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Life in a Nuclear Powered Crowd

(The Problem of Uranium Enrichment)

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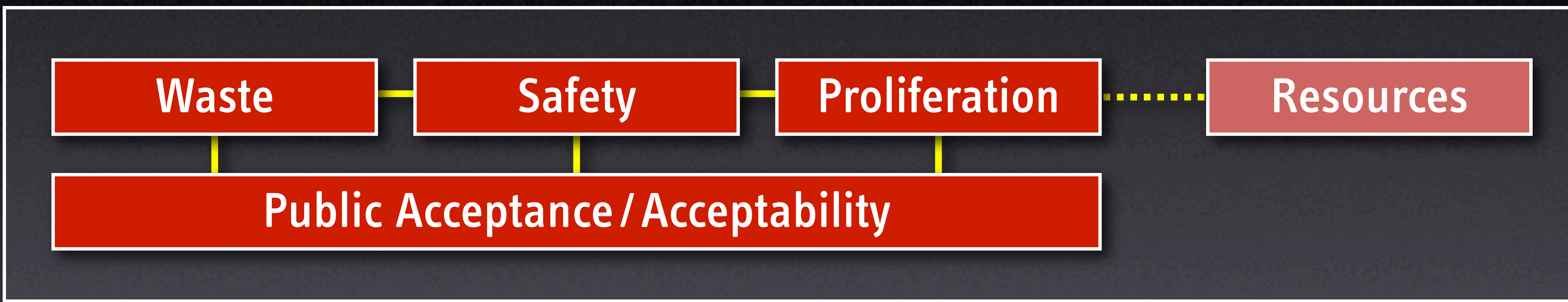
Key Problems of Nuclear Power



Economics may not (or should not) be considered a first-level criterion

The key problems would have to be "solved"
prior to a large-scale expansion of nuclear power

(Needs broad consensus about what "solution" means)

Countries with Nuclear Infrastructure

(June 2005, IAEA Databases)

Countries with operational nuclear reactors	
Commercial reactors	31
Research reactors	57

Countries with operational fuel cycle facilities	
Enrichment facilities	13
Reprocessing facilities	13
Conversion facilities	15
Uranium mines	40

Estimated World Population in 2050

(by country, "top 24")

Country	Population (millions)
India	1620
China	1470
USA	403
Indonesia	337
Nigeria	303
Pakistan	267
Brazil	206
Bangladesh	205
Ethiopia	187
Congo	181
Philippines	153
Mexico	153

Country	Population (millions)
Vietnam	119
Russia	118
Egypt	113
Japan	101
Iran	100
Saudi Arabia	91
Tanzania	88
Turkey	86
Sudan	84
Uganda	84
Germany	79
Yemen	71

Currently, no commercial nuclear power program

Nuclear power expansion to at least 10 GWe ( ) or to at least 1 GWe ( ) as assumed in MIT Study for 1000 GW(e) scenario

54 countries with commercial nuclear power programs
(including 18 countries with 10 GWe or more)

MIT Study, 1000 GW(e) scenario for 2050

The Nuclear Fuel Cycle

(briefly)

Nuclear Fuel Cycle Options

Plutonium recycling in LWR's (as MOX)
does not significantly reduce the SWU demand

(theoretically: 15-20% if Pu is recycled once)

Fast breeder (or Unat fueled) reactors are unlikely to be the answer to the proliferation problem

Enriched uranium in LWR's or HTGR's
(4-5% or < 20% enrichment in "once-through" cycle)
will most likely be the standard fuel in the future

Enrichment Capacities

20 centrifuge facilities operational, under construction, or planned

(but: only 10 facilities with capacities of at least 1000 tSWU/y)

Number of enrichment facilities in a global expansion scenario

360 GW(e) require about 34,000 tSWU per year

Typical size of a commercial centrifuge facility: 1000-2000 tSWU/y, equivalent to 17-34 facilities

