Accelerate the Accelerators ?!

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Motivation

The global stockpile of highly enriched uranium (HEU) was about 1440 ± 100 tons in 2012, enough for more than 60,000 simple, first generation implosion weapons. About 98% of this material is held by the nuclear weapon states, with the largest HEU stockpiles in Russia and the United States.

1. "The U.S. National Nuclear Security Administration said it has agreed to help fund a medical science center's efforts to refine an accelerator-centered means for generating a key medical isotope without relying on weapon-usable uranium" (2012-05-09)
http://www.nti.rsvp1.com/gsn/article/heu-free-medical-isotope-project-wins-us-backing/?mgh=http%3A%2F%2Fwww.nti.org&mgf=1

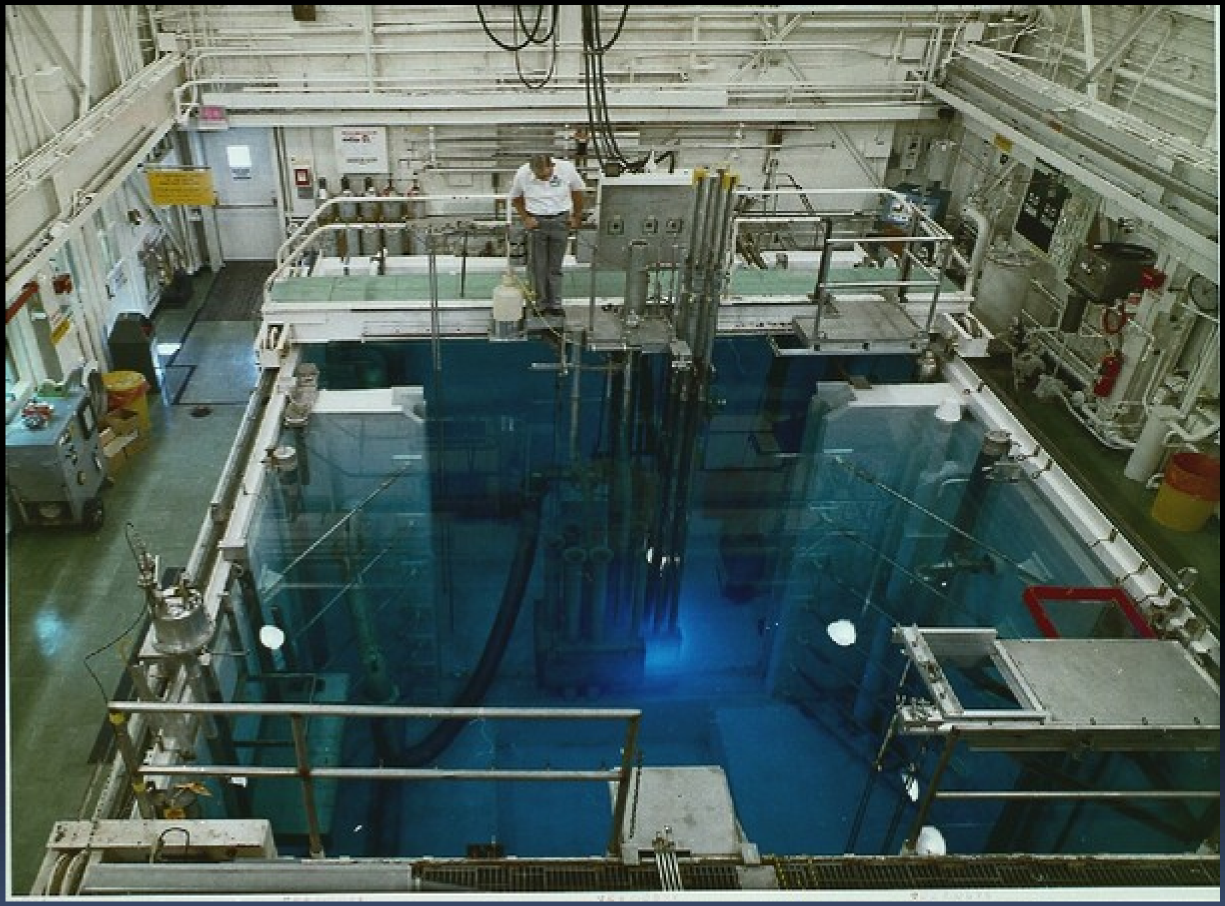
2. …"Iran rejects Western allegations it seeks to develop a capability to assemble atomic arms, saying its nuclear program is entirely peaceful and that the Arak reactor will produce isotopes for medical and agricultural use…" (2012-11-17)
http://www.reuters.com/article/2012/11/17/us-nuclear-iran-reactor-idUSBRE8AG05C20121117

3. "Israel announced that it will replace Soreq's civilian nuclear reactor for a particle accelerator that will be used for medical research". (2012-03-21)
http://news.xinhuanet.com/english/world/2012-03/21/c_131478704.htm

Outline

1. Research Reactors – the overview
2. Research Reactors - are they safe and secure?
3. Medical Isotopes production
4. Linear Accelerators – a better choice?
5. The SARAF Case
6. Final thoughts

1. Research Reactors



http://www.knoxnews.com/photos/galleries/2009/nov/01/oak-ridge-reactors/15372/

TYPES OF RESEARCH REACTORS

Research reactors can be divided into three categories:

- **Steady-power reactors**

Are used primarily as sources of neutrons to irradiate materials for various of purposes

- **Critical assemblies**

Operated at very low power to check calculations of the neutronics of proposed core designs

- **Pulsed reactors**

Mostly used to simulate the effects on electronics in satellites or warheads in space of neutron bursts from nearby nuclear explosions

WHERE AND HOW MANY

- After 1953 , research reactors quickly spread worldwide – almost all provided by the United States or Soviet Union.

- Research reactors are used for research and training, materials testing, or the production of radioisotopes for medicine and industry. They are basically neutron factories.

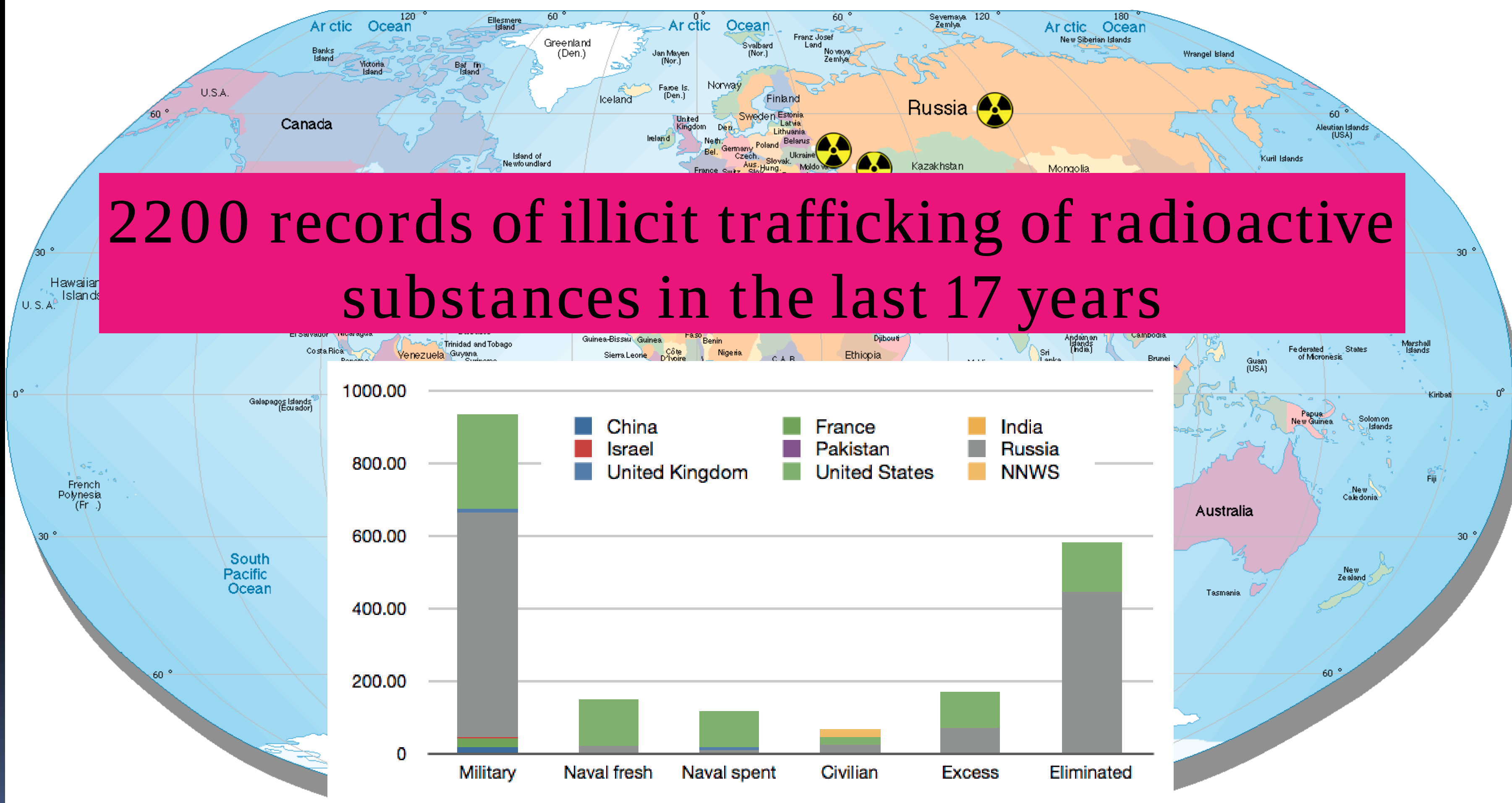
- These are much smaller than power reactors or those propelling ships, and many are on university campuses.

