New Nuclear Technology to Produce Inexpensive Diesel Fuel from Natural Gas and Renewable Carbon

Rolland P. Johnson
Muons, Inc., Batavia, IL USA,

The long-range goal of this project is to sell intrinsically safe and versatile nuclear reactors to address world energy needs. The first application is an Accelerator-Driven Subcritical Reactor that burns non-enriched Uranium, Thorium, or spent fuel from conventional nuclear reactors in a molten salt fuel to produce high-temperature heat to convert Natural Gas and Carbon into liquid fuel for vehicles. This green technology uses only domestic sources and reduces the carbon footprint of vehicles by a factor of three, where construction and operating expenses imply diesel fuel production at $2/gallon. The project involves the development and interfacing between known technologies that 1) use a superconducting RF accelerator to produce an intense source of neutrons to 2) generate process heat in a molten-salt-fueled subcritical nuclear reactor to 3) prepare natural gas and renewable carbon for the Fischer-Tropsch generation of petroleum products. The project includes 1) reducing accelerator construction and operating expenses, 2) integration of the molten-salt reactor technology developed at ORNL with an internal spallation neutron target, 3) construction and test of a molten-salt to gas process heat transfer model device and 4) attracting private funding and DOD interest to build the first plant.

A few preliminary comments:

- Muons, Inc. is a small company founded 9 years ago to help the DOE solve its problems through SBIR-STTR projects and contracts with national labs and universities
    - Staff of 22 Ph.D. level accelerator physicists and engineers
    - The name comes from our obsession to have a muon collider be the next energy frontier machine, and with muon beam cooling
    - Developed G4beamline, a program to interface to GEANT4
- We have founded a new company to raise private capital to support R&D for ADSR using molten salt fuel:
    - Infomercial at http://acceletech.us
- We believe ADSR needs close collaboration between accelerator and reactor people and have been very lucky to collaborate with Charlie Bowman of ADNA
    - 1992 patent: Apparatus for nuclear transmutation and power production using an intense … Charles D. Bowman

Muons, Inc.

Goal – US government pays industry to remove nuclear waste and produce energy from it

- Setting the stage – where we are – opportunities/problems
- Solid fuel nuclear reactor technology - what goes wrong
  - fuel rods – accidents waiting to happen?
- Molten-salt Reactor Experiment (MSRE) 1965-1969
  - continuous purging of volatile radioactive elements – no zircaloy
- Accelerator-Driven Subcritical Reactors (ADSR)
  - reactor concept uses molten salt fuel (e.g. UF_4 or ThF_4)
  - GEM*STAR example
    - Avoids nuclear weapon proliferation concern of reprocessing for 200 years
- The next step is a prototype ADSR machine to inspire industry
  - basic design issues, safety systems, reliability, availability, residual radiation from beam losses, beam delivery, independent reactor control, economy of construction and operation, …
- Inexpensive natural gas changes things
  - Nuclear Power in the US cannot compete with 4.5 c/kw-h from natural gas
  - ADSR process heat can make synthetic diesel out of natural gas and carbon

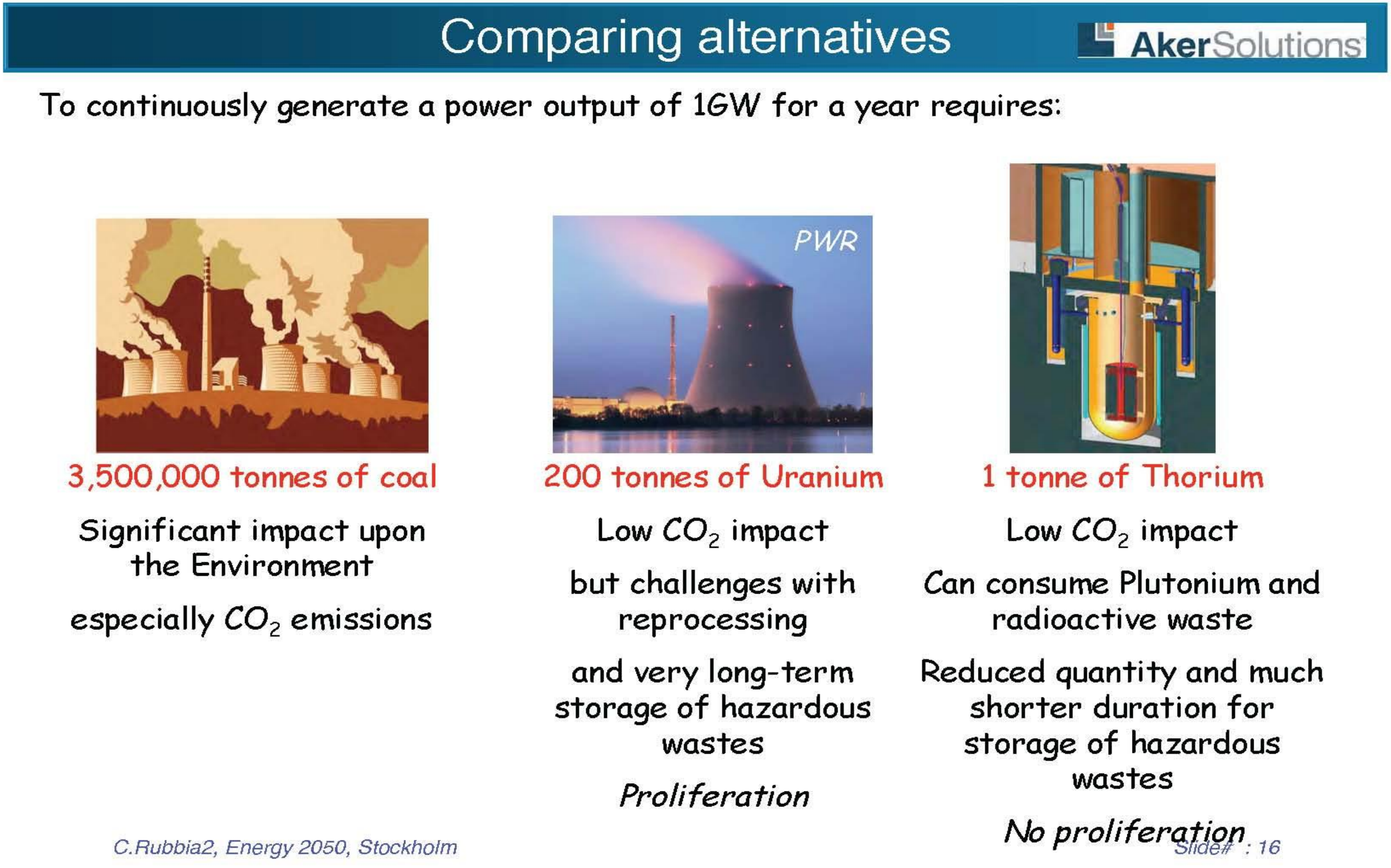
Nuclear Power Capacity as of 02/2012

Country	# reactors	GW capacity	Nuclear share of electricity production	
Belgium		5.9	51.7%	
Canada		12.7	14.8%	
China (PRC)		10,2	1.9%	←
France	59	63.2	75.2%	
Germany		20.3	26.1%	
India		4.8	2.9%	←
Japan	54	47.3	28.9%	
Korea, South		18.7	31.1%	
Russia		23.0	17.8%	
Spain		7.4	17.5%	
Sweden		9.4	37.4%	
Taiwan		4.9	20.7%	
Ukraine		13.2	48.6%	
United Kingdom		11.0	17.9%	
United States	104	101.2	20.2%	
Rest of World		25.4		
World		378.9	14%	

Available US Nuclear Waste

- The United States Department of Energy alone has 470,000 tonnes of depleted uranium. About 95% of depleted uranium is stored as uranium hexafluoride
- The US currently has more than 75,000 metric tons of spent nuclear fuel stacked up at 122 temporary sites in 39 states across the US, according to DOE reports. The nation's 104 commercial nuclear reactors produce about 2,000 tons of spent nuclear fuel annually. Thousands more tons of high-level military waste also need a final home.
- Natural uranium U_3O_8 costs $114,000/tonne today, $17,600 in 2001
  - yellowcake is 70-90% U_3O_8
- If 1 tonne /GW-y, all of US electricity (500 GW-y) can be provided by:
  - Spent fuel 75,000/500 = 125 years
  - Depleted uranium = 470,000/500 = 940 years

Carlo Rubbia



Comparing alternatives

To continuously generate a power output of 1GW for a year requires:

3,500,000 tonnes of coal

Significant impact upon the Environment

especially CO_2 emissions

200 tonnes of Uranium

Low CO_2 impact

but challenges with reprocessing

and very long-term storage of hazardous wastes

Proliferation

1 tonne of Thorium

Low CO_2 impact

Can consume Plutonium and radioactive waste

Reduced quantity and much shorter duration for storage of hazardous wastes

No proliferation

C.Rubbia2, Energy 2050, Stockholm

Slide# : 16

What does Carlo's slide mean?

It compares power according to how much you dig up and how you use it.

- Only 0.7% of natural uranium is U-235, which is
  - capable of self-sustaining nuclear fission (<u>fissile</u>),
  - (the only element that exists in nature in sufficient quantity…)
  - So you need to dig up over 143 tonnes of U to get 1 of U-235
  - Then you enrich it (using centrifuges, which have proliferation concerns)
- the rest is U-238, which, like thorium-232, is <u>fertile</u>, not fissile.
  - i.e. you need to provide neutrons to convert it to a fissile isotope.
  - (Criticality is the point at which a nuclear reaction is self-sustaining; subcritical means additional neutrons are needed)

fertile — *fissile*

- $n + {}^{238}U_{92} \rightarrow {}^{239}U_{92} \xrightarrow[24\text{ m}]{\beta^-} {}^{239}Np_{93} \xrightarrow[2.4\text{ d}]{\beta^-} {}^{239}Pu_{94}$ ← 30% LWR
- $n + {}^{232}Th_{90} \rightarrow {}^{233}Th_{90} \xrightarrow[22\text{ m}]{\beta^-} {}^{233}Pa_{91} \xrightarrow[27\text{ d}]{\beta^-} {}^{233}U_{92}$ ← May limit k<.97

- The extra neutrons needed to convert fertile elements can be provided by:
    - A fast or Breeder reactor using fissile U-235 or Pu-239, above criticality or
    - A particle accelerator – very hot topic 20 years ago!