Three-fold expansion: 50-100 facilities   Ten-fold expansion: 170-340 facilities

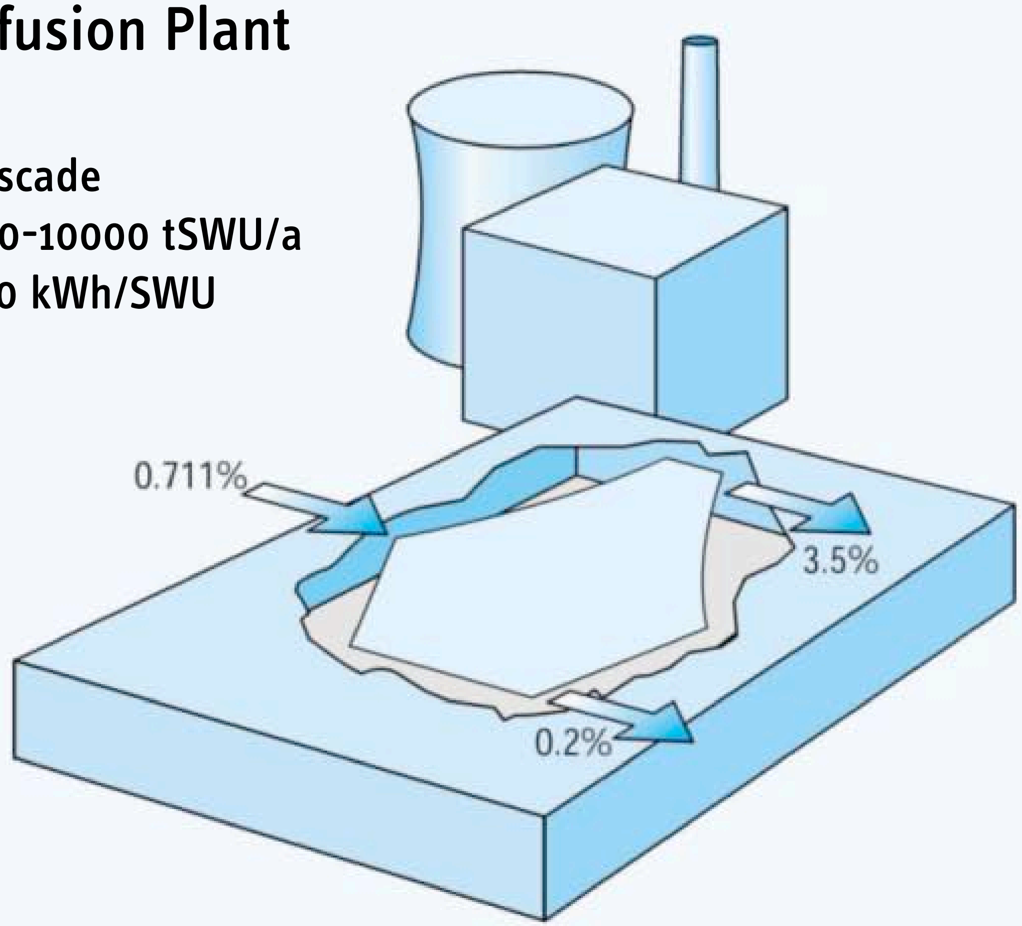
De-facto: Every country with an active nuclear power program would seek to acquire its own enrichment facility

(if typical economy-of-scale criteria for centrifuge facilities are applied)

Gaseous Diffusion vs. Centrifuge

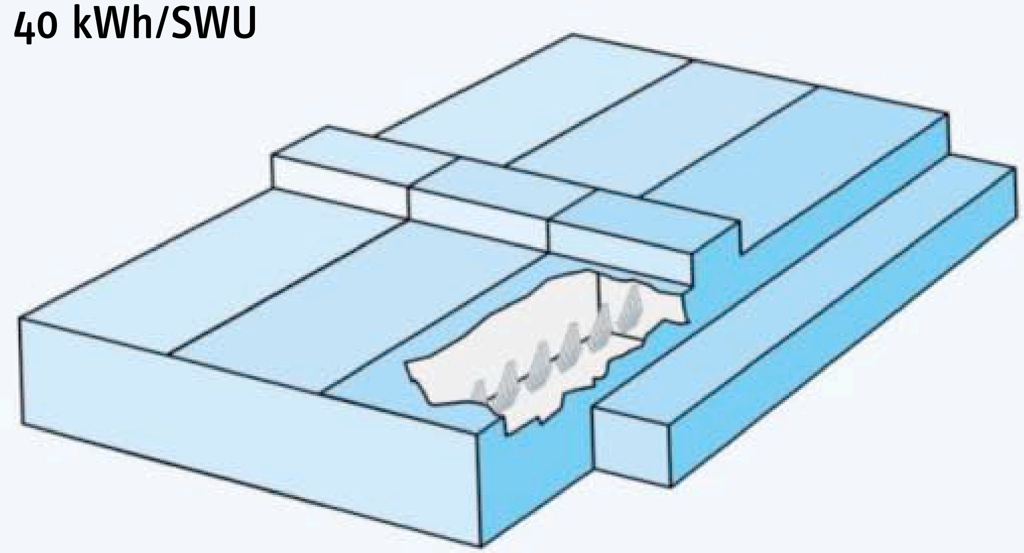
Diffusion Plant

1 cascade
6000-10000 tSWU/a
2400 kWh/SWU



Centrifuge Plant

50 parallel cascades
1000-2000 tSWU/a
40 kWh/SWU



Source: Urenco

Nuclear Reactors in the World and their Estimated SWU Demand

Country	Operational		Under Constr.		tSWU/y Demand	Enrichment Supply
	Units	MW(e)	Units	MW(e)		
Argentina	2	935	1	692	0	
Armenia	1	376	0	0	43	
Belgium	7	5,760	0	0	529	Eurodif
Brazil	2	1,901	0	0	218	Domestic (since 2003)
Bulgaria	4	2,722	0	0	312	
Canada	14	10,018	0	0	0	None
China	7	5,318	4	3,275	610	Domestic and Urenco
China, Taiwan	6	4,883	2	2,700	561	
Czech Republic	6	3,468	0	0	398	
Finland	4	2,656	0	0	305	
France	59	63,073	0	0	5,792	Domestic (Eurodif)
Germany	19	21,283	0	0	1,955	Domestic (Urenco)
Hungary	4	1,755	0	0	201	
India	14	2,503	8	3,622	43	
Iran	0	0	2	2,111	0	Russia (domestic?)
Japan	54	44,287	3	3,696	4,067	Domestic and ???
Korea, Dem. P. R.	0	0	1	1,040	0	