- When HEU production peaked, the United States began to export annually hundreds of kilograms of HEU as research reactor fuel.

There are about 240 research reactors operating, in 56 countries, many of them are fueled with HEU

2. Is it safe & secure?

Security



2200 records of illicit trafficking of radioactive substances in the last 17 years

CONVERSION OF RESEARCH REACTORS FROM HEU TO LEU FUEL

- **Reduced Enrichment for Research and Test Reactors (RERTR) Program**

Conversion of HEU Research Reactors to LEU

- **Global Threat Reduction Initiative (GTRI)**

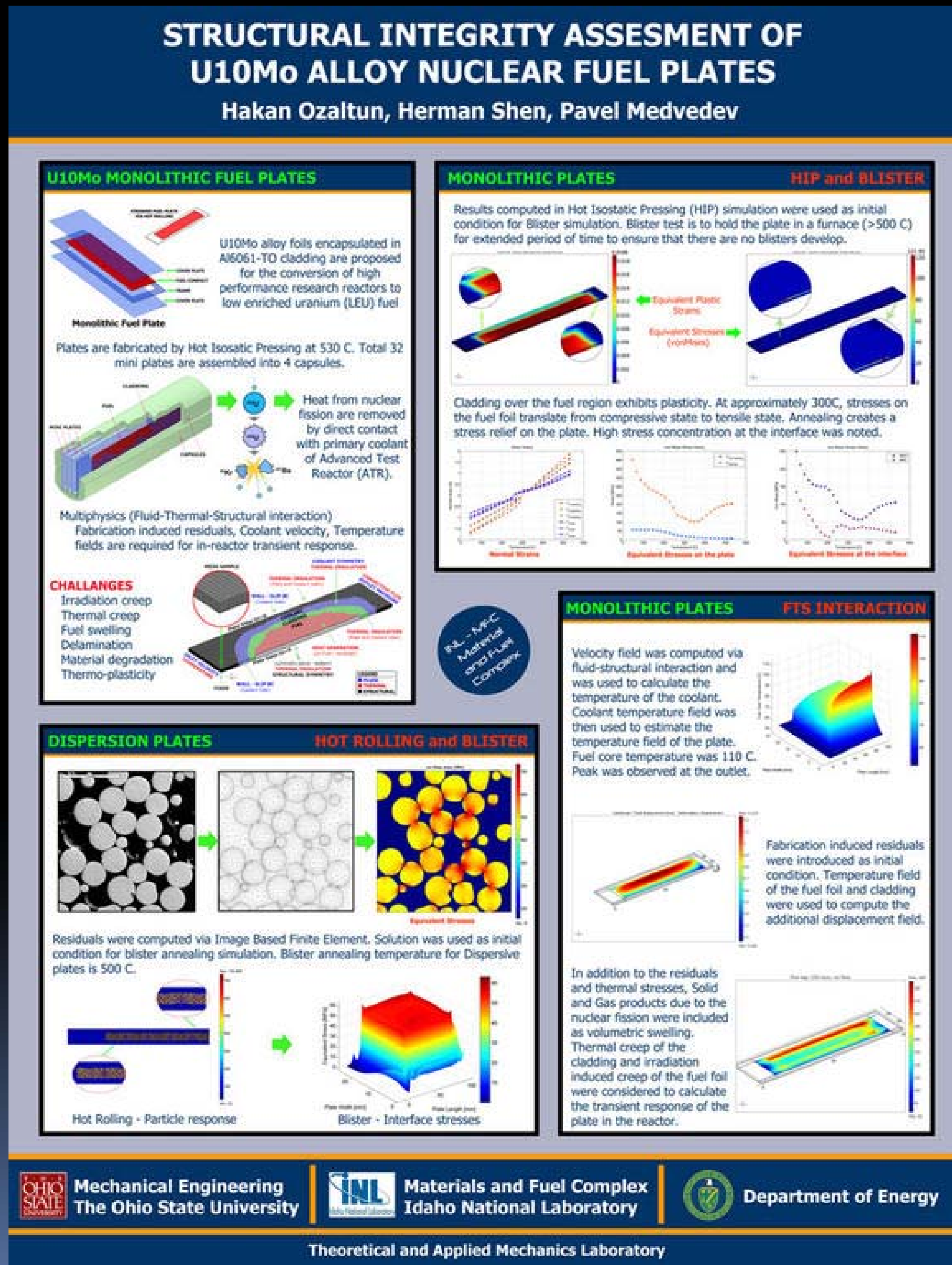
Minimize the amount of nuclear material available that could be used for nuclear weapons by securing, removing, relocating or disposing of relevant materials and equipment.

- **The IAEA projects support**

Differ significantly , depending on a number of factors including, among others, type of research reactor, type of fuel and facility constraints.

- **Different approaches**

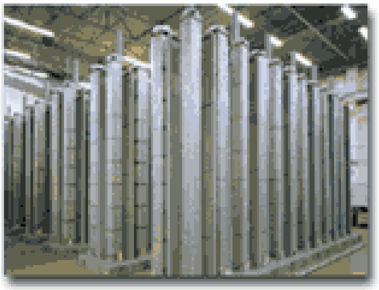
Taken in conversion projects in Chile, Libya, Portugal, Austria, Mexico and Romania.

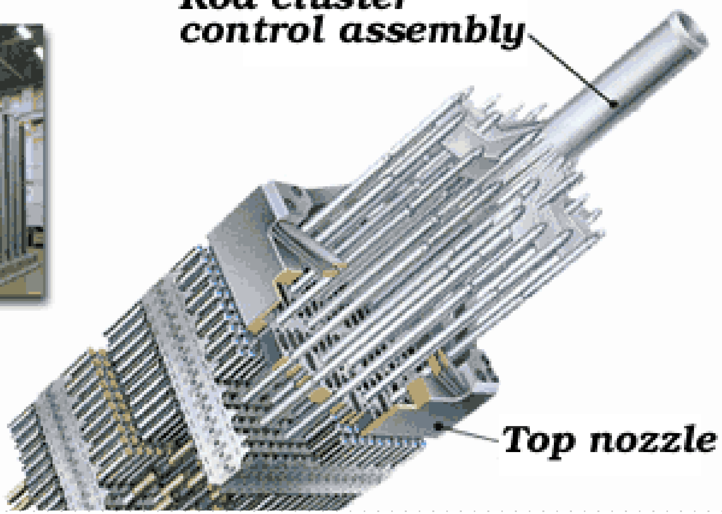


http://mae.osu.edu/labs/tamlab/research/posters

http://www.washingtontimes.com/news/2013/apr/9/defiant-iran-goes-forth-2-nuclear-projects/