- What is new:
    - SRF Proton Linacs can provide extraordinary neutron flux
        - Can easily outperform breeder reactors
    - The advantages of continuous purging of radioactive elements from the nuclear fuel are apparent from Fukushima (and TMI and Chernobyl)
    - Molten salt fuel can be continuously purged in new reactor designs without zircaloy, that can lead to hydrogen explosions
    - Molten salt fuel eases accelerator requirements

- Subcritical ADSR operation has always been appreciated
    - fission stops when the accelerator is switched off

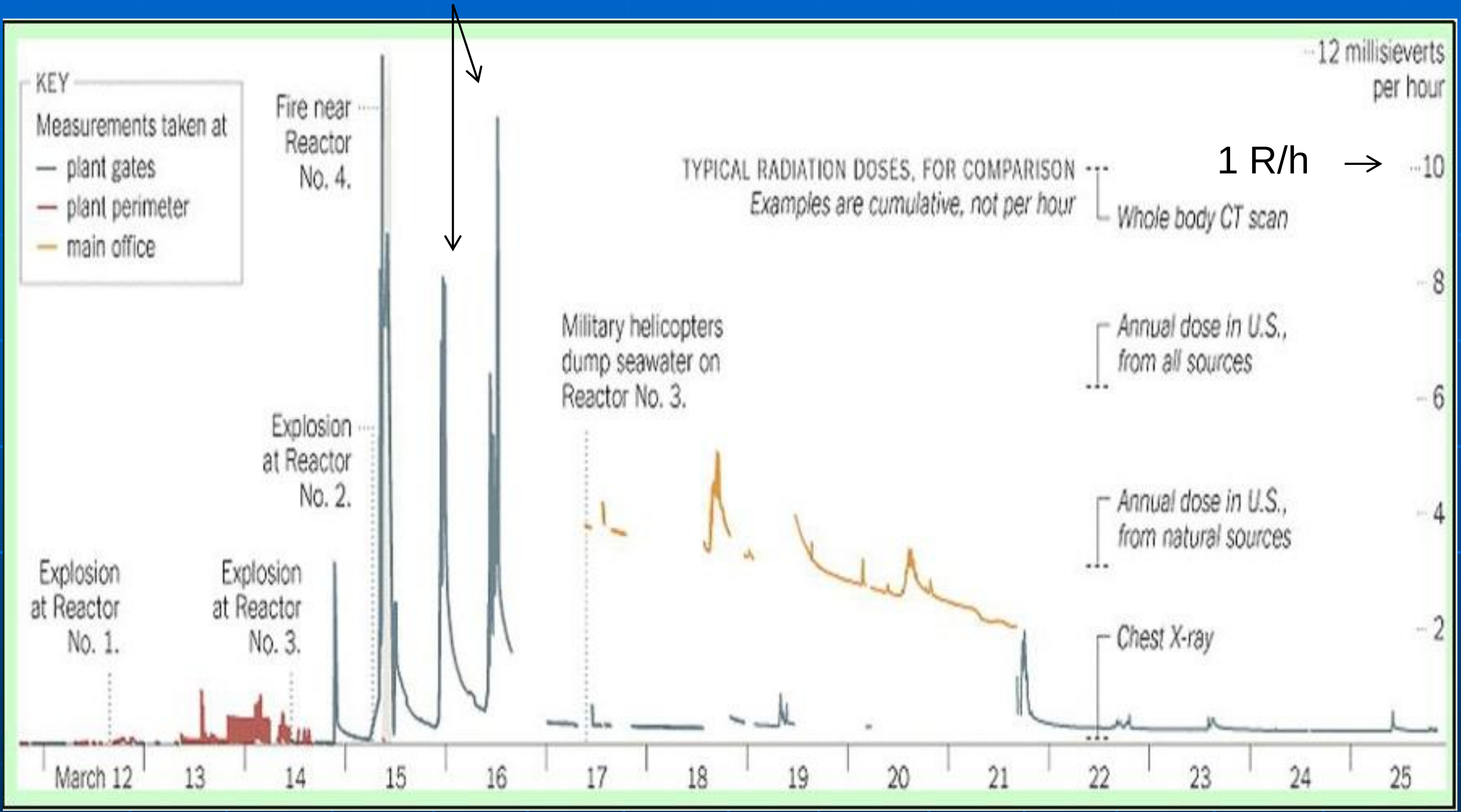
Three Mile Island was a lesson unlearned; Fukushima has provided perhaps several more

- At Fukushima, perhaps 6 separate cases of things going wrong:
- 3 reactor explosions, (perhaps spreading radioactive uranium oxide fuel components over at least a mile),
- fuel in the bottom of 2 of these reactors then melted through the bottom of their pressure vessel.
- At least one storage pond went dry enough to expose used fuel rods so they got hot enough to release radioactivity.
    - After fission stops, heat from decays in rods is ~5% of operating level
    - (17,600 tons of spent fuel stored in ponds at Fukushima)

These events released enough radioactive material for class 7 status,
with almost 10% of the fallout caused by Chernobyl, but without a criticality accident.

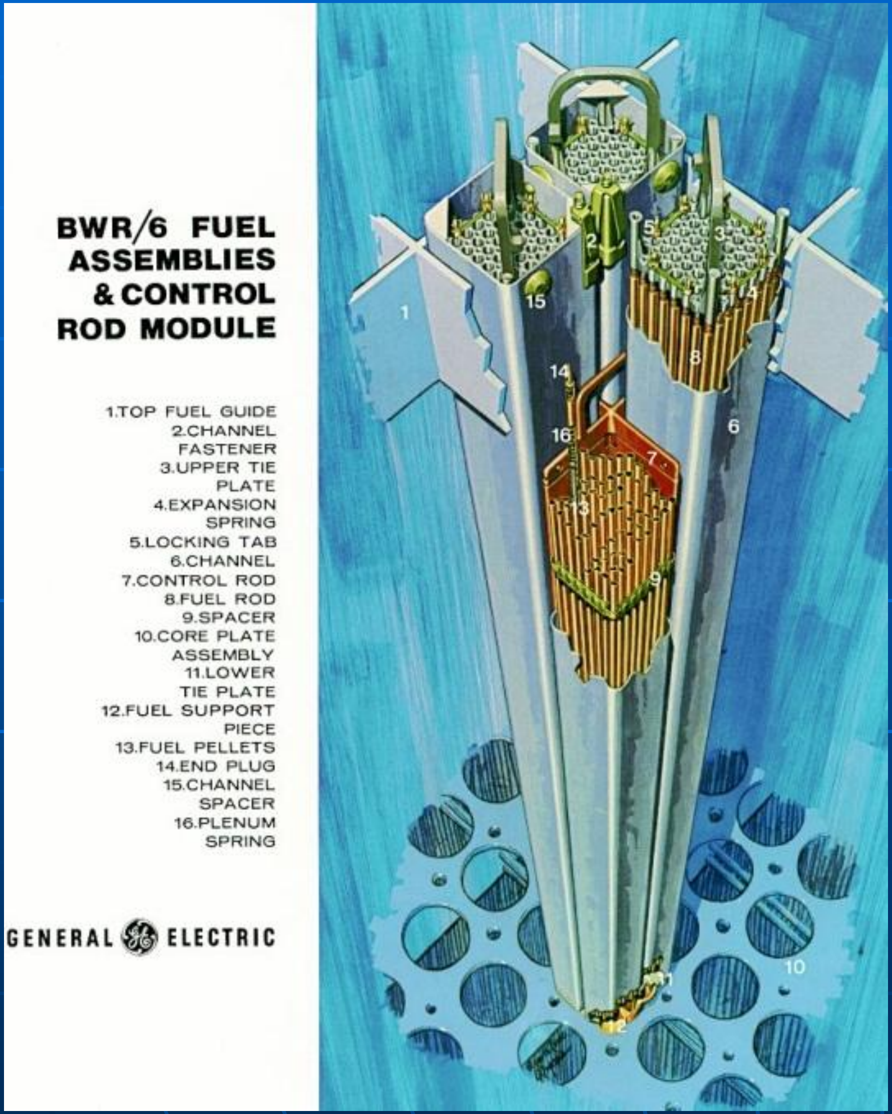
- Fukushima Dai-ichi reactors - 6 BWR-type Light Water Reactors –
- #1, #2 and #3 turned off (scrammed), #4, #5 and #6 were off at the time of earthquake and tsunami. Radiation was released from 1, 2 and 3 and a storage pool.

fuel melts through the bottom of pressure vessel in #2 and #3



Cited from NY Times

Fuel Rods of Conventional Reactors



BWR/6 FUEL ASSEMBLIES & CONTROL ROD MODULE

1. TOP FUEL GUIDE
2. CHANNEL FASTENER
3. UPPER TIE PLATE
4. EXPANSION SPRING
5. LOCKING TAB
6. CHANNEL
7. CONTROL ROD
8. FUEL ROD
9. SPACER
10. CORE PLATE ASSEMBLY
11. LOWER TIE PLATE
12. FUEL SUPPORT PIECE
13. FUEL PELLETS
14. END PLUG
15. CHANNEL SPACER
16. PLENUM SPRING

GENERAL ELECTRIC

are Fuel Rods an intrinsic problem?

- Fuel rods are made of many small cylinders of enriched UO_2 or mixed oxide fuel (MOX) enclosed in a sheath of zirconium alloy.
  - (a plant in France processes spent fuel rods to extract Pu_{239}, which is mixed with $UO_{2\ \mathrm{to}}$ make MOX. Remains are returned to country of origin.)
- During operation, many radioactive elements are created that are contained by the zircaloy sheath
- If, during operation or storage, the zircaloy casing is damaged, these radioactive elements can be released and among other things scare the heck out of a lot of people. (fall-out near Fukushima may be 10% of Chernobyl).
  - Radioactive Fission Products Partially Released from Damaged Fuel
    - Noble gases (Xe, Kr)
    - Volatile fission products (I, Sr, Cs, Ru, …)
    - Non-volatile fission products retained, but may be leached by water
- Hot zircaloy itself is a hazard – it can oxidize in steam to release hot H_2 in large quantities, which can explode when it rises to meet air.
    - $Zr + 2\ H_2O \rightarrow ZrO_2 + 2\ H_2$
    - Exothermic
    - rate increases exponentially with temperature

Fuel Rods an intrinsic problem? (cont.)