Reactor data from Power Reactor Information System (PRIS) of the IAEA, June 2003
(Estimates of SWU demand derived tentatively)

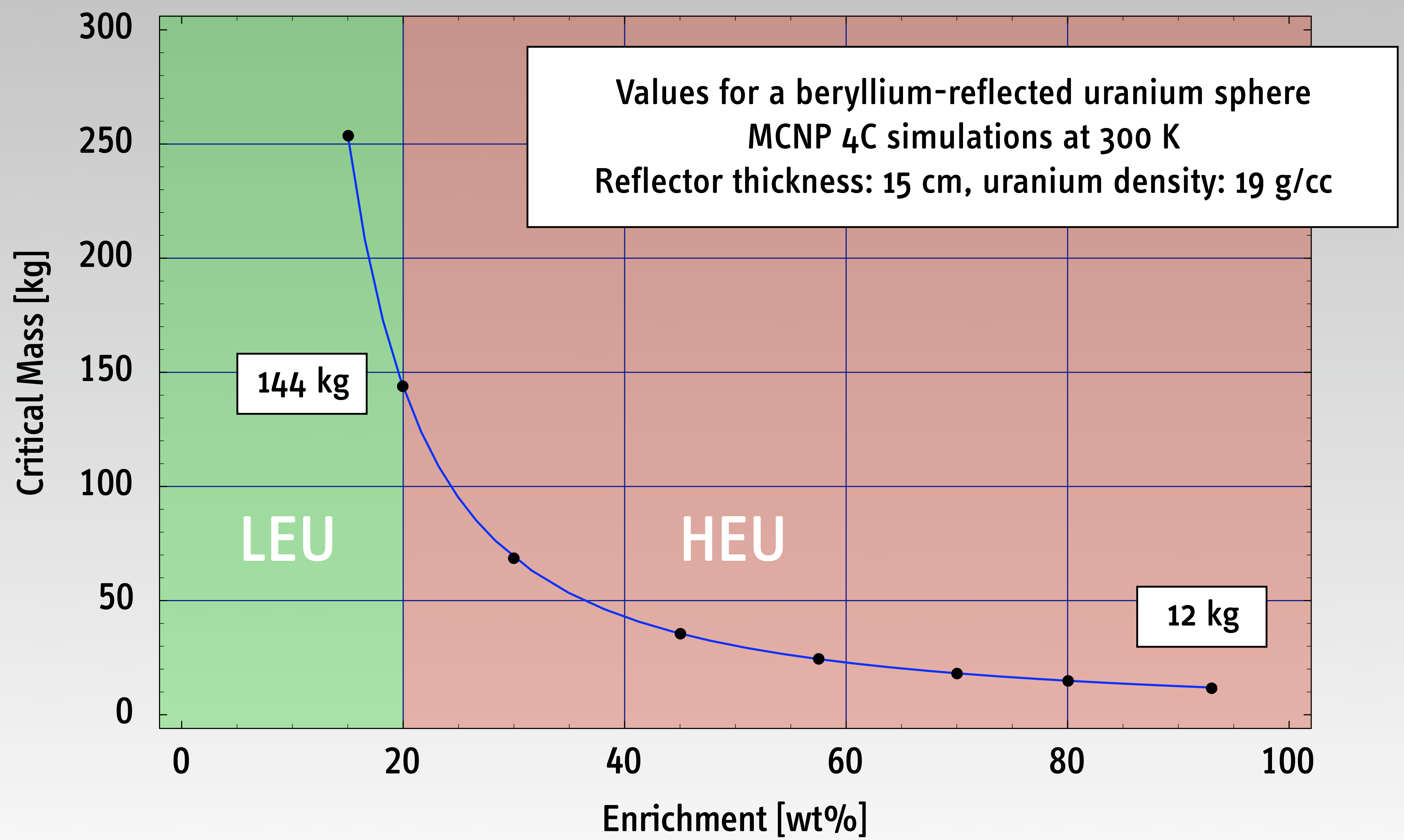
Nuclear Reactors in the World and their Estimated SWU Demand

Country	Operational		Under Constr.		tSWU/y Demand	Enrichment Supply
	Units	MW(e)	Units	MW(e)		
Korea, South	18	14,890	2	1,920	1,367	
Lithuania	2	2,370	0	0	272	
Mexico	2	1,360	0	0	156	
Netherlands	1	450	0	0	52	Domestic (Urenco)
Pakistan	2	425	0	0	24	
Romania	1	655	1	655	75	
Russia	30	20,793	3	2,825	1,910	Domestic
Slovakia	6	2,408	2	776	276	
Slovenia	1	676	0	0	78	
South Africa	2	1,800	0	0	207	
Spain	9	7,574	0	0	869	Eurodif
Sweden	11	9,432	0	0	1,083	
Switzerland	5	3,200	0	0	294	
Ukraine	13	11,207	4	3,800	1,286	Russia
United Kingdom	27	12,052	0	0	415	
United States	104	98,230	0	0	11,276	Domestic and Russia
Total	**437**	**358,460**	**33**	**27,112**	**34,674**	

Reactor data from Power Reactor Information System (PRIS) of the IAEA, June 2003
(Estimates of SWU demand derived tentatively)