Nuclear Fuel Fabrication





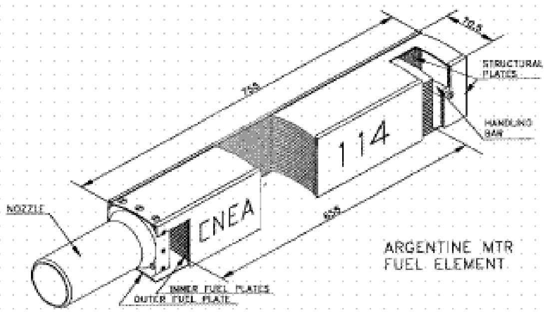


Figure 1: RA-3 Fuel Assembly

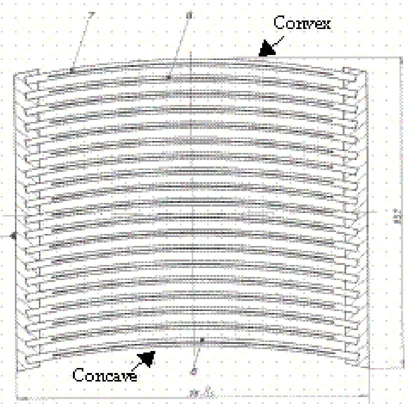
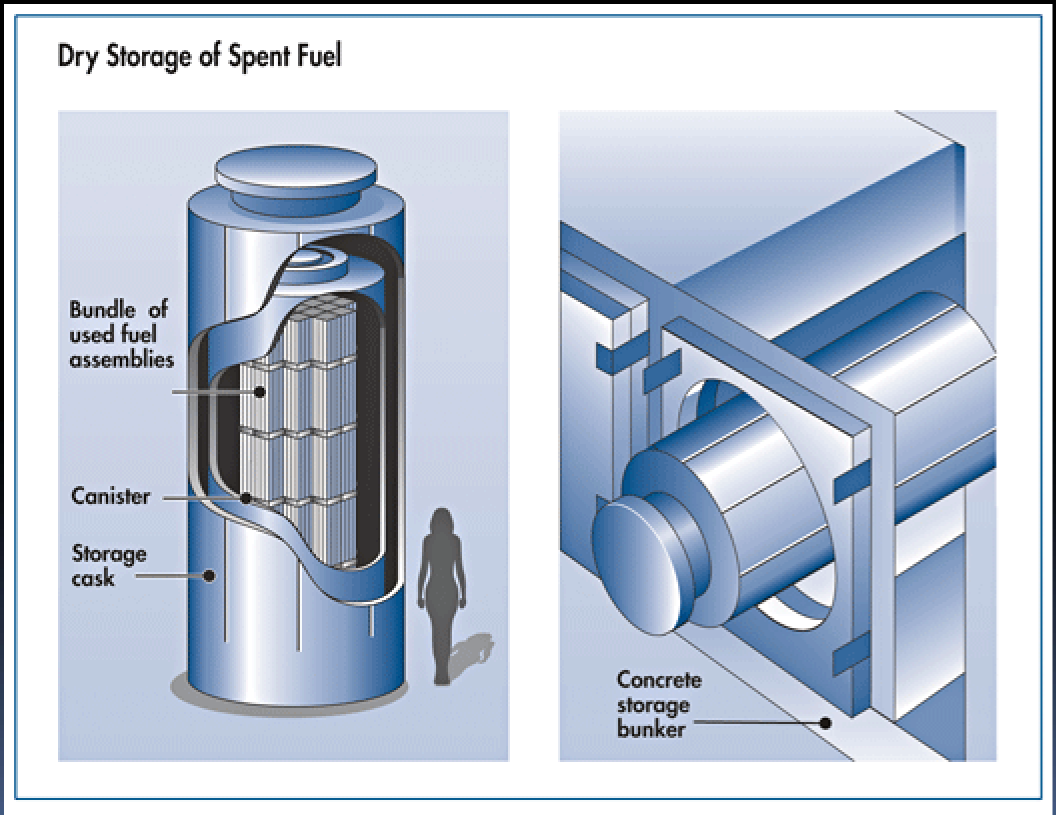


Figure 2: Cross-Sectional View of Fuel Assembly

http://www.virginmedia.com/digital/science/pictures/nuclear-fuel-cycle.php?ssid=7
http://sti.srs.gov/fulltext/ms2000496/ms2000496.html
http://www.infowars.com/alert-fukushima-coverup-40-years-of-spent-nuclear-rods-blown-sky-high/

Spent Fuel



http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dry-cask-storage.html

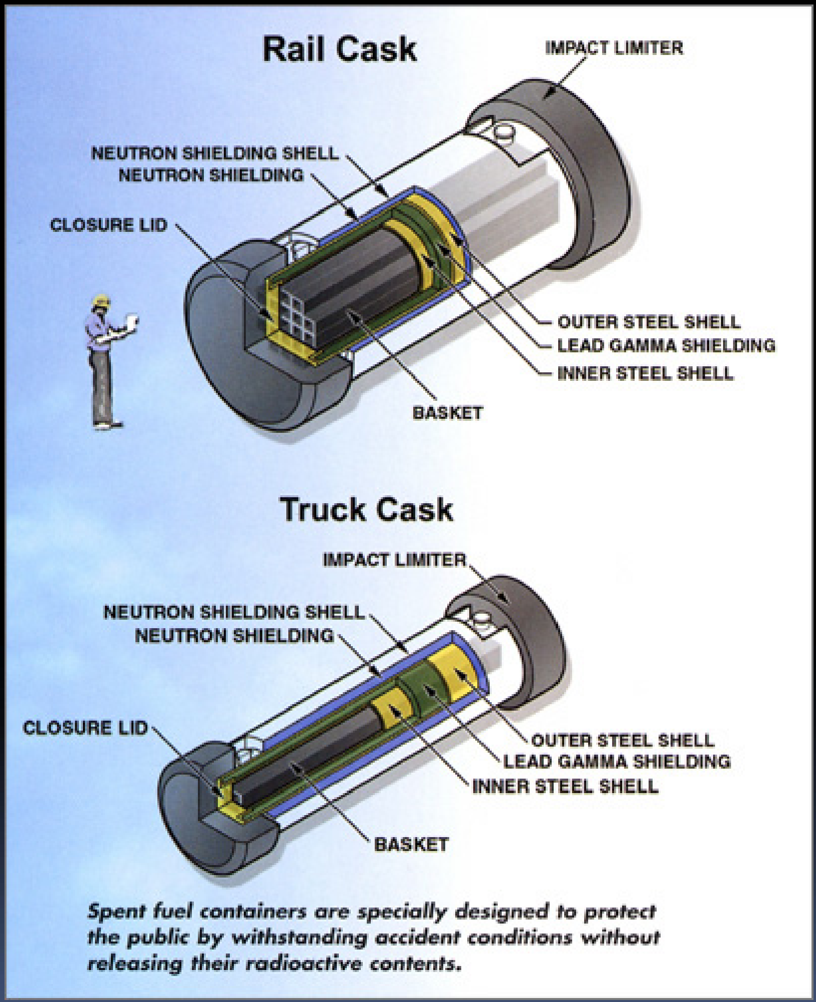
http://www.nacintl.com/

http://www.novinite.com/view_news.php?id=128175

Safety
Transport of Spent Fuel

http://www.posiva.fi/en/nuclear_waste_management/required_permissions_and_procedures/other_required_permissions_and_procedures

http://english.sina.com/world/p/2008/1111/197756.html



http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/transport-spenfuel-radiomats-bg.html

Frank Munger's
Atomic City Underground

Spent HEU fuel from Israel

Friends of the Earth reported this week that spent nuclear fuel from an Israeli research reactor has arrived at Savannah River Site in South Carolina. According to Tom Clements, the group's southeastern nuclear campaign coordinator, the shipment of 102 spent fuel assemblies of "material bearing bomb-grade uranium" was listed in a Dept. of Energy document that identifies U.S.-origin nuclear materials returned to the United States as part of the Global Threat Reduction Initiative. He provided that document as well.

Jennifer Wagner, a spokeswoman for the National Nuclear Security Administration, confimed the shipment, but provided few details. "NNSA cooperated with Israel on the return of U.S.-origin HEU spent nuclear fuel," she said. "The shipment arrived at the Savannah River Site in January in conjuction with a U.S.-origin fuel return from Turkey."

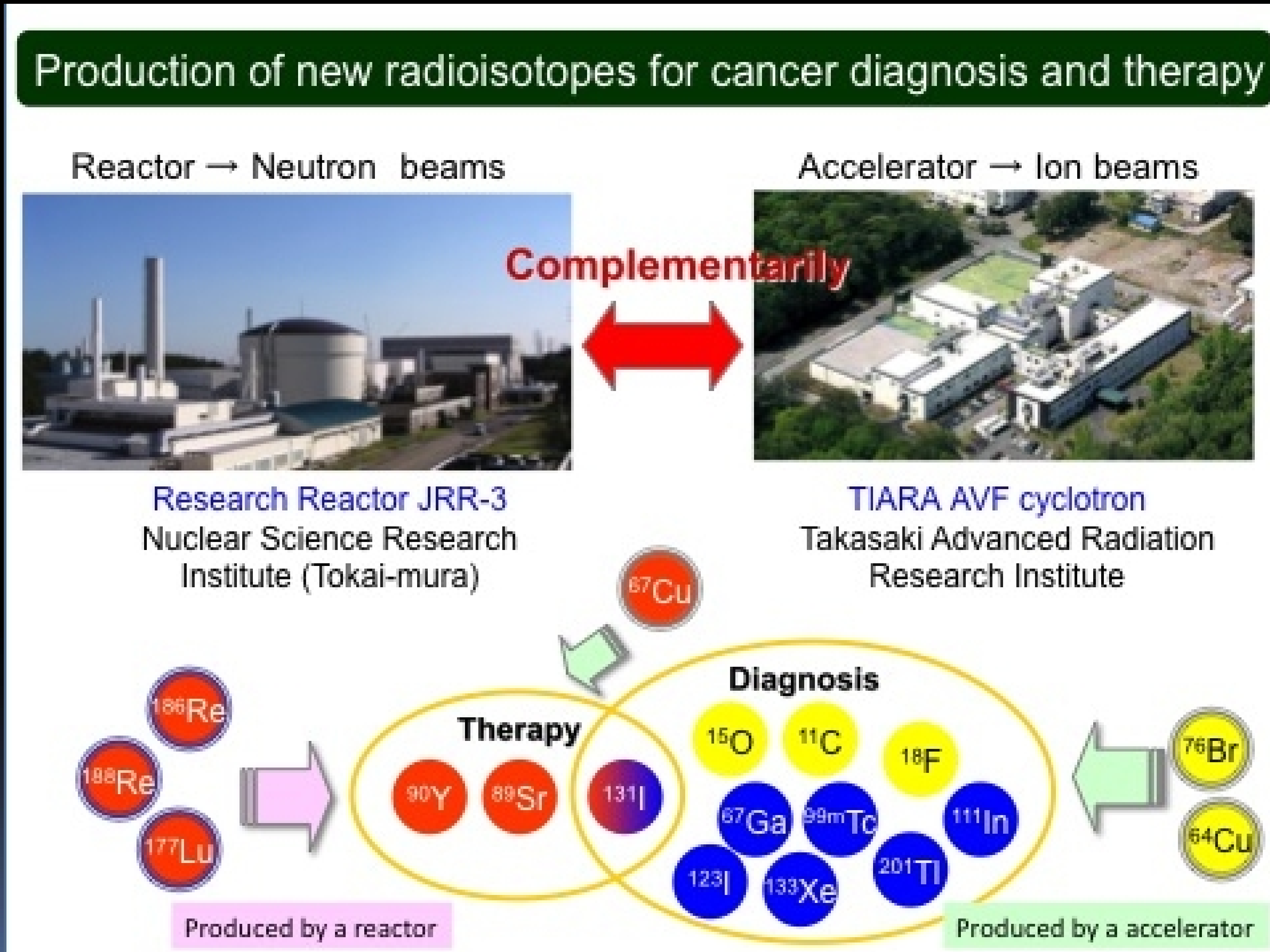
http://blogs.knoxnews.com/munger/2010/01/spent-heu-fuel-from-israel.html

