Thank you, George Takei.

Muons, Inc.
Who we are, what we want to do

Rolland P. Johnson
Muons, Inc. (http://www.muonsinc.com/)

For the first half of its 10 year existence, Muons, Inc. was obsessed with a Muon Collider, the next energy frontier machine to follow the LHC. We believe we helped revive the MC, now the long-range goal of Fermilab and US HEP

In the last few years, Muons, Inc. has emphasized developing general tools and technology for accelerators through DOE contracts and SBIR-STTR grants at seven US universities and seven National Labs

These have allowed us to build a strong staff with a broad range of skills and experience for commercial products and services. For example:

- A new service is to use ACE3P codes on supercomputers to address advanced designs of the next generations of RF devices
- A new product is a Ribbon e-beam Profile Monitor for proton/ion accelerators

Our latest obsession is to design and build a new kind of Accelerator-Driven Subcritical Reactor (ADSR) that is not only intrinsically safe, but can have large profits by producing synthetic diesel from natural gas and renewable carbon.

Muons, Inc.

Completed Muons, Inc. Projects

Year	Completed Projects	SBIR-STTR Funds	Research Partner	Phase III
2002	Company founded			
2002-5	High Pressure RF Cavity	$600,000	IIT (Kaplan)	
2003-7	Helical Cooling Channel	$850,000	JLab (Derbenev)	
2004-5	MANX demo experiment	$95,000	FNAL (Yarba)	$22,230
2004-7	Phase Ionization Cooling	$745,000	JLab (Derbenev)	
2004-7	H2Cryostat - HTS Magnets	$795,000	FNAL (Yarba)	$186,030
2005-8	Reverse Emittance Exch.	$850,000	JLab (Derbenev)	
2005-8	Capture, ph. Rotation	$850,000	FNAL (Neuffer)	$198,900
2006-9	G4BL Simulation Program	$850,000	IIT (Kaplan)	
2006-9	MANX 6D Cooling Demo	$850,000	FNAL (Lamm)	$198,900
2007-10	Stopping Muon Beams	$750,000	FNAL (Ankenbrandt)	$175,500
2007-10	HCC Magnets	$750,000	FNAL (Zlobin)	$175,500
2007-8	Compact, Tunable RF	$100,000	FNAL (Popovic)	$23,400
2008-9	Rugged RF Windows	$100,000	JLab (Rimmer)	
2008-9	H2-filled RF Cavities	$100,000	FNAL (Yonehara)	$23,400
	Completed Projects	$8,285,000		$1,003,860

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Muons, Inc. Projects in Progress

Year	Projects In Progress	Funds	Research Partner	Phase III
2008-12	Pulsed Quad RLAs (NFE)	$850,000	JLab (Bogacz)	
2008-12	Fiber Optics for HTS (NFE)	$800,000	NCSU (Schwartz)	
2008-12	RF Breakdown Studies	$850,000	LBNL (Li) ANL (Gai)	
2009-12	HOM Absorbers	$850,000	Cornell (Hoffstaetter)	
2009-12	Quasi Isochronous HCC	$850,000	FNAL (Neuffer)	$198,900
2009-10	DC Gun Insulator	$100,000	JLab (Poelker)	
2009-12	H-minus Sources	$850,000	ORNL/SNS (Stockli)	
2009-12	Hi Power Coax Coupler	$850,000	JLab (Rimmer)	
2009-10	Hi Field YBCO Magnets	$100,000	NCSU (Schwartz)	
2009-12	Φ & f–locked Magnetrons	$850,000	FNAL (Popovic)	$198,900
2010-11	ps detectors for MCDE	$100,000	U Chicago (Frisch)	
2010-11	Crab Cavities	$100,000	JLab (Rimmer)	
2010-11	MC detector bkgnds	$100,000	NIU (Hedin)	
2010-13	Epicyclic PIC	$850,000	JLab (Derbenev)	
	Projects In Progress	$8,100,000		$397,800

