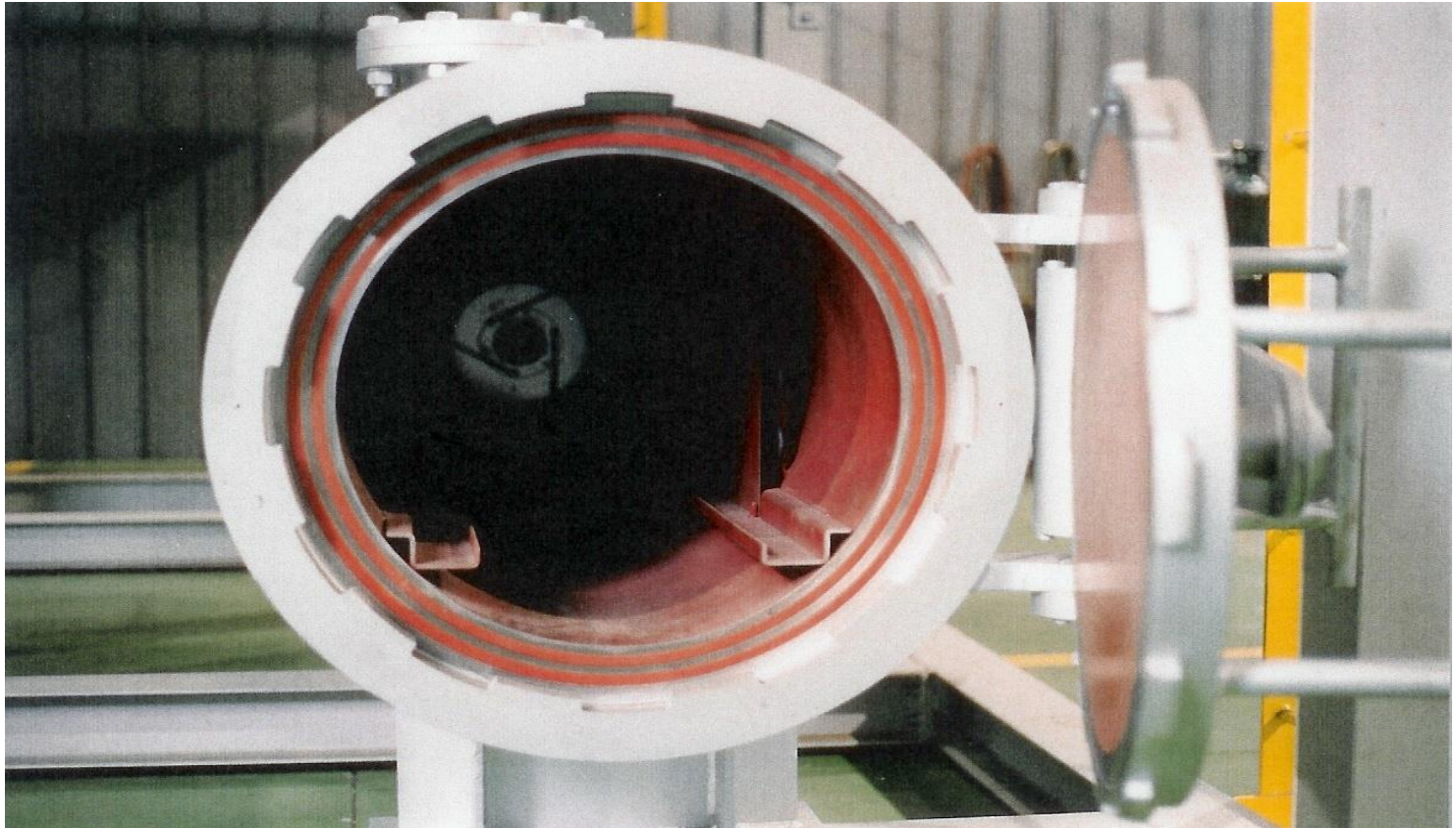
Bank of Autoclaves



Feed and Withdrawal System, for Libyan Plant, manufactured in South Africa by node of AQ Khan Network



Feed Autoclave for uranium hexafluoride cylinders of up to 12 inch diameter



Illicit Procurement for
Centrifuges:
Tradeoffs in Choosing a
Centrifuge Type

Illicit trade has been critical to proliferant state centrifuge programs

- Strictly indigenous production of centrifuges has been historically rare
 - Not route for most pressing cases
 - Unlikely for new developing states
- Outside assistance entails:
 - Use of illicit procurement networks
 - Foreign consultants
- Countries have not reliably made centrifuges without illicit trade

States Using Illicit Trade

- Countries heavily reliant on illicit nuclear trade to obtain centrifuges:
 - Brazil, Iran, Iraq, North Korea, Pakistan, India, and South Africa have
 - Iran, North Korea, Pakistan, and likely India still do
- All required key centrifuge and centrifuge-related technology from overseas
- Required key goods from abroad that were too difficult to make. Recent cases involve:
 - Measuring equipment
 - Vacuum pumps and high speed valves
 - High grade maraging steel, high strength aluminum, and high strength carbon fiber
- Countries have even sought items overseas that they could have made themselves. The goal has been to save costs and time and obtain higher quality, more reliable goods.