3. Why do we need them? Production of radiopharmaceutical isotopes

http://www.itnonline.com/article/cardiac-imaging-agent-helps-make-world-safer-nuclear-weapons

SOME FACTS

- Today, most radiopharmaceutical isotopes are produced by protons and part by Deuterons
- Every year, medical professionals worldwide carry out more than 30 million procedures using medical isotope, over half of these in the US.
- Technetium-99m (99mTc) is used in approximately 85% of nuclear medicine diagnostic imaging procedures worldwide.
- Almost all the 99mTc used for this purpose is obtained from the radioactive decay of molybdenum-99 (99Mo)
- Molybdenum-99 is produced by processing irradiated uranium targets in Belgium (IRE), Canada (AECL/Nordion), the Netherlands (Covidien) and South Africa (NTP).

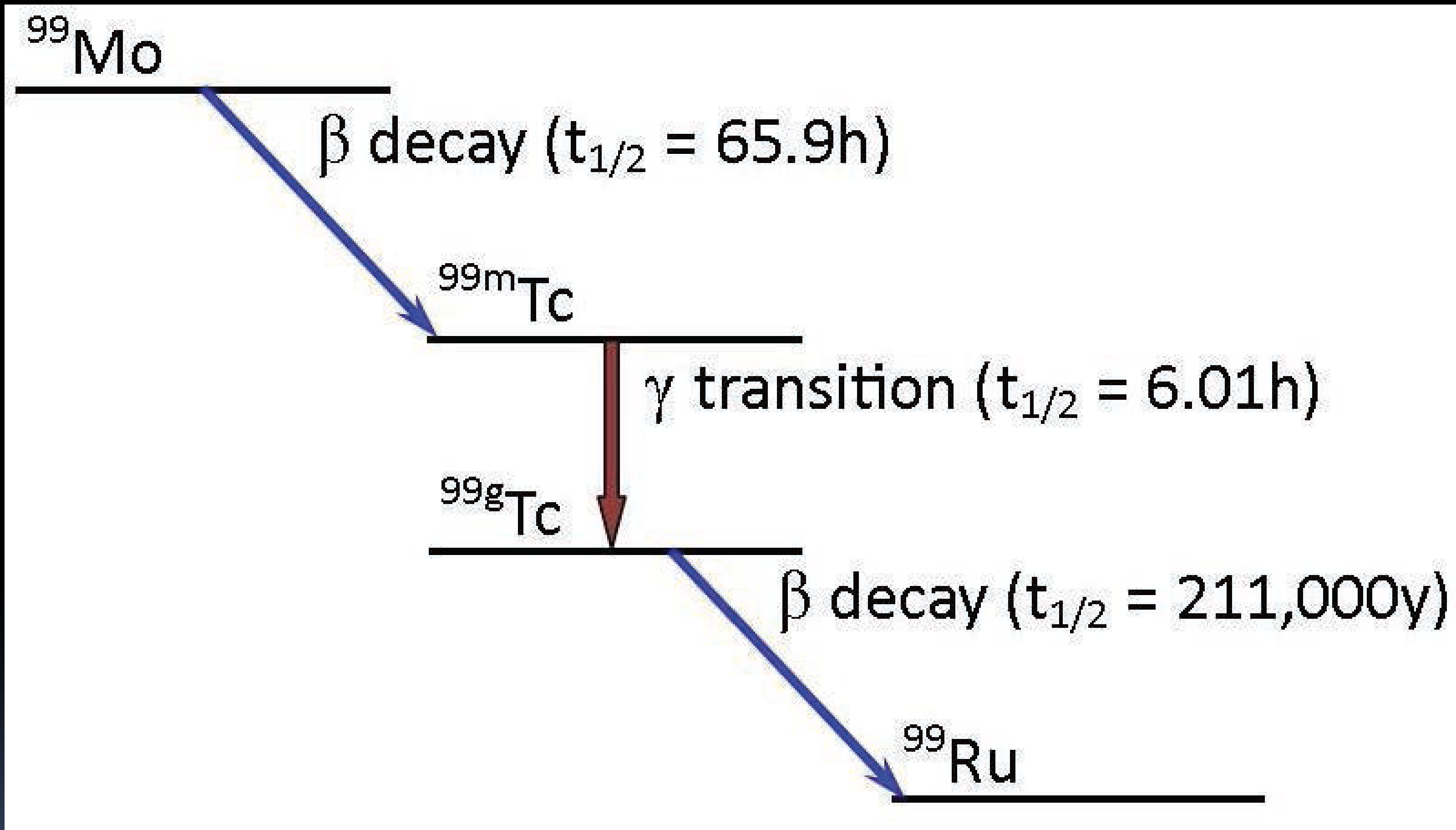


http://www.taka.jaea.go.jp/rab_div/en/mra/index_e.html

THICK TARGET YIELD (TTY) COMPARISON

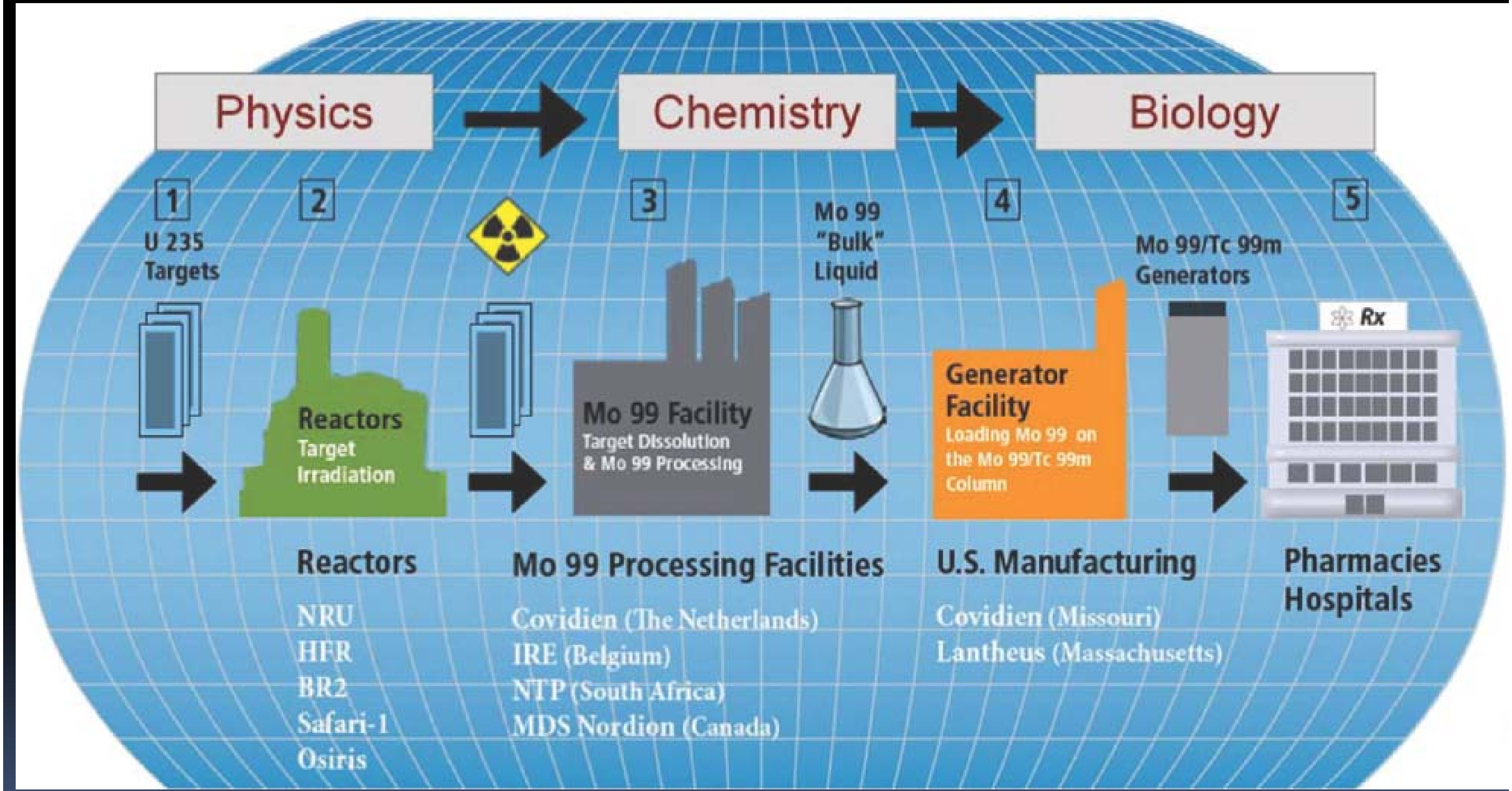
Target/ Product	Protons energy range (MeV)	Protons TTY MBq/mAh	Deuterons energy range (MeV)	Deuterons TTY MBq/mAh
$^{103}Rh/^{103}Pd$	20 → 8	12	20 → 8	22
$^{186}W/^{186}Re$	30 → 8	11	20 → 10	19
$^{111}Cd/^{111}In$	30 → 8	95	20 → 8 (^{nat}**Cd**)	20