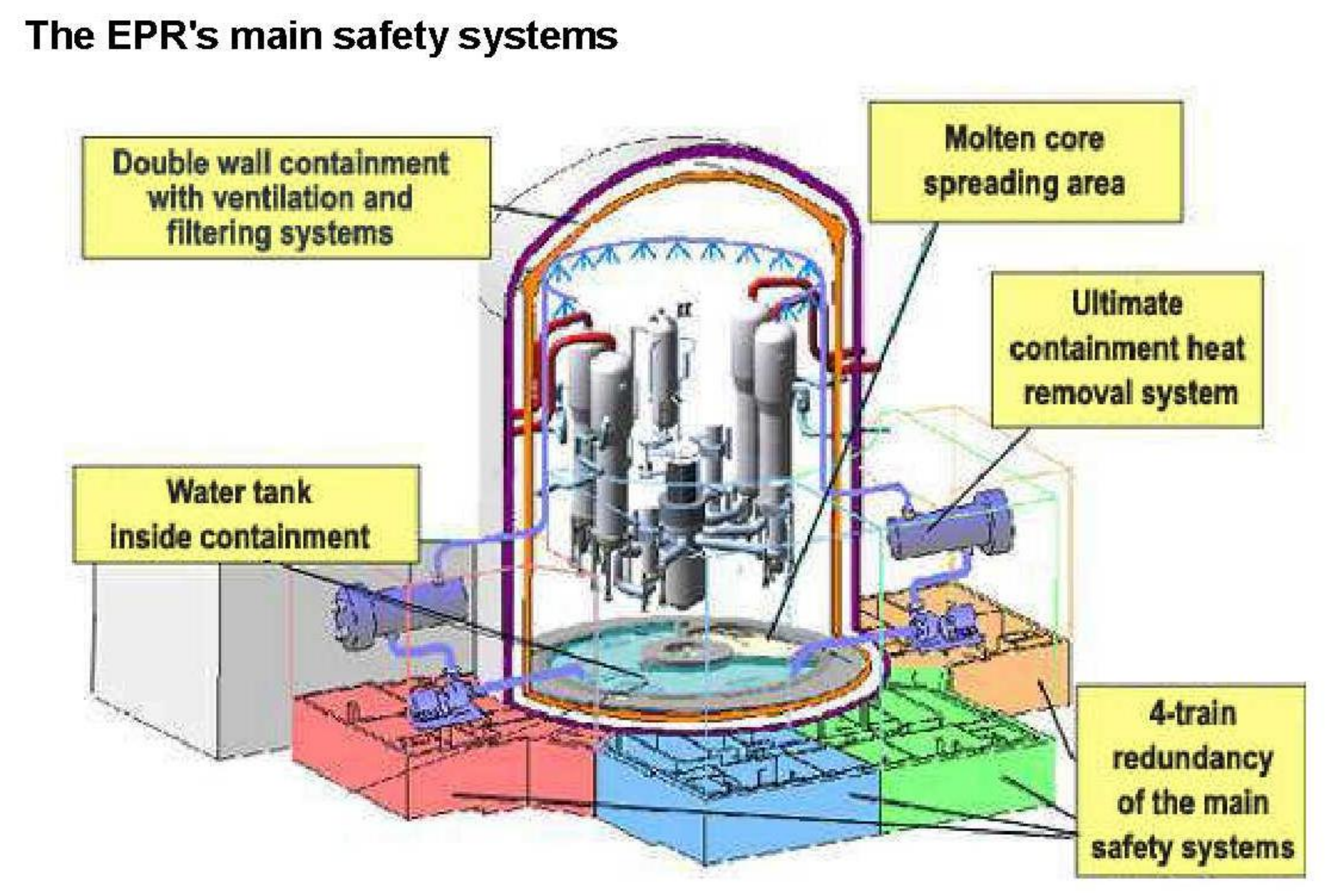
- It will be more and more apparent that stored used fuel rods are not without risk. Losing coolant in these could cause zircaloy failures that could lead to released volatile radioactive elements.

- For reactors, there are lots of layers of protection that have been invented and used to mitigate the problems that follow from solid fuel rod technology.
  - See latest iteration on next slide.

- Is there an intrinsic safety solution?
- Like the manhole cover to protect workers below?
  - e. g. Trap door →safety chain →procedures → for safety
  - Or just making the hole round with a round cover of larger diameter?

Safety systems for conventional solid fuel reactors are still evolving

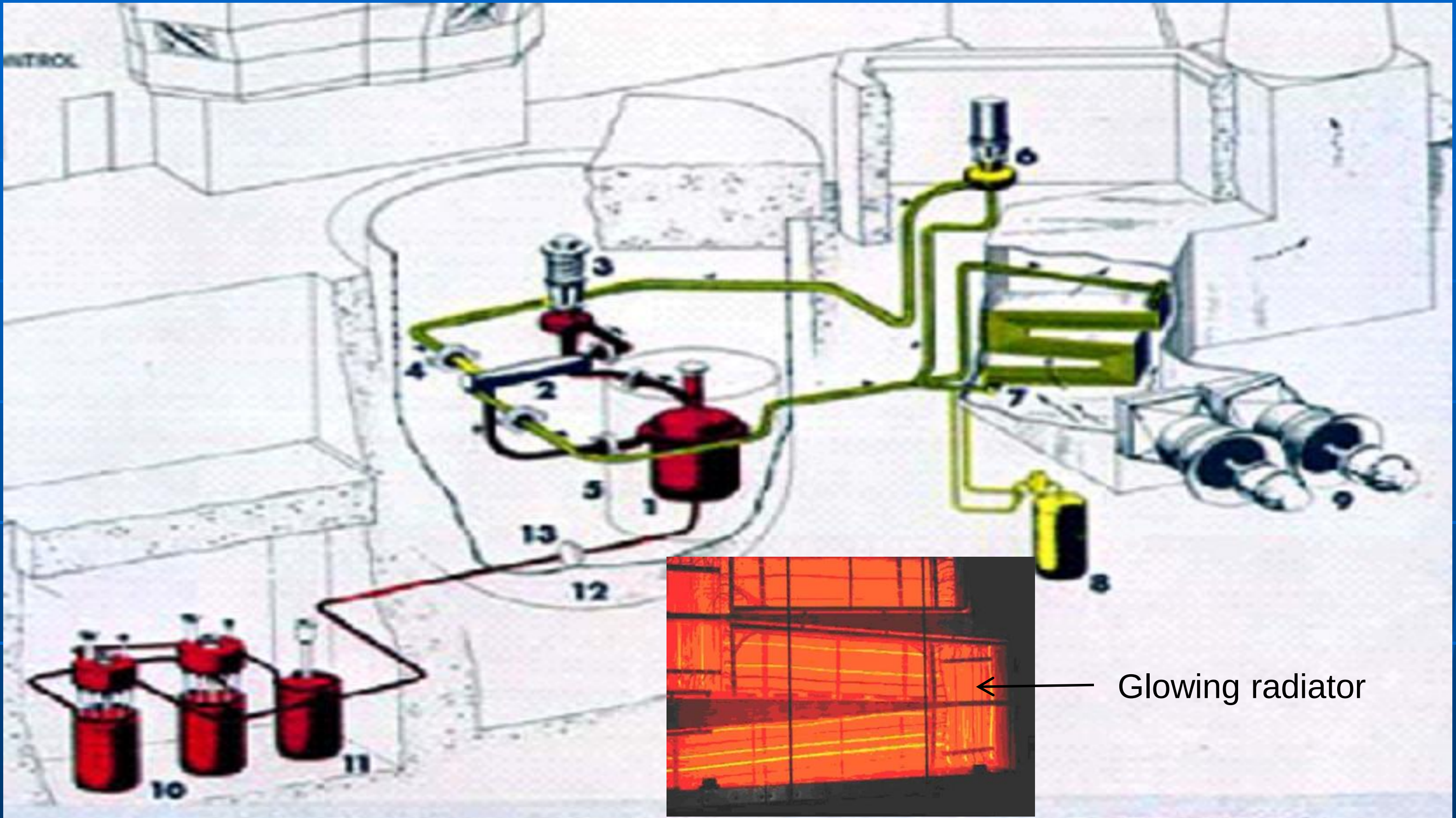
AREVA Evolutionary Power Reactor
http://en.wikipedia.org/wiki/European_Pressurized_Reactor



- An intrinsic safety problem for conventional reactors is enclosed solid fuel.
- a natural solution is to use molten-salt fuel
- that is also well suited to accelerator -driven subcritical reactors.
  - A major difficulty is fatigue of UO_2 fuel in rods caused by accelerator trips – no such problem for molten salt fuel
- The technology of molten-salt fuel was developed in the 1960s in the Molten-Salt Reactor Experiment (MSRE) at ORNL.
  - Use of molten salt fuel was later abandoned
    - not enough Pu-239 for bombs?
    - President Nixon?