States Forgoing Assistance: Few Successes

- States that have forgone outside assistance, including more developed nations, have encountered significant obstacles to developing optimally performing centrifuges:
 - Australia, which proceeded indigenously with a limited number of engineers and technicians, took years to produce a functioning centrifuge program
 - Sweden spent years developing centrifuges but did not build a functioning one before cancelling its program.
 - In the 1990s, China decided to drop its indigenous centrifuge program in favor of buying centrifuges from Russia.

Nation state seeking nuclear Weapons: How many centrifuges?

- A nation state would want to produce at least a few bomb's worth (25 kg) of weapon-grade uranium per year.
- Centrifuges with say 2 SWU/yr would require a plant with ~2,500 centrifuges to make 1 bomb's worth each year
- Would take twice that number to get to a minimum annual capacity, of two bombs per year
- Higher performance centrifuges, say 10 SWU/yr would require ~500 centrifuges to make 1 bomb's worth per year. Would need 1,000 centrifuges to get a minimal annual capacity.

Why Seek Increases in Separative Work Output

Figure 10: Centrifuge Output vs. Goods Required

Centrifuge Output (swu/year/cent.)	Number Centrifuges (produce 25 kg WGU/yr)	Examples of Amount of Equipment	
		Bottom Bearings(a)	Fast-Acting Valves(b)
0.5	10,000	10,000	30,000
1.0	5,000	5,000	15,000
2.0	2,500	2,500	7,500
5.0	1,000	1,000	3,000
10	500	500	1,500

Comments:

- (a) For comparison purposes, the production of 25 kilograms of weapon-grade uranium (WGU) is taken as requiring 5,000 swu, or 200 swu per kilogram of WGU; so the plant would produce enough WGU for one nuclear weapon per year.
- (b) One way to protect centrifuges against crashing is to have a computer control system that allows for the rapid shut off of feed, product, and tails gas in each centrifuge. In designs used by Pakistan and Iran, each centrifuge has three fast acting valves. Additional bellows sealed valves are used in each cascade; up to 25 per cascade is not unusual. Since low end centrifuges would also need more cascades, they would also need many more bellows sealed valves than higher output centrifuges.

Compare the two routes

- Low performance might be somewhat easier to build, but the cascades require more parts.
- Higher performance can be the same size, just have more sophisticated materials to achieve higher rotational speed.
- In both cases, sub-critical operation most likely.
- Higher performance requires more difficult to obtain or to manufacture materials and parts.
- But making large numbers of rotating components of low performance centrifuges is difficult.
- Things never go well when you are building centrifuges!

Findings for Centrifuge Programs in the Next 5-10 Years

- Proliferant state centrifuge programs are likely to continue depending on overseas procurement for a range of key goods.
- State programs are unlikely to utilize very low-end centrifuges (e.g. 0.5 swu/year/centrifuge) as a way to avoid overseas procurements. In fact, it is doubtful if developing states could build low-end centrifuges without outside assistance and foreign procurements.
- A future effort by a proliferant state to build its first gas centrifuge plant able to make enough weapon-grade uranium for a nuclear explosive may be limited to centrifuges with an output of less than 2 swu/year/centrifuge. However, most such programs can be expected to seek centrifuges in the range of 2-5 swu/yr/centrifuge, partly in order to limit the size of the plant and overseas requirements for goods. With a greater level of foreign assistance, such a program may seek a centrifuge with an output of 10 swu/yr.

Source: Future World of Illicit Nuclear Trade: Mitigating the Threat
http://www.nps.edu/Academics/Centers/CCC/PASCC/Publications/2013/Albright_Future_World_of_Illicit_Nuclear_Trade_PASCC.pdf

Findings for Centrifuge Programs 5-10 Years in the Future (cont.)

- Some established programs, such as Pakistan, Iran, and North Korea could achieve centrifuges in the range of 10-20 swu/yr centrifuge in the next 5-10 years.
- Proliferant states are unlikely to achieve centrifuge outputs significantly higher than 30-40 swu/yr/centrifuge.
- Declared or undeclared centrifuge programs could develop, or re-start, in countries that are newly industrialized or in more rapidly developing countries, such as South Korea, Turkey, and South Africa. These programs would be expected by then to be mostly capable of making centrifuges indigenously. However, they are expected to depend on overseas procurement for certain items in order to save costs and time and obtain higher quality, more reliable goods.

Terrorist Group: How many centrifuges & how many SQs

- Terrorists may be capable of building low end centrifuges although the large numbers required to make one significant quantity of weapon-grade uranium make this route unlikely, unless a terrorist group can establish itself securely and safely for years in a host state.
- A terrorist group developing uranium enrichment capability would require significant help from outside. They would have to enlist illicitly experts in nuclear technology.
- For such a group, one SQ and one device might suffice, and it would be delivered by para-military methods, e.g. train, plane, auto, boat.
- It would take several years at a minimum to produce a device.
- Overall, this scenario is unlikely during the next five to ten years.