$^{114}Cd/^{114m}In$	30 → 8	2,2	20 → 9	3,6
$^{nat}Er/^{170}Tm$	30 → 9	0,065	20 → 9	0,055
$^{169}Tm/^{169}Yb$	30 → 9	2,2	20 → 9	3,74
$^{192}Os/^{192}Ir$	20 → 9	0,18	20 → 9	0,88
$^{100}Mo/^{99}Mo$	40 → 8	14,3	40 → 20	16,2
$^{176}Yb/^{177}Lu$	NA	NA	20 → 8	1,02

Hermanne, *Nucl. Data* (2007)



^{99}Mo
β decay ($t_{1/2}$ = 65.9h)
^{99m}Tc
γ transition ($t_{1/2}$ = 6.01h)
^{99g}Tc
β decay ($t_{1/2}$ = 211,000y)
^{99}Ru

THE RACE AGAINST TIME…



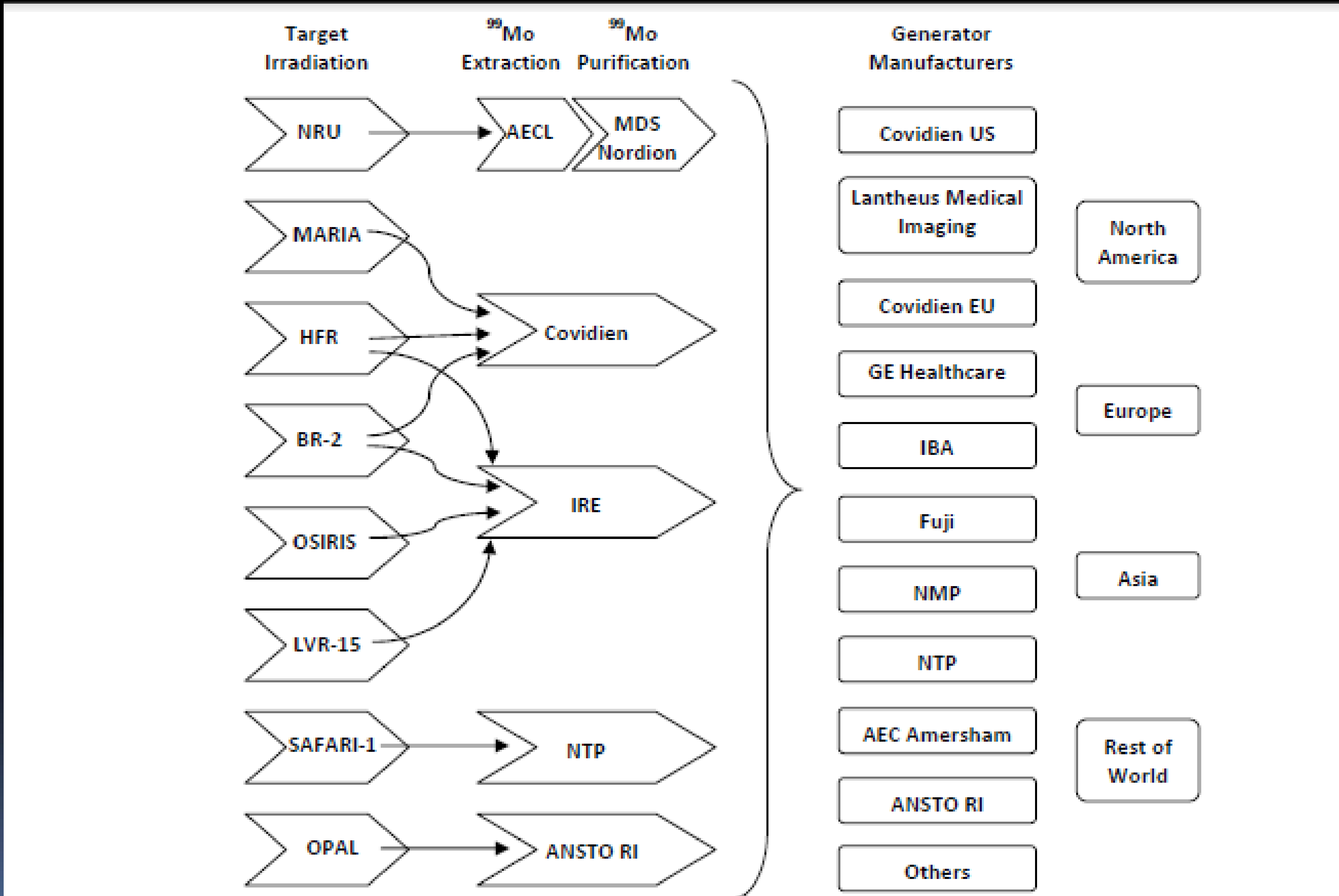
http://www.sciencemediacentre.ca/smc/index.php?option=com_content&view=article&id=94%3Aisotopes&catid=1%3Alatest-news&Itemid=49&lang=en

MAJOR CURRENT 99MO PRODUCING REACTORS

Reactor name	Location	Annual operating days	Normal production per week[a]	Weekly % of world demand	Fuel/targets[b]	Date of first commissioning
BR-2	Belgium	140	5 200[c]	25-65	HEU/HEU	1961
HFR	Netherlands	300	4 680	35-70	LEU/HEU	1961
LVR-15[d]	Czech Rep.	–	>600	–	HEU[e]/HEU	1957
MARIA[d]	Poland	–	700-1 500	–	HEU/HEU	1974
NRU	Canada	300	4 680	35-70	LEU/HEU	1957
OPAL	Australia	290	1 000-1 500	–[f]	LEU/LEU	2007
OSIRIS	France	180	1 200	10-20	LEU/HEU	1966
SAFARI-1	South Africa	305	2 500	10-30	LEU/HEU[g]	1965
RA-3	Argentina	230	200	< 2	LEU/LEU	1967