      (See MSRE on wikipedia for nice summary)

Molten-Salt Reactor Experiment



Glowing radiator

. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield,
. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks,
11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

Molten-salt Reactor Experiment

From 1969 MSRE Report Abstract

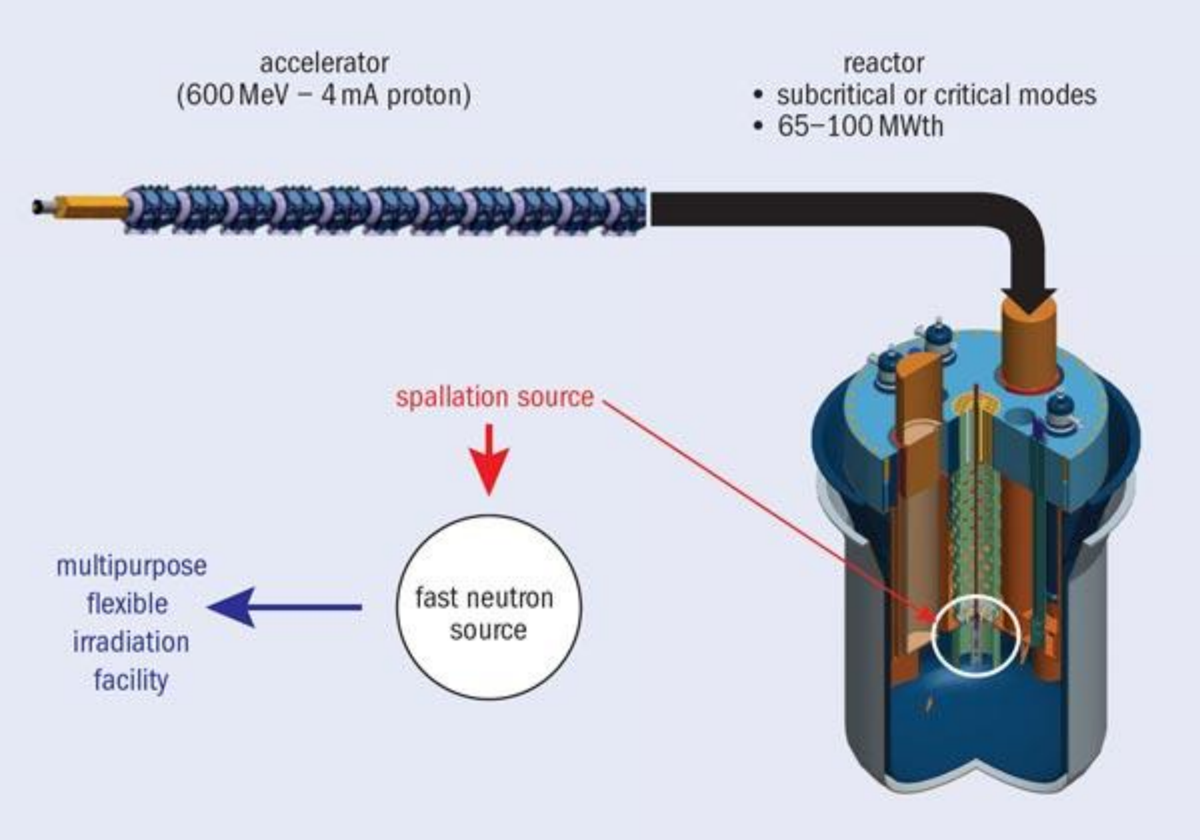
"The MSRE is an 8-MW(th) reactor in which molten fluoride salt at 1200°F (650 C) circulates through a core of graphite bars. Its purpose was to demonstrate the practicality of the key features of molten-salt power reactors.

Operation with 235U (33% enrichment) in the fuel salt began in June 1965, and by March 1968 nuclear operation amounted to 9,000 equivalent full-power hours. The goal of demonstrating reliability had been attained - over the last 15 months of 235U operation the reactor had been critical 80% of the time. At the end of a 6-month run which climaxed this demonstration, the reactor was shutdown and the 0.9 mole% uranium in the fuel was stripped very efficiently in an on-site fluorination facility. Uranium-233 was then added to the carrier salt, making the MSRE the world's first reactor to be fueled with this fissile material. Nuclear operation was resumed in October 1968, and over 2,500 equivalent full-power hours have now been produced with 233U.

The MSRE has shown that salt handling in an operating reactor is quite practical, the salt chemistry is well behaved, there is practically no corrosion, the nuclear characteristics are very close to predictions, and the system is dynamically stable. Containment of fission products has been excellent and maintenance of radioactive components has been accomplished without unreasonable delay and with very little radiation exposure.

The successful operation of the MSRE is an achievement that should strengthen confidence in the practicality of the molten-salt reactor concept."

NOW FAST FORWARD 40 YEARS and add an accelerator



MYRRHA Plans in Mol, Belgium

SNS ORNL Linac

*GEM*STAR concept without fuel reprocessing*

How best to deal with accumulated spent fuel depends on assumptions.

Because of nuclear weapon proliferation concerns, the USA decided not to reprocess spent fuel (i.e. separate into its components).
(This decision has not really been challenged because reprocessing is more expensive than digging up fresh uranium and enriching it).

If this is to be the policy in the future, one possible approach to eliminate spent fuel is to consider iterations of fuel burning where neutron absorption by accumulated fission products (FP) is compensated by higher neutron flux. (not easy to do with a fast or breeder reactor)

This implies successive particle accelerator generations produce neutrons more efficiently.

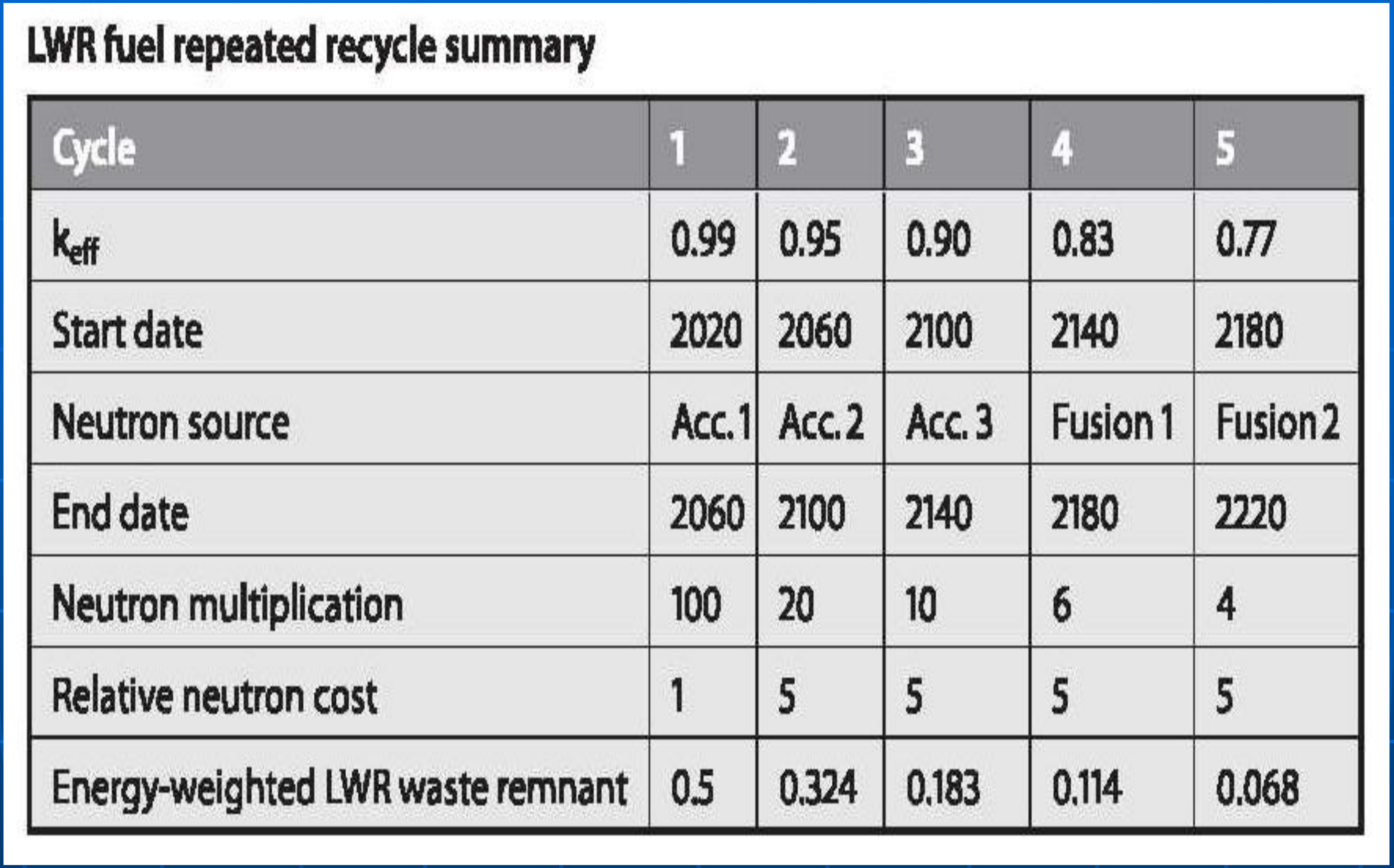
First, spent UO_2 fuel is converted to UF_4 salt, then

Gen 1 SRF Gen 2 SRF Gen 3 SRF
*UF_4 salt -> GEM*STAR -> UF_4 outflow -> GEM*STAR -> UF_4 outflow-> GEM*STAR-> etc.*
with more FP with more FP

*After 5 years, the GEM*STAR has reached equilibrium, and its output can start a second unit.*

*GEM*STAR concept without fuel reprocessing*

In all cases, the accelerator uses less than 15% of the generated power



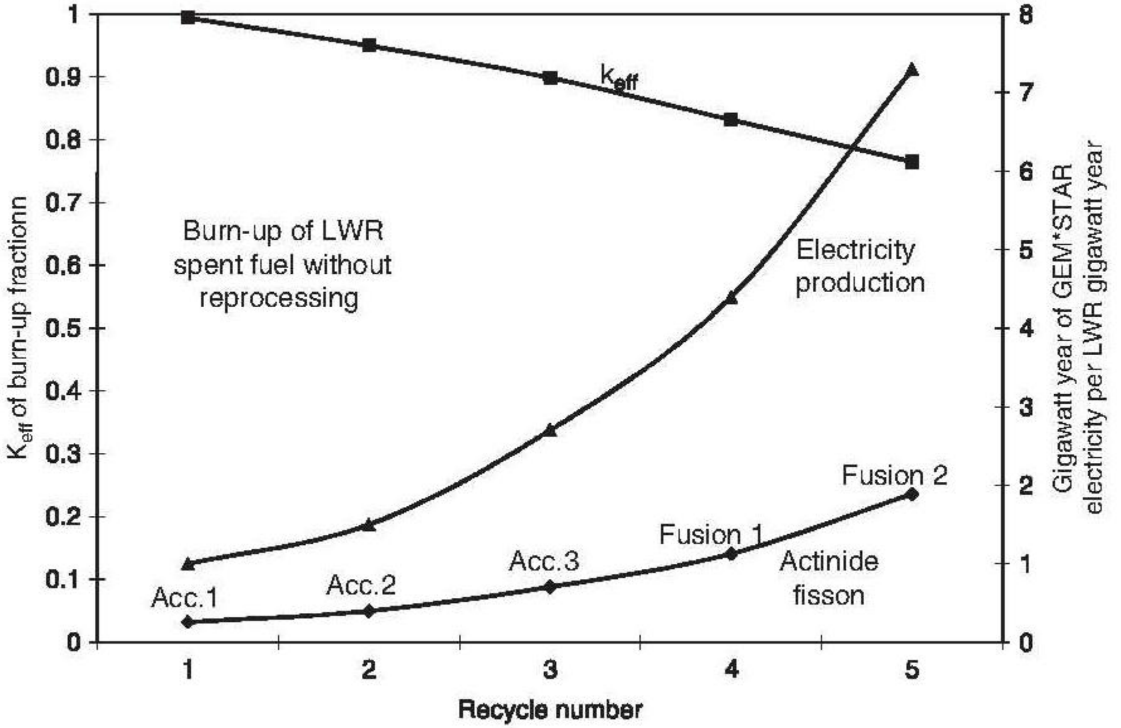
LWR fuel repeated recycle summary

Cycle	1	2	3	4	5
k_{eff}	0.99	0.95	0.90	0.83	0.77
Start date	2020	2060	2100	2140	2180
Neutron source	Acc. 1	Acc. 2	Acc. 3	Fusion 1	Fusion 2
End date	2060	2100	2140	2180	2220
Neutron multiplication	100	20	10	6	4
Relative neutron cost	1	5	5	5	5
Energy-weighted LWR waste remnant	0.5	0.324	0.183	0.114	0.068

Charles D. Bowman, R. Bruce Vogelaar, Edward G. Bilpuch, Calvin R. Howell, Anton P. Tonchev, Werner Tornow, R.L.Walter. GEM*STAR: The Alternative Reactor Technology Comprising Graphite, Molten-Salt, and Accelerators. Handbook of Nuclear Engineering, Springer Science+Business Media LLC.