Uranium Enrichment and the Case of the Gas Centrifuge

Critical Mass of Uranium

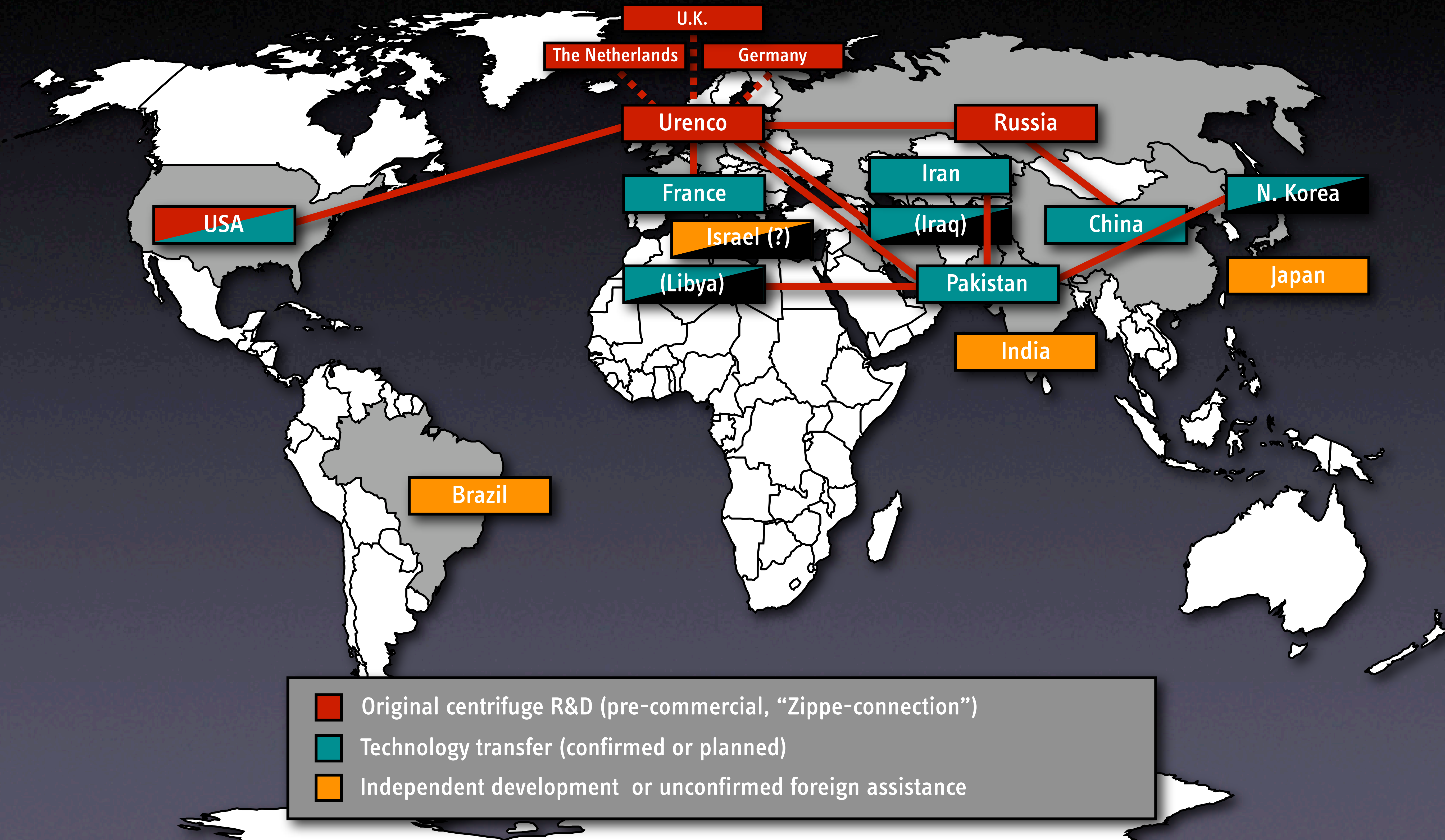


Characteristics of Highly Enriched Uranium

Easy to handle
Easy to use in nuclear weapon or explosive device
Difficult/Impossible to detect