The supply of medical radioisotopes, OECD 2010, NEA No. 6967

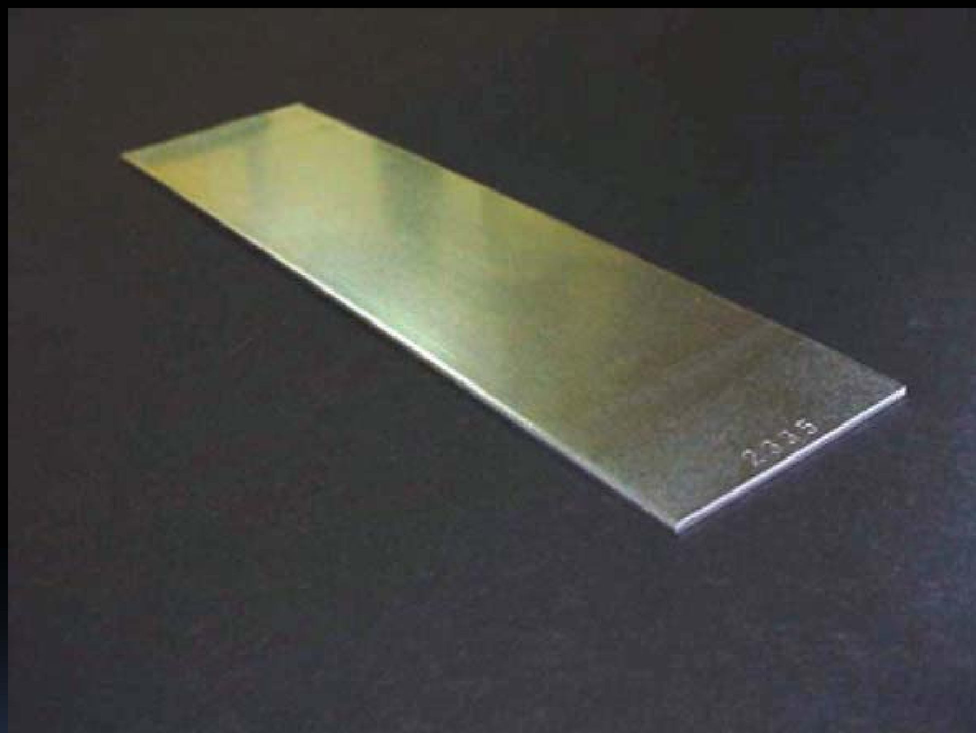
SUPPLY CHAIN



The supply of medical radioisotopes, OECD 2010, NEA No. 6967

"WHAT THE DOCTOR ORDERED? ELIMINATING WEAPONS-GRADE URANIUM FROM MEDICAL ISOTOPE PRODUCTION" !

HTTP://WWW.NTI.ORG/ANALYSIS/ARTICLES/WHAT-DOCTOR-ORDERED-ELIMINATING-WEAPONS-GRADE-URANIUM-MEDICAL-ISOTOPE-PRODUCTION/



CNEA's LEU-Aluminium dispersion targets. These targets have been used since 2002 to produce 99Mo in Argentina. The target is 13.0 cm in length and 3.5 cm in width

TECHNOLOGY READINESS LEVELS (TRL) OF LEU TARGETS

(**Non-HEU Production Technologies for Molybdenum-99 and Technetium-99m,** IAEA NUCLEAR ENERGY SERIES No. NF-T-5.4, 2013)

(n, f) target material *LEU in the form of dispersion mix, oxide, or metal*		**TRL (9=high)**	**Production scale** *S = small, M = medium, L = large*
UAlx	(2.6– 3.0 gU/cc)	9	S, M, L
U3Si2	(4.8 gU/cc)	6/7	S, M, L
U3Si2	(6.0 gU/cc)	6	S, M, L
U foil	(19.0 gU/cc)	8	S, M
		5	L
U nitride	(7.0 gU/cc)	5/6	S, M, L
U metal pellets/discs		8	S
U oxide pellets/powder		8	S, L

SO… IS IT SAFE & SECURE?

LIMITATION – NUCLEAR RESEARCH REACTORS SECURITY, TECHNOLOGY, SAFETY

- **HEU risks -** Fuel production, handling, storing, production and transporting targets, spent fuel and used targets.
- **Complexity of Nuclear Technology -** production, handling, transporting, waste
- **Safety -** production, maintenance, handling, transporting, waste.
- **Costs -** Reactors were initially used for many needs and not designed specifically to manufacture radioisotopes. Therefore, the production and its costs do not take into account the costs of operating the reactor.
- **Aging -** In most countries the nuclear reactors are very old and currently operate only for radioisotopes production. The current fleet of aging reactor is subject to longer and more frequent planned and unplanned shutdowns.
- **Converting HEU to LEU -** Technological barrier, Cost, Yield.

LIMITATION – MEDICAL ISOTOPES PRODUCTION
SECURITY, TECHNOLOGY, SAFETY

- The 99Mo/99mTc supply chain is very complex and faces a number of significant challenges both short and long term
- To targets containing less than 20% U-235 (LEU) may have impacts on reactor and processor economics based on additional conversion and operating costs.
- The conversion to LEU may increase concerns as more targets may need to be processed to obtain the 99Mo, resulting in increased waste volumes and elated in costs.
- In the past years the extraction and purification stages were subsidies by governments.
- The current economic structure does not support the investment required for new production infrastructure required balance and reserve capacity necessary for a reliable supply chain.
- Using reactor limitation on capacity and reliability, processing capacity, geographical location, reserve capacity
- Waste management – Final treatment and disposal costs of the liquid radioactive waste.

The present process for producing 99Mo for medical isotope use involves the neutron fission of 235U (i.e. 235U(n,f)99Mo) in multipurpose research reactors

Molybdenum-99 can be produced through a number of other schemes:

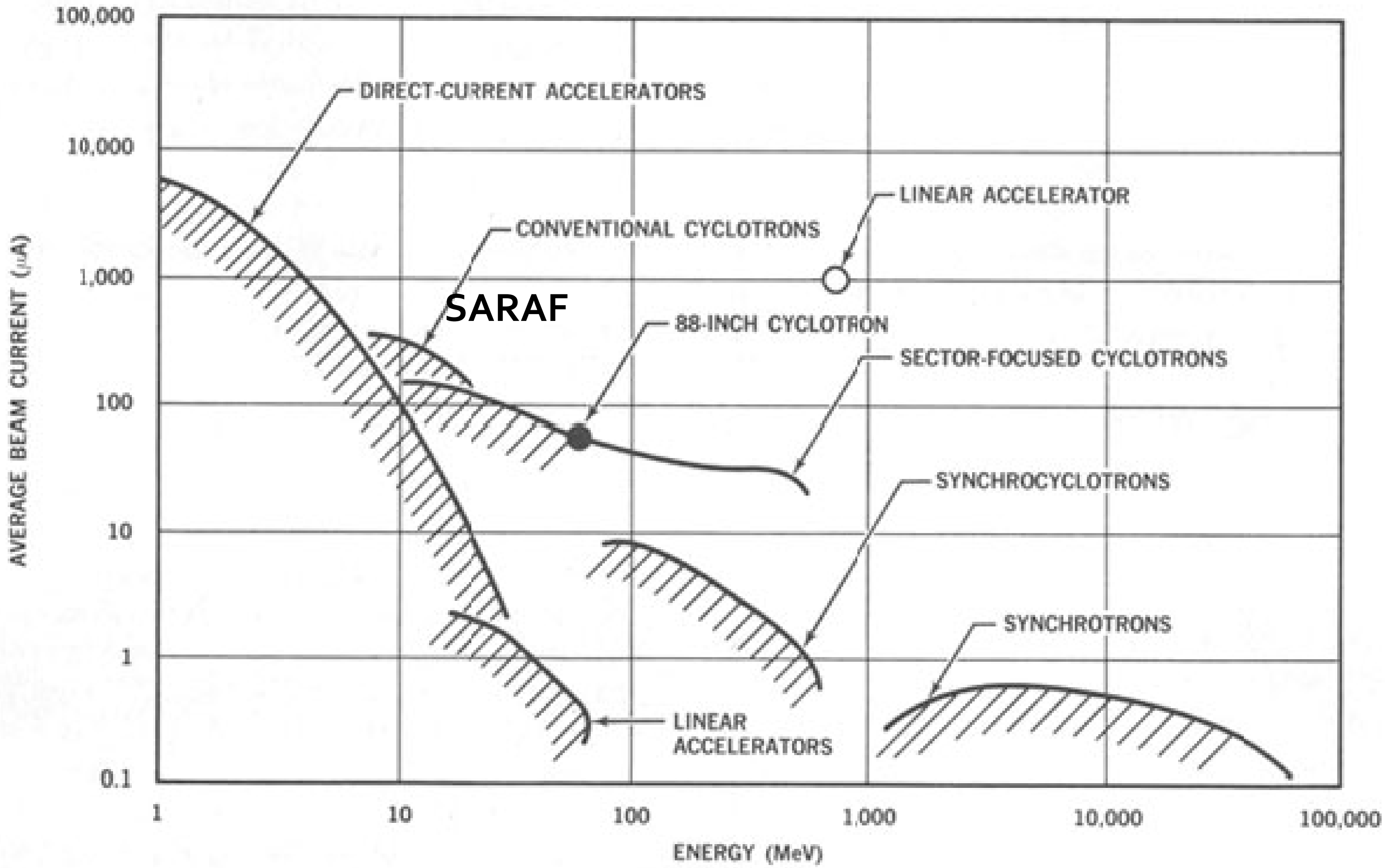
- **Fission of 235U** with neutrons produced in deuteron and proton accelerators through (D, n) and (p, n) reactions on heavy targets.
- **Neutron activation of 98Mo** (i.e. 98Mo(n,γ)99Mo). This process is only practical for reactor based production
- **Photofission of 100Mo** (i.e. 100Mo(γ,n)99Mo). The energetic photons used in this production scheme are obtained by irradiating heavy targets with electron beams produced by linear accelerators.
- **Technetium-99m can also be produced directly** through (p, 2n) reactions on targets containing 98Mo. This production scheme eliminates the need for intermediate production steps involving the recovery and purification of 99Mo. However, it is suitable only for short (e.g. city scale) supply chains because of the short half-life of 99mTc.