*GEM*STAR concept without fuel reprocessing*

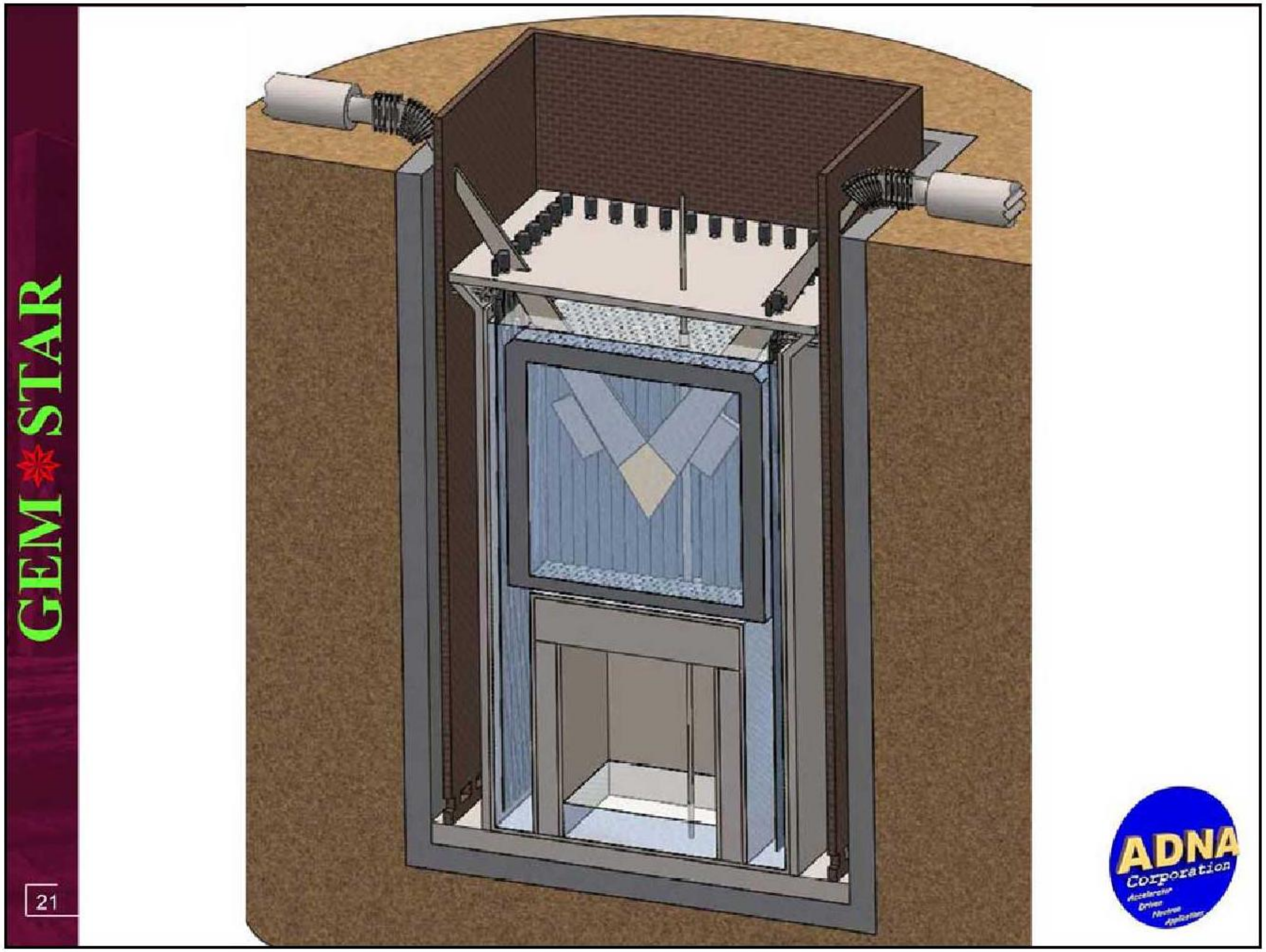
How best to solve the dilemma of accumulated spent fuel depends on assumptions.



◘ Figure 11

Five successive burn cycles for LWR spent fuel in GEM*STAR. The *top line* shows k_{eff} for each of the five cycles. The *bottom line* shows the cumulative burn-up fraction for the five cycles. Note that each subsequent cycle consumes a larger fraction of the remaining ^{238}U. The *middle line* shows the cumulative energy extracted from five successive recycles of LWR spent fuel. Note that if the total energy generated from the fresh fuel sent into the LWR is of interest, one must add 1.0 to the right ordinate. In each case, the power to produce the neutrons is assumed to never exceed 15% of the output power (see ❯ *Table 9*)

An Accelerator-Driven Subcritical Reactor Example with Molten Fuel (ThF_4 or UF_4)

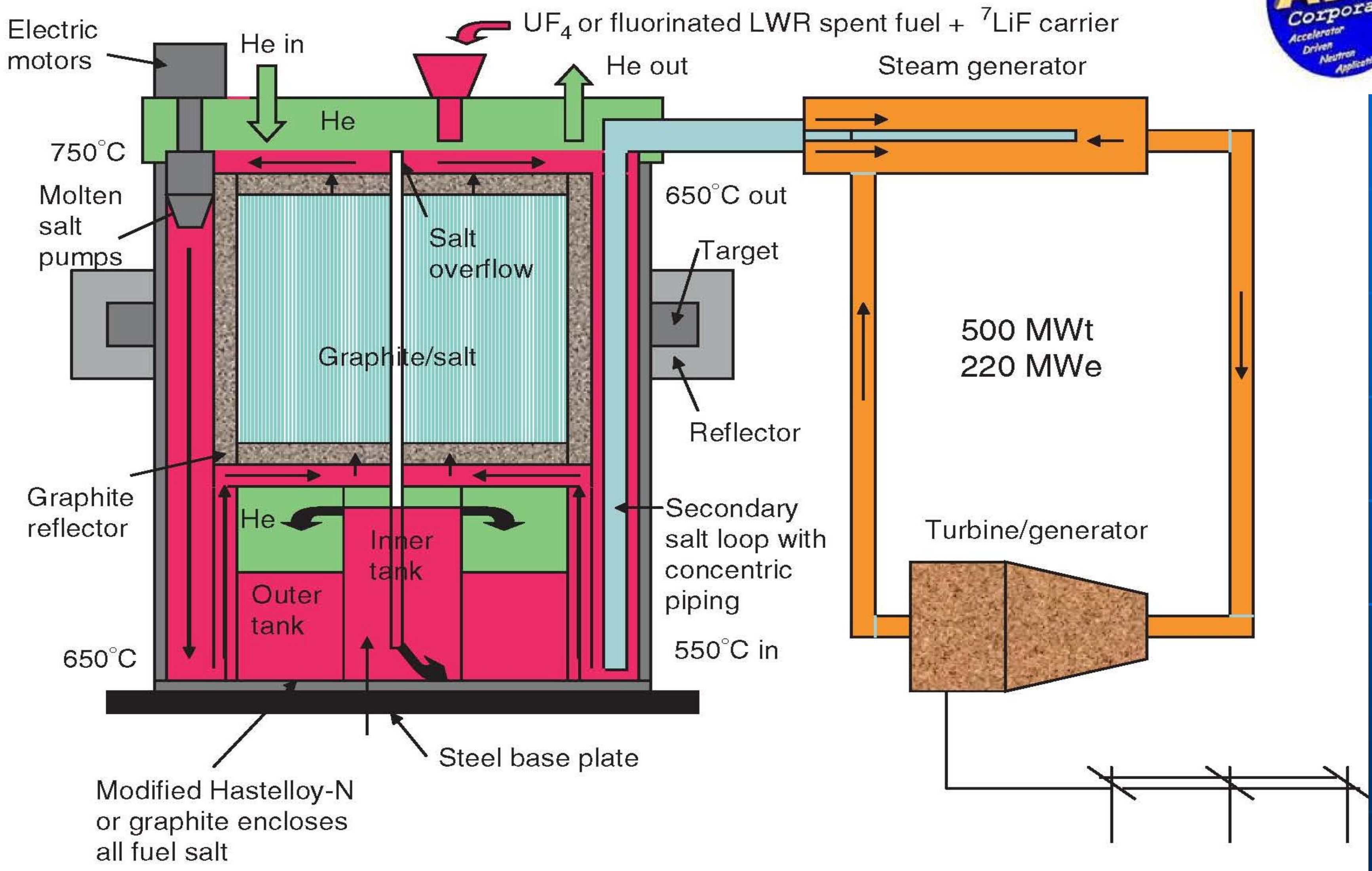


Conceptual design of the GEM*STAR reactor in its underground placement. The vertical dimension is about 30 ft. The gray box is the graphite reflector for the core. Horizontal beams from two accelerators are shown at the top being bent by magnets about 45 degrees into the core where both strike a uranium metal target shown schematically in the center of the core.