Difficult to produce

"Genealogy" of the Gas Centrifuge



Country	Name/Location	Status	Start-up	Capacity	Safeguards
Brazil	BRN Aramar	Operational	1992	5 tSWU/y	(No)
	BRF Aramar	Operational	1998	4 tSWU/y	(No)
	Resende	Under Construction	2004	120 tSWU/y	(IAEA/ABACC)
China	Shaanxi	Operational	1997	200 tSWU/y	IAEA
	Lanzhou 2	Under Construction	2005	500 tSWU/y	(IAEA)
France	GBII Tricastin	Planned	?	7,500 tSWU/y	(IAEA/Euratom)
Germany	Jülich	Operational	1964	Laboratory	
	Gronau	Operational	1985	1,800 tSWU/y	IAEA/Euratom
India	Rattehalli	Operational	1990	3–10 tSWU/y	No
Iran	Natanz	Under Construction	?	?	(IAEA)
Iraq	Al Furat	Destroyed in 1991	—	—	(No)
(?) Israel	Dimona	Operational	1980	Pilot scale	No
Japan	Ningyo-Toge	Shutdown in 2004	1979	75 tSWU/y	
	Ningyo-Toge	Shutdown in 2004	1989	200 tSWU/y	
	Rokkasho	Operational	1992	1,050 tSWU/y	IAEA
Libya	?	Abandoned in 2004			
Netherlands	Almelo	Operational	1973	2,200 tSWU/y	IAEA/Euratom
North Korea	?	Under Construction		?	(No)
Pakistan	Kahuta	Operational	1984	5 tSWU/y	No
Russia	Sverdlovsk	Operational	1949	7,000 tSWU/y	No
	Seversk	Operational	1950	4,000 tSWU/y	No
	Angarsk	Operational	1954	1,000 tSWU/y	No
	Krasnoyarsk	Operational	1984	3,000 tSWU/y	No
United Kingdom	Capenhurst	Operational	1972	2,300 tSWU/y	IAEA/Euratom
Unites States	Portsmouth	Awaiting license	?	Pilot scale	
	?	Planned	?	?	

Total centrifuge capacity operational in 2004	$\sim$ 23,000 tSWU/y	
Total enrichment capacity available in 2004 (all processes)	$\sim$ 53,500 tSWU/y	
Total enrichment capacity required in 2004	$\sim$ 35,000 tSWU/y	

Cascade Hall
(Urenco-type machines at the Gronau facility in Germany)

Source: Urenco

Proliferation Concerns Associated with Enrichment Technologies

(and with centrifuge technology in particular)

	Declared Facility	Undeclared Facility
Covert (operation as declared)	Diversion of LEU (abrupt or protracted)	Production of HEU (possibly using LEU feed)
Covert (with modifications)	Excess LEU production (or production of HEU)	
Overt	Break-out scenario	

"A Safeguards Nightmare"

Excess Production of LEU
(using undeclared feed)

Currently no verification of plant capacity (independently from operator's declaration)

Covert HEU Production

Standard approach: "Limited Frequency Unannounced Access"

New: Ex-post-facto confirmation by environmental sampling (used since mid 1990's)

Break-Out

What Can Be Done With 5000 SWU?

Assumptions about available equipment and material

Small enrichment capacity: 5000 kgSWU/yr (about 2500 1st-generation machines)
Adequate (but limited) feed-stock: 10 metric tonnes of natural uranium (at 0.71%) per year

Standard operation
using U(nat) feed

1015 kg of LEU at 4% (Tails at 0.34%)

152 kg of LEU at 20% (Tails at 0.41%)

29 kg of HEU at 93% (Tails at 0.44%)

Breakout scenario using a three-year supply of LEU (3045 kg, 4%) as feed-stock

Process the entire feed-stock in 1 year: 103 kg of HEU at 93% (Tails at 0.87%)

Process as quickly as possible (to obtain first significant quantity earlier):

1st SQ (25 kg) of HEU at 93% can be produced in about 7½ weeks (53 days, Tails at 3.26%)

2nd SQ about 9 weeks later (65 days, Tails at 2.51%)

Centrifuge Generations

Level of Technology	Rotor Material	kgSWU/yr (estimated)	Deployment	Examples
Low	Aluminum	2	1970's	Pakistan P-1 (Netherlands D-1)
Medium	Maraging Steel	5	1980's	Pakistan P-2 (Germany G-2)
Medium	Carbon Fiber (subcritical machine)	10	?	Russia
High	Carbon Fiber	40	1990's	Urenco TC-12
High	Carbon Fiber	100	2000's	Urenco TC-21
High	Carbon Fiber	200-300	2000's	USEC Set III/V

Note: Reportedly, the following machines are similar (as they are based on the Dutch D-1): Pakistan P-1, Iran I-1, and Libya L-1

Centrifuge Characteristics

Rotor speed is prime: $\delta U \sim v^2$

Material of high tensile strength

...

Rotor length is important: $\delta U \sim h$

Operation of supercritical machines

Extremely well-balanced rotors

...