4. Linear Accelerator - A better alternative?!

An electron, a proton, or a heavy-ion accelerator in which the path of the particles accelerated are essentially straight lines rather than circles or spirals (LINAC)

http://commons.wikimedia.org/wiki/File:CERN_Linac.jpg

WORLDWIDE ION ACCELERATOR



ACCELERATOR PRODUCTION OF 99MO FOR 99MTC

bombardment of 40 MeV and 2 mA deuterons for 24 h

reaction	method	Activity (Ci / 24 h)	Specific activity (Ci/g)	Specific activity (Ci/g-Mo)	target
^{98}Mo(n,γ)	Lead box	20	0.0016	0.0016	12.5 kg @ r=10 cm
^{100}Mo(n,2n)	Fast n	52	0.31	0.31	nat. Mo, based on [1]
^{238}U(n,f)	Fast n	8	0.016	CF	500 g target
^{102}Ru(n,α)	Fast n	8	0.00083	CF	8 kg 0.8 liter enriched
^{98}Mo(d,p) 26MeVx3mA	direct	150	19	19	10 cm^2 x 0.08 cm nat. Mo
					80 kW 1 GeV p [2]
^{98}Mo(n,γ)	C box	237	0.018	0.011	20 kg MoO_4 [2]
^{235}U(n,f)	C box	494	2.1	CF	LEU-20% 364 g [2]

CF=carrier free

[1] Y. Nagay and Y. Hatsukawa, Journal of the Physical Society of Japan, 78(2009)033201
[2] S. Buono, N. Burgio, L. Maciocco, Physics for Health, CERN, February 2010

T. Hirsh *et al.* ARIA 2011

COST – NO NEED OF NUCLEAR FUEL!

The accelerator cost is composed of three main components :

- **Beam power cost**

Which is determined by the RF system cost. This cost is fixed for a required beam power and is thus independent on the peak electric field.

- **Structure length cost**

Which includes the real estate and infrastructure costs. A higher electric field allows the use of fewer cavities so this cost decreases with the peak electric field.

- **Structure Power Cost**

Which is the operation cost of the accelerator. The operation cost strongly depends on the dissipated power in the cavities, which increases with the square of the electric field, or even more steeply when the quality factor (Q) decreases. This is true both for normal and superconducting structures.

TECHNOLOGY READINESS LEVELS (TRL)

Non-HEU Production Technologies for Molybdenum-99 and Technetium-99m, IAEA NUCLEAR ENERGY SERIES No. NF-T-5.4, 2013

PHOTONEUTRON, (γ,n), TRANSFORMATION OF 100Mo

(classified as medium capacity for a single device)

Technology	TRL	Comment
Accelerator	6	Concept well established, requires development for high power
Targets	3	Enriched target, development work needed
Processing	5	Prototype exists, in clinical trials for other radioisotopes
Production of 99mTc generators	5	See above
Waste management	4	Minimal waste, although tracking of 99gTc and non-moly isotopes required
Regulatory approval:		
— Nuclear	5	Extensive testing required
— Health	7	

The technology is rated overall as 4.

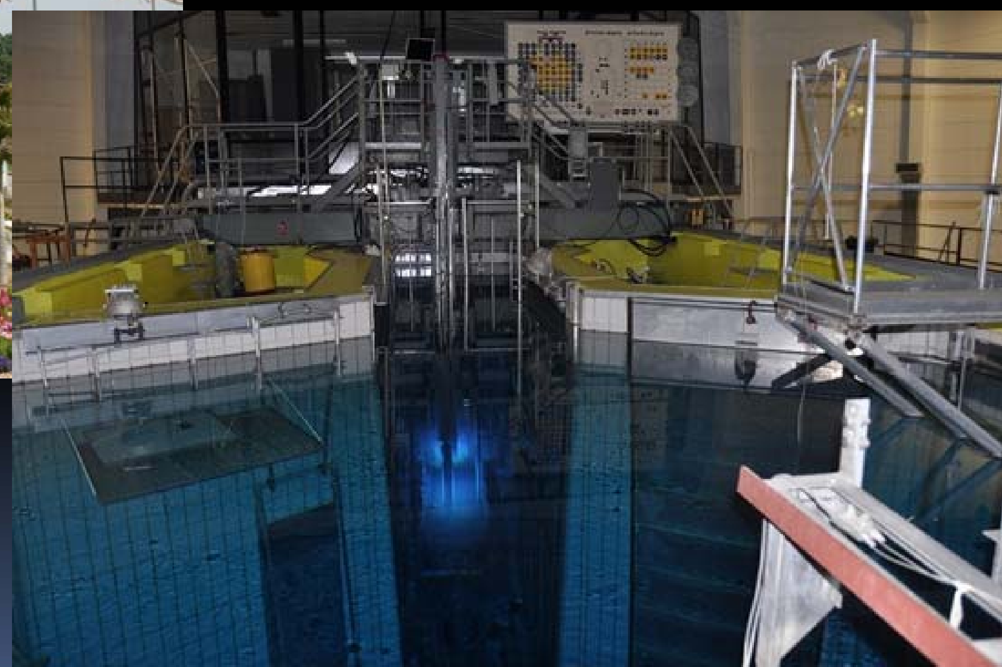
DIRECT PRODUCTION OF 99mTc VIA 100Mo(p,2n) REACTION

(classified as small capacity for a single device)

Technology	TRL	Comment
Accelerator	8–9	Use of existing cyclotrons; proposed new cyclotron not field tested
Targets	4	Under development
Processing	4	Working at lab scale
Production of 99mTc generators	n/a	Not used; the 99mTc is distributed directly from the cyclotron centre
Waste management	4	Minimal, tracking of 99gTc required
Regulatory approval:		
— Nuclear	9	Cyclotrons have been reviewed by nuclear regulatory authorities for this process
— Health	5	Extensive testing required to validate the quality of 99mTc produced

The technology is rated overall as 5.

5. Soreq Nuclear Research Center (SNRC) – Yes, we can!



http://iaec.gov.il/Soreq/About/Pages/default.aspx

BACKGROUND

In 1958 construction began on the Soreq NRC. The Research reactor in this center became critical in 1960.

Cooling and moderation are done using purified water.
The reactor's nominal capacity is 5 MW.

Periodic authorizations to operate the reactor are granted following extensive safety tests.

The reactor of the Soreq NRC is operated under IAEA safeguards (subject to a facility-spesific safeguards agreement (INFCIRC/66 type).

Radiation control is one of the NRC's fields of activity. To that end, the NRC provides consulting services regarding ionizing and non-ionizing radiation.

Extensive research is conducted at the Soreq NRC, especially in the field of electro-optics. Additional activities are held at the Shalheveth Freier Center and at the National Data Center (NDC).

- Laser physics and technology
- Non-linear optics
- Interactions of high power lasers with matter
- Nuclear, ultrasound and optical techniques in non-destructive testing
- Simulating the space environment encountered at a variety of earth orbits and
- monitoring the quality of materials and electronic components deployed in satellites
- Development and production of cryogenic vacuum enclosures for infra-red detectors
- Operating a "nuclear pharmacy" for unit dose production and distribution
- Production of FDG (radio-pharmaceutical for PET-scanning medical diagnostics)
- Electro-thermal techniques for acceleration of projectiles into the hypervelocity range
- Magnetic and Electro-magnetic sensing technologies

SARAF – SOREQ APPLIED RESEARCH ACCELERATOR FACILITY

- SARAF is an innovative particle linear accelerator being built at the SNCRC and is in the last stage of completion of the "proof of concept" phase
- IRR1 is 5MW "Material test reactor Pool" type fueled by 93% HEU. Israel has no option for converting the HEU reactor to LEU
- If performed successfully, SARAF will prove that high current (few mA), low energy (few tens Mev) proton/deuteron accelerators, can perform most of the research tasks currently performed by research reactors, by producing comparable or better neutron fluxes.

SARAF – GOALS

There are 3 common types of low-energy ion accelerators :

- DC (Van-de-Graff) linear accelerator
- Cyclotron
- RF linear accelerator.

Why RF LINAC ?