GEM*STAR ADSR MS Example

- GEM*STAR is shown schematically on the next slide.
  - Charles D. Bowman, et al. GEM*STAR: Handbook of Nuclear Engineering,
- The graphite core shown in gray surrounded by a reflector.
- The molten salt fuel takes up about 7% of the core volume and it is shown in red outside of the core. (less than critical mass!)
- The fuel flows upward to a free surface above the core and over to the sides where it is pumped down as shown on the left to the bottom of the unit. It turns upward and then horizontally and reenters the core through apertures in the bottom reflector.
- Heat is removed by a secondary (non-fissile) salt of lower melting point as shown on the right. (A reservoir can be added for reliability)
- The secondary salt flows downward on the inside of an array of pairs of concentric tubes, turns the corner at the bottom and flows upward through the outer tube with heat flow through the outer tube wall from the fuel salt to the secondary salt. A secondary salt reservoir is possible.
- The secondary salt then flows through a steam generator.

GEM*STAR Technology



GEM*STAR ADSR MS Example (cont.)

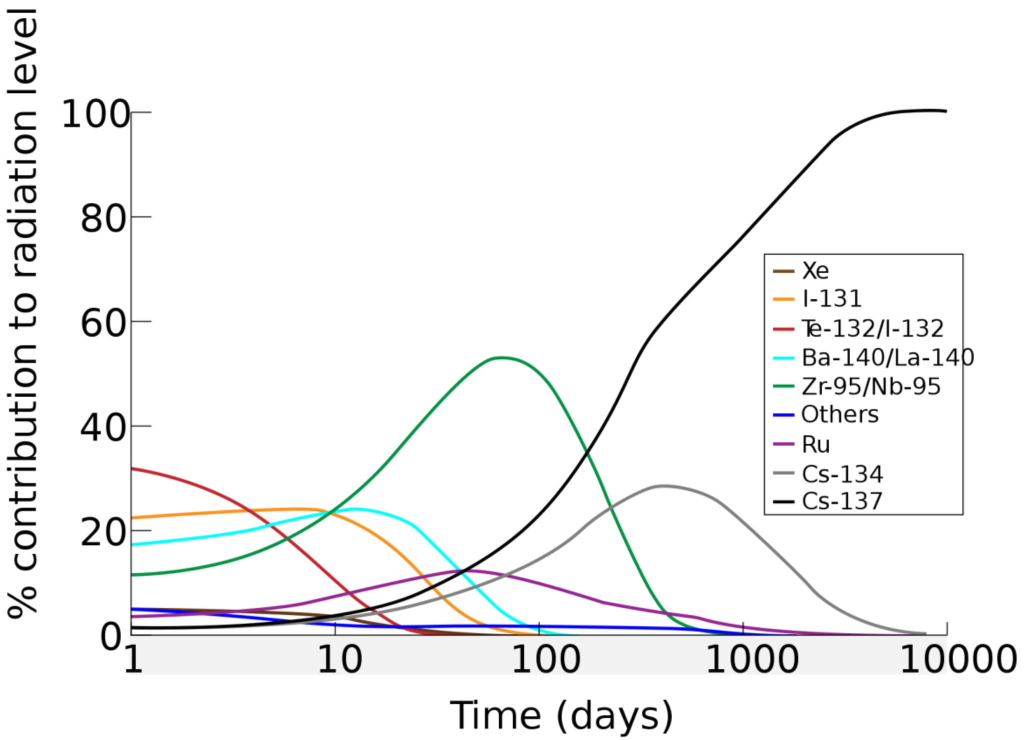
- The maximum temperatures are 750 C for the fuel salt at the top core, 650 C for the secondary salt exiting the core and 550 C for the steam entering the turbine.
- The expected thermal-to-electric conversion efficiency exceeds 44 %.
- Fuel is fed in liquid form at the rate of about 1 liter per hour for a power production of 220 MWe. The vertical pipe shown allows the fuel to overflow into an inner tank and then to an outer tank below the reactor.
- The tanks have storage capacity for forty years of fuel overflow. The overflow can be fed to another GEM*STAR unit.
- More than one internal target for neutron production will be normally present in the core instead of the external targets shown schematically.
- A flow of He across the salt surface above the core enables the prompt collection and removal of noble gases for storage away from the core so that the inventory of volatile fission products in the core is reduced by about 10 million from that of an LWR of the same power.

Radiation dose in air (Chernobyl)

The portion of the total radiation dose in air contributed by each isotope vs. time after the Chernobyl disaster, at the site thereof [*].

The radioactivity in the fission product mixture is mostly caused by short-lived isotopes such as ^{131}I and ^{140}Ba, after about four months ^{141}Ce, ^{95}Zr/^{95}Nb and ^{89}Sr take the longest share, while after about two or three years the largest share is taken by ^{144}Ce/^{144}Pr, ^{106}Ru/^{106}Rh and ^{147}Pm. Later ^{90}Sr and ^{137}Cs are the main radioisotopes, being succeeded by ^{99}Tc.

(* Reference: OECD report, the 2nd Edition of the radiochemical manual.)



These are the volatiles that are removed from the 750C core by the GEM*STAR helium flow. They quickly decay away in an underground storage vault after cryogenic or centrifuge separation from the helium.

Conclusions: SRF Linacs with today's technologies* can drive an ADSR with Molten-Salt-Fuel to simultaneously address

- elimination of dangerous stored nuclear waste
- production of safe, environmentally-friendly energy

ADSR nuclear power stations using molten salt fuel operate

- in an inherently safe region below criticality,
- without accidental releases of radioactive volatile elements,
- without generation of greenhouse gases,
- producing minimal nuclear waste,
- without byproducts useful to rogue nations or terrorists,
- fueled by and eliminating existing stockpiles of
  - LWR nuclear waste and depleted uranium
- and/or efficiently using abundant natural thorium or uranium,
  - which does not need enrichment.

*Molten-salt fuel allows an end-run around the solid fuel fatigue problem so that short-term accelerator trips are not important. Non-radioactive salt heat transfer reservoirs allow multi-hour interruptions.

Comment on electrons for ADSR

Electrons have low mass so they have a high velocity even at low energy. This makes SRF electron accelerating structures easier and intrinsically efficient, compared to protons perhaps a factor of >2 more efficient (discussion to follow)

Electrons interact electromagnetically but not strongly, and as a consequence are not very effective for spallation to produce neutrons. On a uranium target, a 1 GeV electron beam will produce about 2% of the neutrons that a 1 GeV proton beam will.

*In the previous example of a 1st generation ADSR with proton accelerator taking 5% of the energy of the reactor, a corresponding electron accelerator would take 50/2 * 5% = 125% of the reactor output.*

*In the previous example of a 2nd generation ADSR with proton accelerator taking 15% of the energy of the reactor, a corresponding electron accelerator would take 50/2 * 15% = 375%*

Neutrons: Where do they come from?

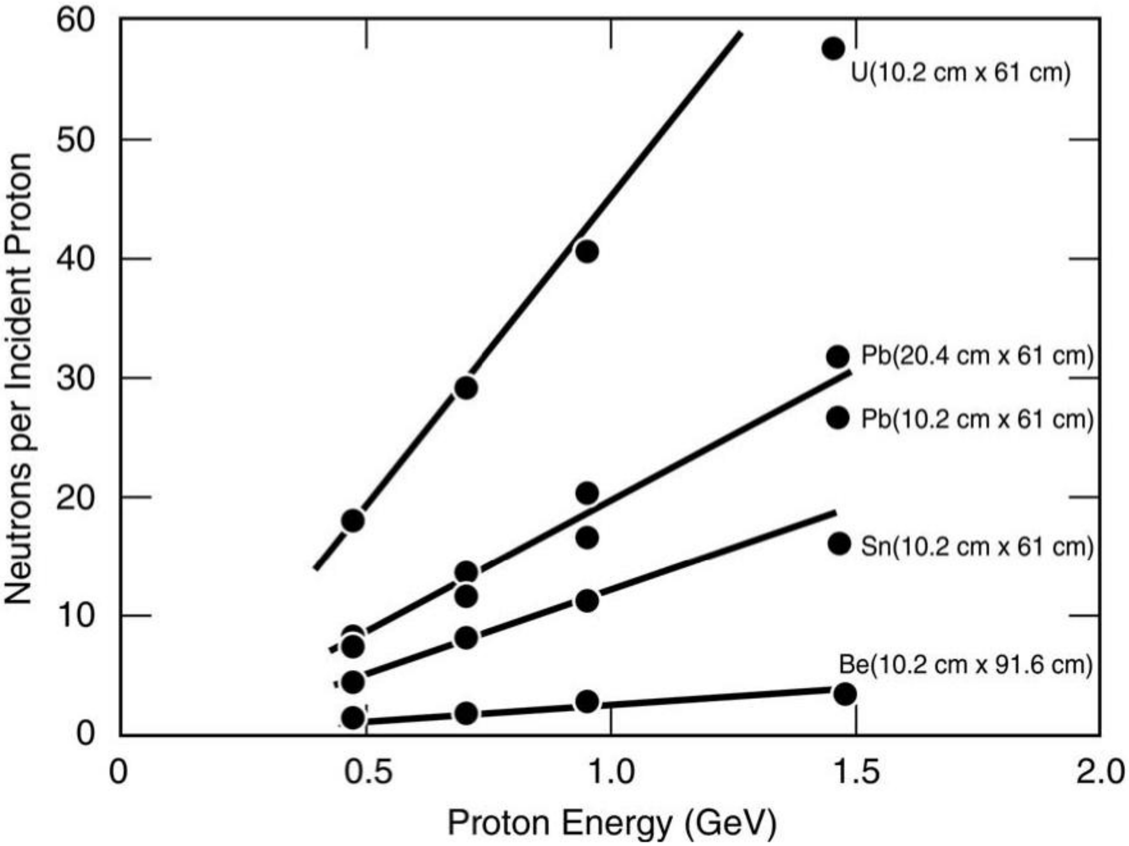
Measured Spallation Neutron Yield vs. Proton Energy for Various Targets, J. Frazer, et al. (1965)

Absolute Global
Neutron Yield

Yield (neutrons/proton)

$= {}^{0}.{}^{1}(E_{GeV} - 0.12)(A+20)$,
except fissionable materials;

$= {}^{50}.(E_{GeV} - 0.12)$, ${}^{238}U$.