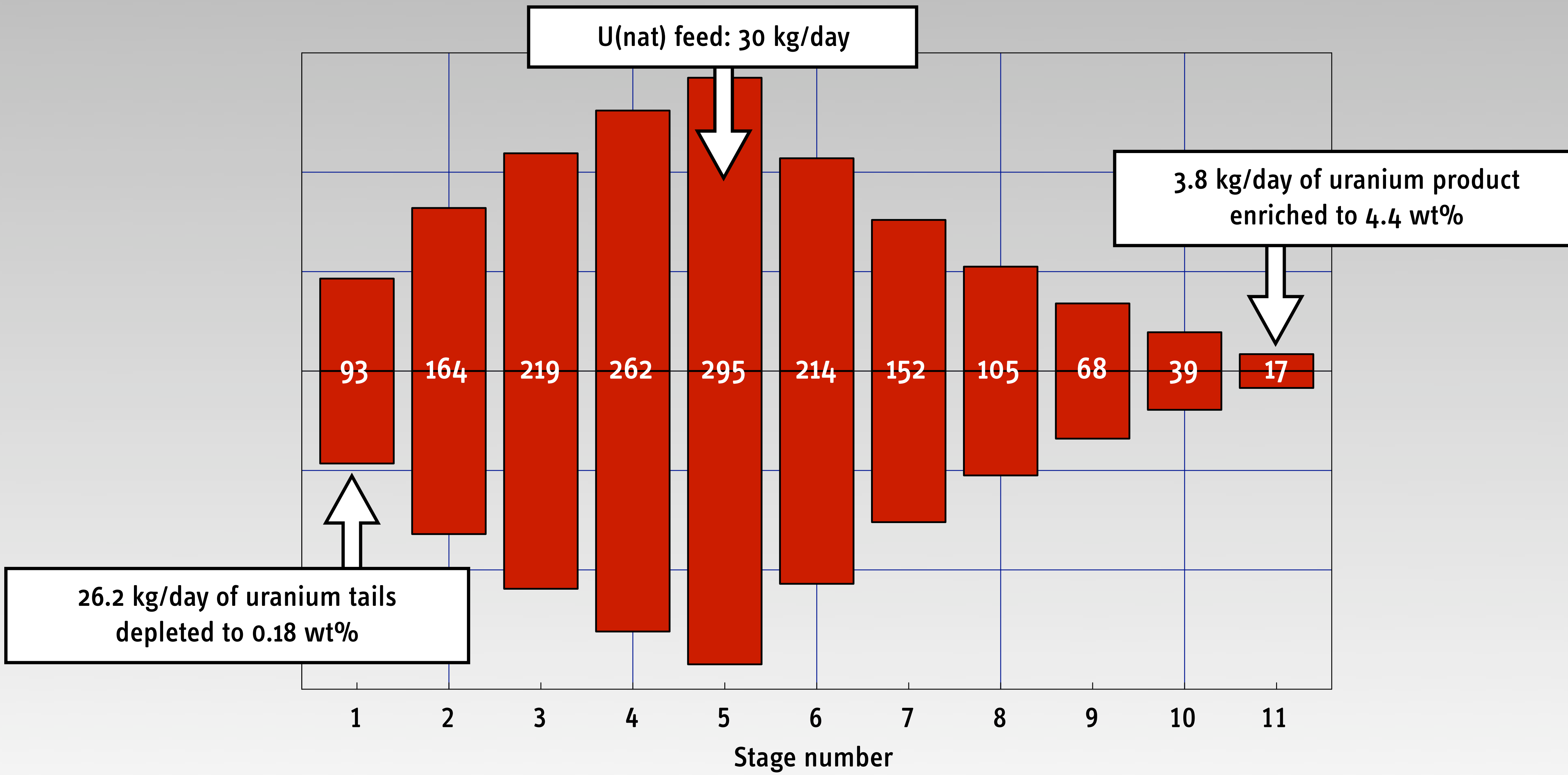
High separation factor $\longrightarrow$ Few stages

Few stages + Short hold-up time $\longrightarrow$ Low inventory

Low inventory $\longrightarrow$ Short equilibrium time

Operation of Centrifuge Cascade

(Preliminary data)



1628 machines, feed rate: 5.8 mg/sec, hold-up: 12.93 seconds

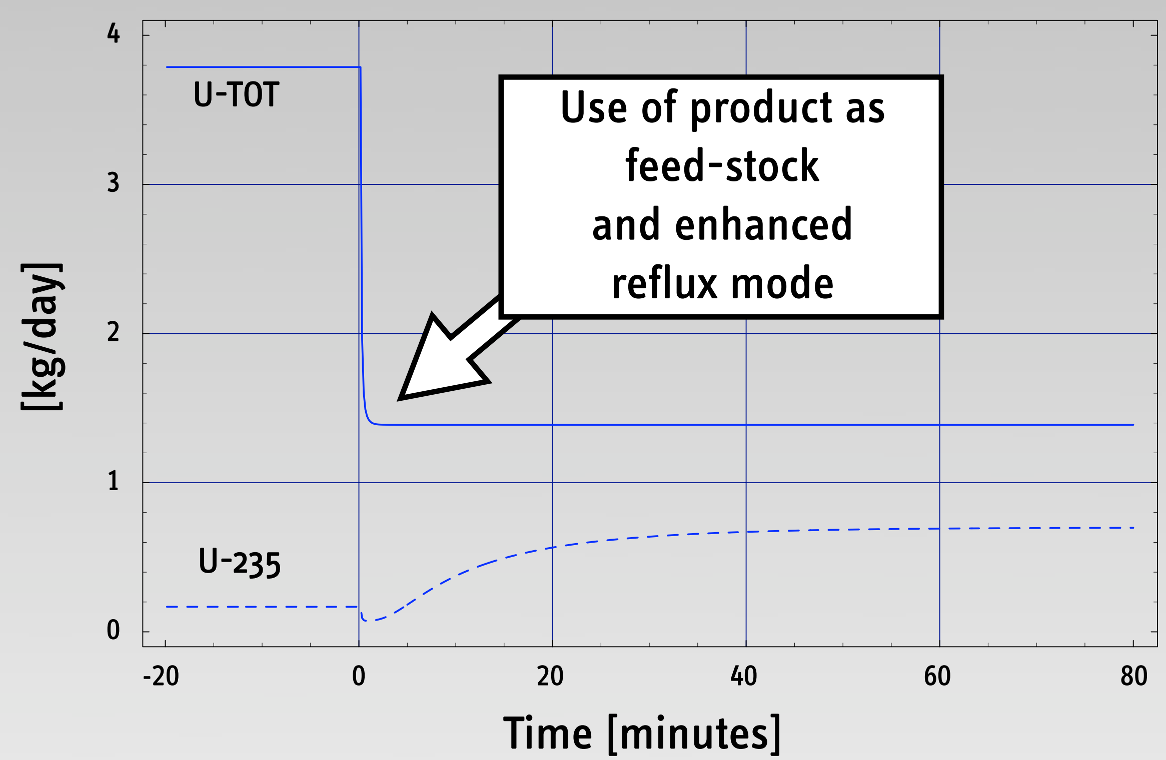
Assumed uranium inventory: 75 mg per machine, 122 grams in cascade