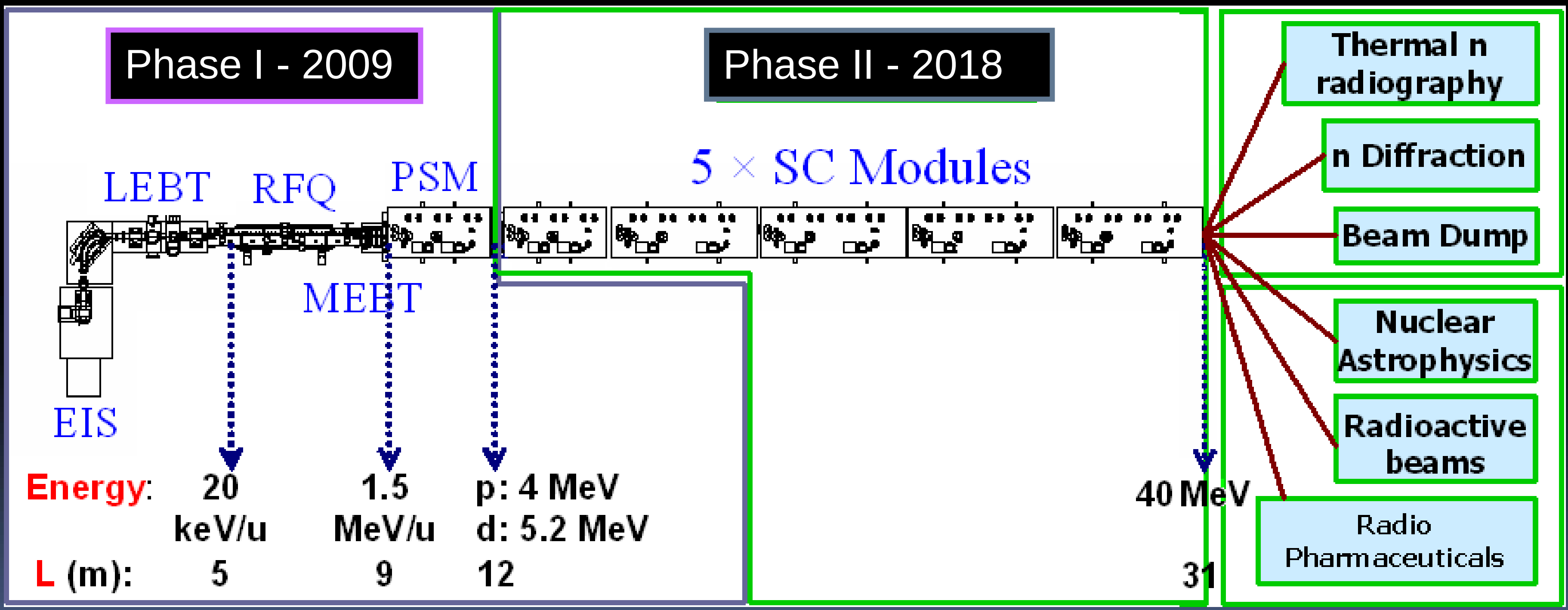
Among the three common types, an RF LINAC is the most suitable accelerator type for SARAF and current requirements, as well as for the ions accelerated and the need for hands-on maintenance

Goals

- To enlarge the experimental nuclear science infrastructure and promote research in Israel
- To develop and produce radioisotopes primarily for bio-medical applications
- To modernize the source of neutrons at Soreq and extend neutron based research and applications

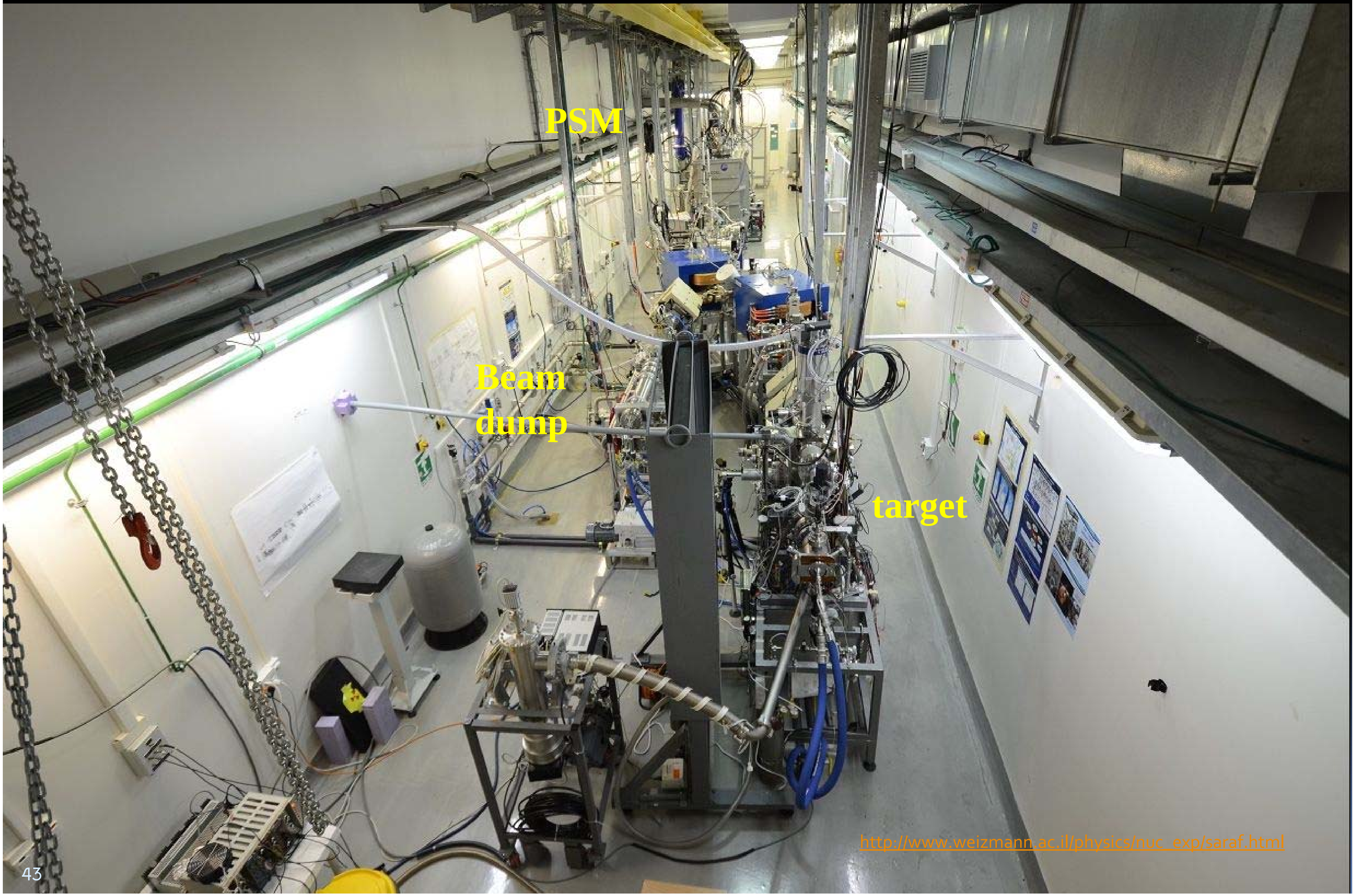
SARAF ACCELERATOR COMPLEX

The SARAF accelerator is composed of an ion source (EIS), a Low Energy Beam Transport (LEBT), a Radio Frequency Quadrupole (RFQ), a Medium Energy Beam Transport (MEBT), six Superconducting Modules (SM), and a High Energy Beam Transport (HEBT)



http://www.weizmann.ac.il/physics/nuc_exp/saraf.html

SARAF phase-1 LINAC: downstream view



http://www.weizmann.ac.il/physics/nuc_exp/saraf.html

Accelerators – yes or no

- ☹ **TECHNOLOGY** – LINAC that can substitute nuclear research reactors for producing medical isotopes and neutron based research and applications are still in the R&D phase but the feasibility exist
- ☺ **NONPROLIFERATION ("Dual Use")** - Operating in High current (few mA), low energy (few tens Mev) proton/deuteron accelerators, reduce proliferation risks (possible production of fissile materials like U-235/233, Pu-239)
- ☹ **TARGETS** - LEU targets still needed to be fully developed (the same as in research reactors)
- ☺ **SAFETY / SECURITY** - No need for most processes, production, maintenance , handling and transportation of HEU product / byproducts
- ☺ **COSTS** – much lower in comparing to construction and operating research reactors
- ☺ **RADIOACTIVE WASTE** - minimal waste and no need for solution for nuclear spent fuel
- ☹ **REGULATION** – still needs approvals

Final thoughts

…"the United States is committed to eliminating the use of HEU in all civilian applications…because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes." (June 2012)

- Domestic Medical isotopes production capability is essential to mitigating future shortage (Accelerator is a better answer)
  - Converting HEU research reactors to LEU – costly, complicated.
  - New facilities required in any case (R.R. / Acc.).
- Accelerators are the right substitute – rigorous technical cooperation is needed.
- Targets are key element
- Speedy licensing processes and passing all regulatory hurdles
- Permanent dialogue between governments and industries (create incentives)
- IAEA should consider inspection policy
- Don't forget the nuclear waste