From Fraser *et al.*, measurements at Brookhaven Cosmotron

2000-05264 uc/arb

Conventional proton Front End

- Ion Source, H- , DC, < 1mA
- LEBT, ~30-50 kV, short
- RFQ, 162MHz , < 2.2MeV, DC, warm
- MEBT, probably very short

"Low" Energy SRF Linac

- Single Spoke, ~10MeV
- Double Spoke ~100MeV
- Triple Spoke ~400MeV
- Beta=0.81 ~1.2GeV
- Beta=1, ~2.xGeV
- FODO, quads

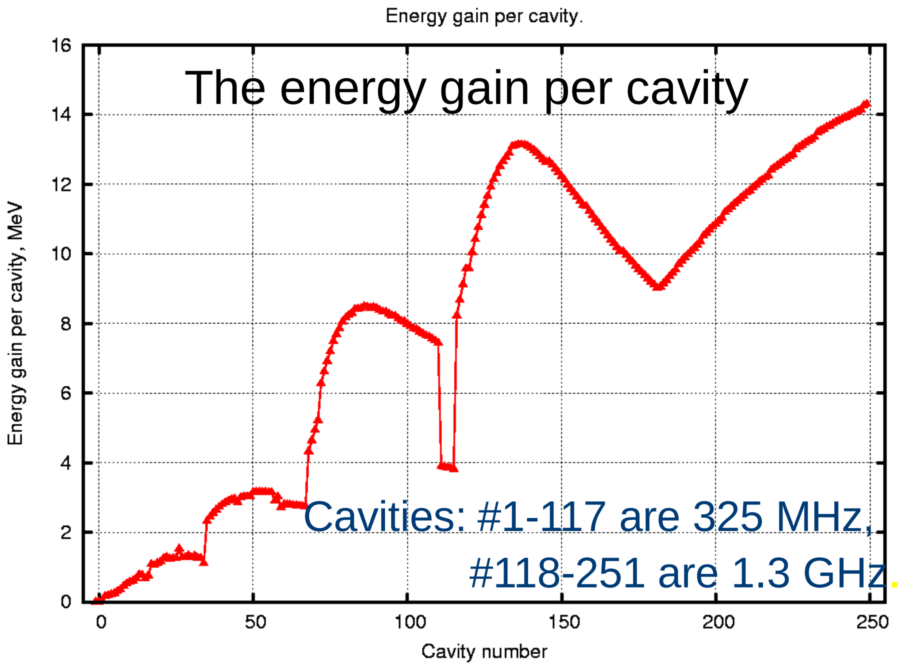
(Almost) Copy of ICD-2,

Nagaitsev, Solyak, Yakovlev, et al

Copy of ICD-1, (Almost)

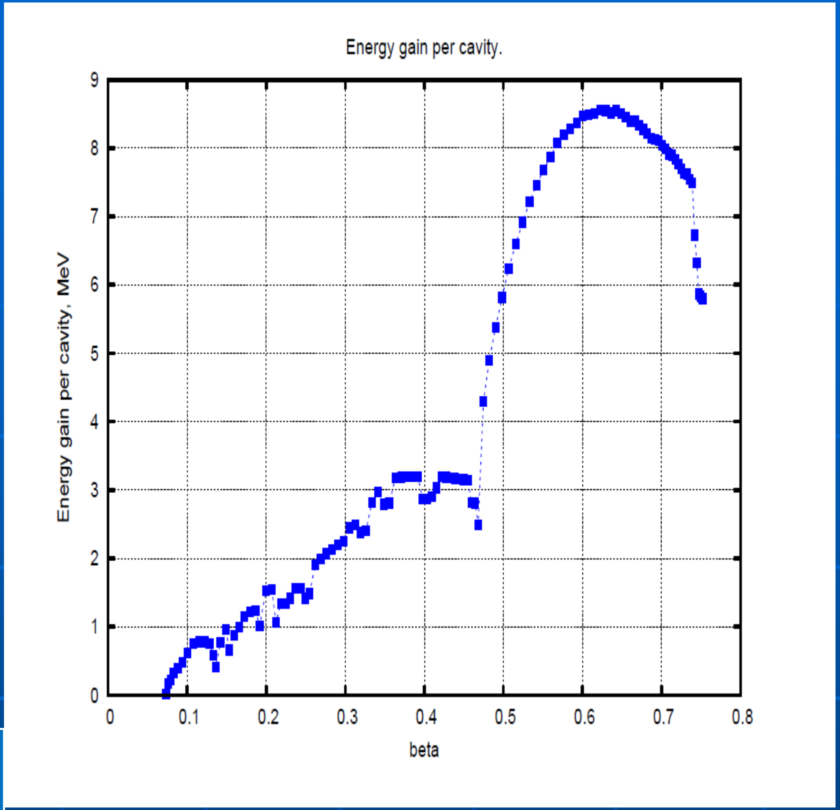
Ostroumov, et al

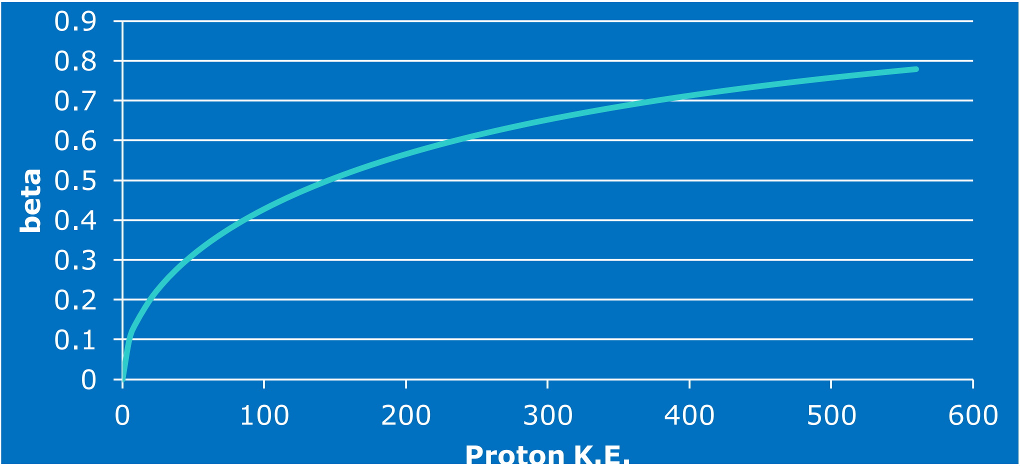
From Solyak and Yakovlev ICD-2 CW Linac Update



The energy gain per cavity

Cavities: #1-117 are 325 MHz, #118-251 are 1.3 GHz.





Blue: re-optimization of the 325 MHz linac (SSR0+SSR1+SSR2+TSR)

- 14 SRR0 (instead of 16)
- Increase gradient, optimum phases
- Better longitudinal/transverse dynamics

Cavity Parameters

325 MHz

cavity type	F [MHz]	$U_{acc, max}$ [MeV]	E_{max}, [MV/m]	B_{max} [mT]	R/Q, Ω	G, Ω	$Q_{0,2K}$ $\times 10^9$	$Q_{0,4K} \times$ 10^9	$P_{max,2K}$ [W]	$P_{max,4K}$ [W]
SSR0	325	0.78	53	59.5	120	57	9.5	0.7	0.77	10.4
SSR1	325	1.53	34.4	50.8	242	84	14.0	1.0	0.94	13.2
SSR2	325	3.16	33	54	322	112	18.0	1.3	2.07	28.6
TSR	325	8.5	31.4	67	554	117	19.0	1.4	7.9	106.9

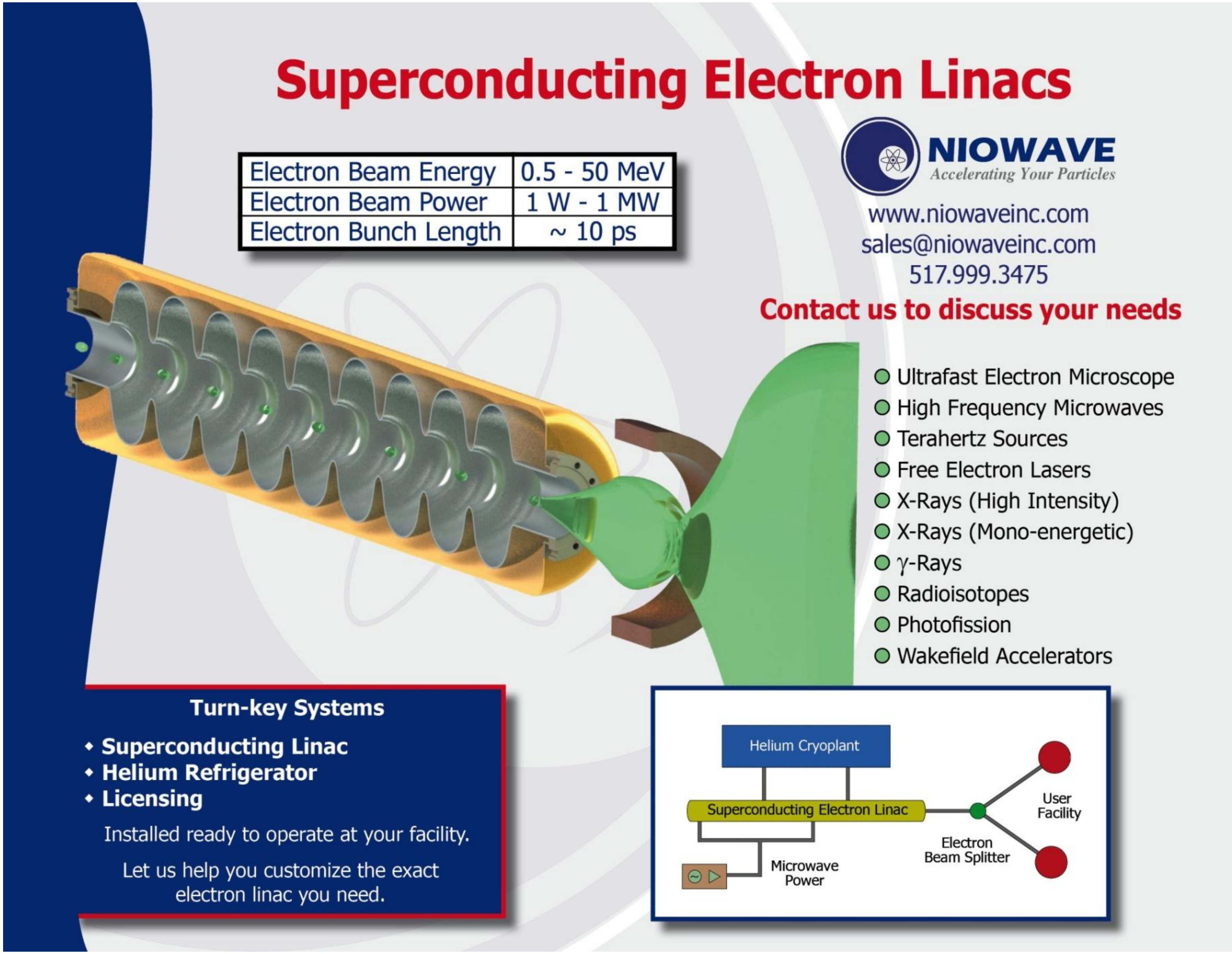
1.3 GHz

cavity type	F [MHz]	E_{acc} [MV/m]	L_{eff}, mm	E_{max} [MV/m]	B_{max} [mT]	R/Q Ω	G Ω	$Q_{0,2K}$ $\times 10^9$	$Q_{0,4K} \times$ 10^9	P_{2K} [W]
11-cell, β=0.81	1300	14.4	1028	34	72	750	228	12.7	n/a	22.4
9-cell, ILC	1300	16.9	1038	34	72	1036	270	15.0	n/a	19.0