Capacity of cascade ca. 11 tSWU/yr

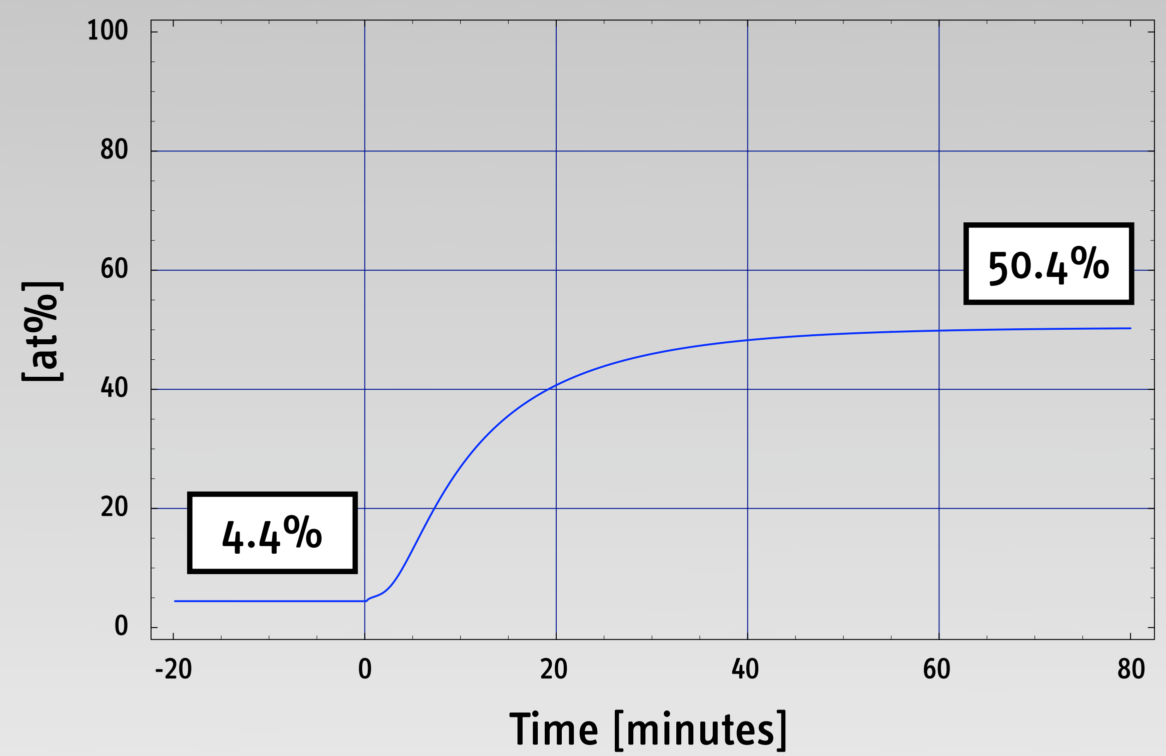
Operation of Cascade

(Enhanced reflux mode)