Cyclotron H$^-$ Front End

- An H$^-$ cyclotron with peak magnetic field of just over 1T can safely achieve 100 MeV without significant Lorentz stripping
- A good example of such a machine is the PSI Injector, which accelerates up to 2 mA of protons to 72 MeV (beta=0.37)
- It is projected that such a cyclotron can accelerate over 3 mA average current from an injected current of as little as 9 mA
- DC H$^-$ ion sources have provided as much as 20 mA into a normalized rms emittance of 0.4 microns
- The width at extraction resulting from this emittance is only about 3 mm. The space charge effect in an isochronous machine is to create round bunches; this means bunch lengths are also about 3 mm, allowing them to fit easily into the 325 MHz linac buckets
- Since the energy spread tolerated by the cyclotron is very small, the cyclotron injector should not be an RFQ but a DC device as exists at PSI
- 3 MW at 1 GeV is enough to run GEM*STAR
- See Linac08 MOP011, for first suggestion that Project-X should be CW and for the Cyclotron option. C. Ankenbrandt et al.

From 100 MeV to 1GeV - US Industry can provide the SRF components!



Superconducting Electron Linacs

Electron Beam Energy	0.5 - 50 MeV
Electron Beam Power	1 W - 1 MW
Electron Bunch Length	~ 10 ps

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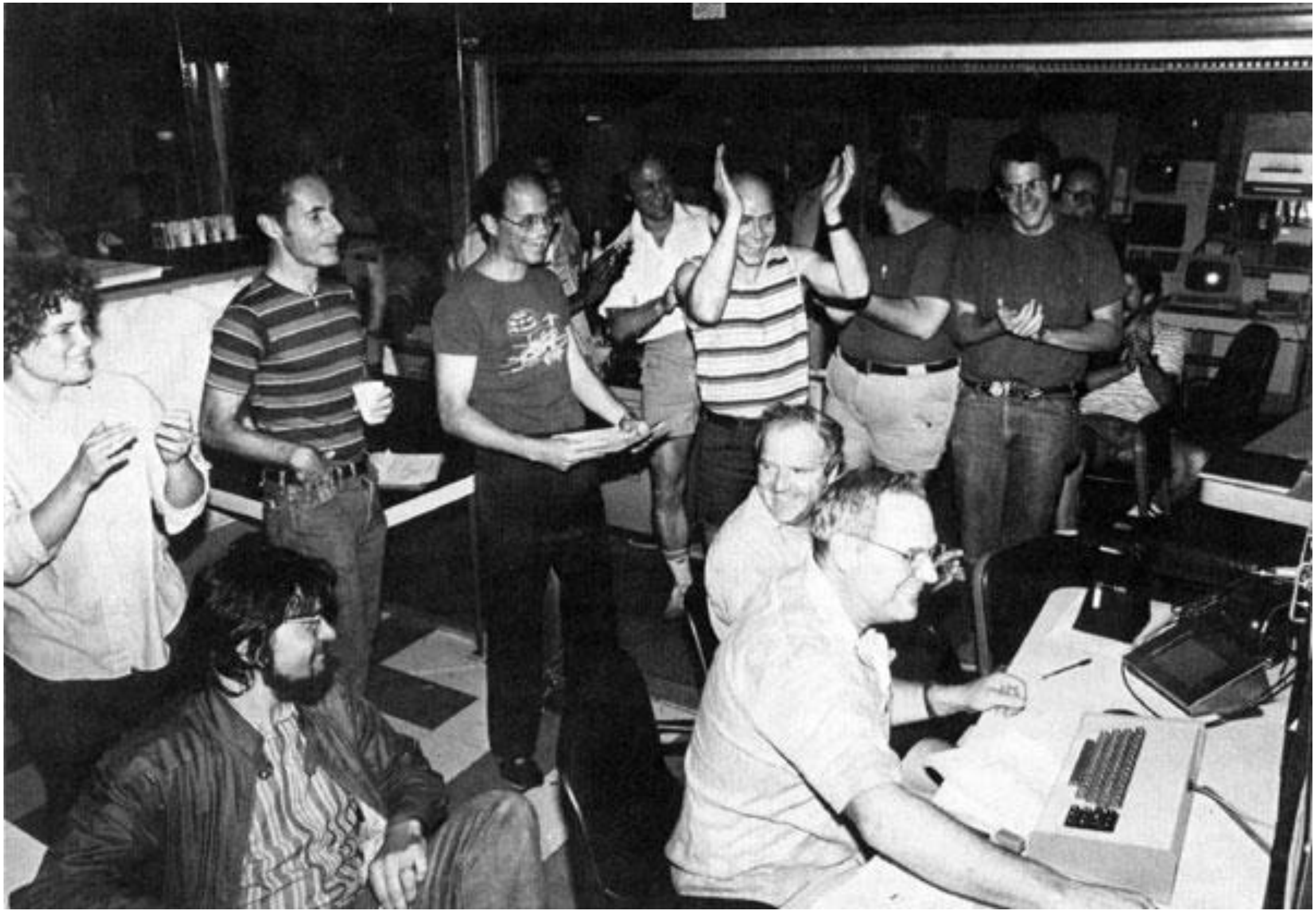
512 GeV at Fermilab



Nothing like making difficult accelerators work well!

BUSINESS September 14, 2011

Gas-to-Liquid Site May Hit $10 Billion

HOUSTON—Sasol Ltd., a chemical company long known for squeezing motor fuel out of coal, is now turning its sights on the glut of natural gas in the U.S.

South Africa-based Sasol on Tuesday announced plans to build a plant in Louisiana, at a cost of up to $10 billion, that would convert natural gas into diesel fuel for trucks and other vehicles.

The company's board last week approved an 18-month feasibility study for the project, which would be constructed on land adjacent to Sasol's existing chemical facility in Calcasieu Parish, La.

Wikipedia: The Fischer–Tropsch process involves a series of chemical reactions that lead to a variety of hydrocarbons ($C_nH_{(2n+2)}$). Useful reactions give alkanes:

$$(2n+1)\ H_2 + n\ CO \rightarrow C_nH_{(2n+2)} + n\ H_2O$$

To turn natural gas and carbon to H_2 and CO takes ~700 C

New Nuclear Technology to Produce Inexpensive Diesel Fuel from Natural Gas and Renewable Carbon

Attractive features for the U. S. transportation economy:

- Can eliminate all foreign petroleum imports by producing clean, synthetic liquid fuel
- Drop-in technology retains automobile technologies and fuel distribution infrastructure
- Nuclear power and renewable carbon to produce liquid fuel reduces the carbon footprint of all vehicles by a factor of three
    - Diesel/gasoline fuel useful for trucks, aircraft, and ships without modifications
    - Possible carbon sources include wood chips, agricultural refuse, manure digester solids, urban trash
    - DOD and other government green energy goals can be addressed
- Does not compete with the natural gas economy but extends it to mobile uses

New Nuclear Technology to Produce Inexpensive Diesel Fuel from Natural Gas and Renewable Carbon

Attractive features of ADSR, Molten-Salt Fuel for the nuclear industry:

- Subcritical operation - proton accelerator provides the extra neutrons for fission
  Never a critical mass in the reactor - **no Chernobyls**
- Volatile radioactive elements are continuously purged to reduce accident release sources by a factor of a million - **no TM Islands or Fukushimas**
- Molten salt fuel can include natural uranium, depleted uranium, natural thorium and nuclear waste from Light Water Reactors - **Yucca Mountain not needed**
- Nuclear proliferation issues avoided since the molten salt fuel
  1) does not need to be enriched - no centrifuges
  2) does not need to be reprocessed to remove fission products or higher actinides
- Molten salt fuel technology already demonstrated at the ORNL Molten Salt Reactor Experiment (MSRE)

New Nuclear Technology to Produce Inexpensive Diesel Fuel from Natural Gas and Renewable Carbon

Attractive features for the Proton Accelerator industry:

- High-temperature process heat is the most appropriate first application of ADSR
- Molten salt fuel and off-line power operation practically eliminate accelerator reliability issues
- The required efficiency and power can be supplied with superconducting radio frequency (SRF) Linacs

Developed at National Labs, and now produced by US Industry

New Nuclear Technology to Produce Inexpensive Diesel Fuel from Natural Gas and Renewable Carbon

Attractive features for US Society:

- Elimination of petroleum imports improves US balance of payments by
    - ~$0.75 trillion/year
- US insulated from variations in foreign fuel cost and supply
- The technology can be exported for liquid fuel synthesis and for electricity production (long-term goal)
- Large profits from diesel production drives the development of ADSR technology
- Reduces CO_2 from transportation and eliminates CO_2 from electricity generation
- Reduced cost of transportation fuel and electricity stimulates US manufacturing
- Enhances jobs across the spectrum, from high tech to labor in cellulose supply
- Based on US inventions and technology development (e.g. MSRE and SRF))

New Nuclear Technology to Produce Inexpensive Diesel Fuel from Natural Gas and Renewable Carbon

ARPA-E
Concept Paper due next week
Invitation for Proposals

Need 20% cost share as profit-making business