Product Stream



Enrichment of Product

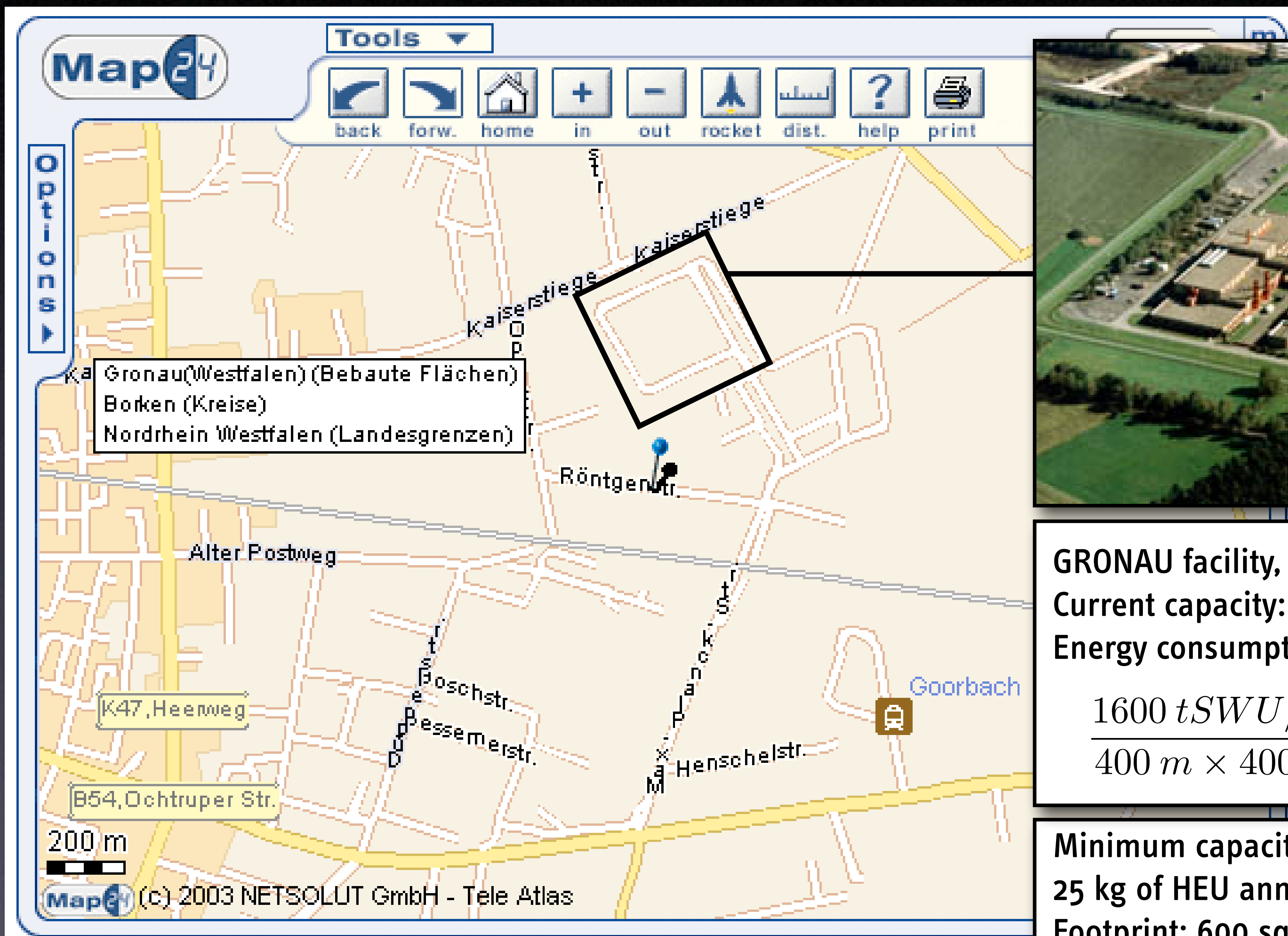


At T = 0, pre-enriched feed-stock is used and
the stage cut is slightly reduced (by -0.05) in each stage of the enriching section

Assumed hold-up of material per machine: 75 mg

Detection of Undeclared Facilities

Specific Size of a Centrifuge Facility



GRONAU facility, Germany
Current capacity: 1600 tSWU/a (Mid 2003)
Energy consumption: 40 kWh/SWU

$$\frac{1600\ tSWU/yr}{400\ m \times 400\ m} = 10\ \frac{SWU/yr}{m^2}$$

Minimum capacity of facility to produce 25 kg of HEU annually: ca. 6000 SWU/yr
Footprint: 600 sq. meter (80 ft x 80 ft)

Nonproliferation Characteristics of Various Enrichment Processes

	Proliferation Sensitivity	Detectability (Selected Criteria): Size	Detectability (Selected Criteria): Energy Consumption	Detectability (Selected Criteria): Wide Area EM
Calutron/EMIS	(high)	Yes	Yes	Yes
Gaseous Diffusion	low	Yes	Yes	Yes
Chemical Exchange	very low	(Yes)	(No)	(Yes)
Centrifuge	high	No	No	No
Laser	(high)	No	No	No

What Can Be Done About It?

Possible Strategies to Limit the Front-End Proliferation Risks of the Nuclear Fuel Cycle

uncontroversial

- Tighten export controls (further)
- Increase the effectiveness of (and the confidence in) safeguards
- Increase the ability to detect undeclared facilities
- Delegitimize enrichment in today's "non-enrichment" states
- Require multinational operation of enrichment facilities
- Strive for internationalization of the nuclear fuel cycle
- Devalue nuclear weapons
- Revisit alternative enrichment technologies
- Consider global phase-out of nuclear power

unrealistic (?)

Nonproliferation Conditions of Existing Multinational Arrangements

(adapted from Krass et al., 1983)

	Urenco	Eurodif
Only NPT parties	Yes	Yes (was: No)
Governmental participation	Yes	No
International safeguards	Yes	Yes (was: No)
Withdrawal exclusion	No	No
Prohibition of national control	No	No
Multinational R&D only	No	No
One facility	No	Yes
Prohibition of technology transfer	No	No
Exclusion of internal technology sharing	No	Yes (in theory)
HEU production exclusion	No	No
Proliferation-resistant process	No	No (was: Yes)

Conclusions

Any plausible nuclear expansion scenario would inevitably require a corresponding increase of installed enrichment capacity

The gas centrifuge will be the "workhorse" of the enrichment industry in the future

Technology is extremely difficult to safeguard and impossible to detect

Safeguards system "as we know it" may be inadequate to address proliferation concerns in such a scenario

A moratorium on new enrichment facilities?