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Recent Phase II Competition

2011-12	Adjustable Coax Coupler	$100,000	ANL (Nassiri)	
2011-12	SAW Photoinjector	$100,000	JLab (Poelker)	
2011-12	2-Stage Magnetron	$100,000	FNAL (Yakovlev)	$23,400
2011-12	Efficient H-minus Source	$100,000	FNAL (Bollinger)	$23,400
2011-12	Achromatic Low Beta	$100,000	JLab (Derbenev)	
2011-14	FRIB Separator Magnet	$1,100,000	BNL (Gupta)	
2011-14	FiberOptic Quench Detection	$1,100,000	NCSU (Schwartz)	
2011-14	HCC Engineering Design	$1,100,000	FNAL (Yonehara)	$23,400
		$3,800,000		$70,200

New Phase I Grants

2012-13	S-Band RF Load	$100,000	SLAC (Krasnykh)	
2012-13	Ribbon e Beam Monitor	$100,000	ORNL/SNS (Aleksandrov)	
2012-13	RF Photoinjector Cavity	$100,000	JLab (Rimmer) SLAC(Li)	MuPlus
2012-13	Complete Cooling Channel	$100,000	JLab (Derbenev)	MuPlus
		$400,000		

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Contracts with National Labs

			Phase III
2009-10	Mono-E Photons	2 contracts w PNNL	$172,588
2009-10	Project-X and MC/NF	contract w FNAL	$260,000
2009-10	MCP and ps timers	contract w ANL	$108,338
2010	MAP - L2 mngr	2 contracts w FNAL	$55,739
2010	805 MHz RF Cavity	contract w LANL	$230,000
2012	MAP - L2 mngr	contract w FNAL	$40,000
2012	PX cooling for Mu2e	contract w FNAL	$75,490
2012	g-2	contract w FNAL	$40,160
2012	ACE3P 12 GeV Upgrade Studies	contract w JLab	$50,000
			$1,032,315

Pending Projects

2012	Advanced Modeling Tools	Contract with FNAL	$116,415
2012	Proton Driver Design	Contract with FNAL	$123,469
2012	G4beamline development + Support	Contract with FNAL	$87,311
2012	MC Backgrounds at the CD Interface	Contract with FNAL	$121,241
2011-12	SMES Design Calculations	Contract with BNL	$30,000
1012-13	DOD High Power RF Tubes	SBIR with NIU	$150,000

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Muons, Inc. Staff – CV Index

Muons, Inc. Staff	
Rolland P. Johnson, Ph. D.	President
Charles M. Ankenbrandt, Ph. D.	VP Personnel Development
Mike Neubauer, MSEE	VP Chief Engineer
Thomas J. Roberts, Ph. D.	VP Technology Development
Randall C. Furlong, Ph. D., J.D.	Patent Attorney/Physicist
Robert J. Abrams, Ph. D.	Senior Experimental Physicist
Alan Dudas, MSEE	Senior RF Engineer
Vadim Dudnikov, Ph. D.	Senior Accelerator Physicist
Stephen Kahn, Ph. D.	Senior Accelerator Physicist
Gigory Kazakevich, Ph. D.	Senior Accelerator Physicist
Frank Marhauser, Ph.D.	Senior Accelerator Physicist
James Nipper, BEE, MBA	Senior Engineering Manager
Leonid Vorobiev, Ph. D.	Senior Accelerator Physicist
Mary Anne Cummings, Ph. D.	Experimental Physicist
Linda Even, MSCE	Environmental Engineer
Gene Flanagan, Ph. D.	Experimental Physicist
Justin Rodriguez, BA	Computational Physicist
Cary Yoshikawa, Ph. D.	Computational Physicist

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More People

- Under SBIR-STTR grants, Muons, Inc. supported or is supporting seven full-time junior Ph. D. accelerator scientists directly (Drs. Mohammad Alsharo’a, Kevin Beard, Gene Flanagan, Pierrick Hanlet, Masahiro Notani, David Newsham, Kevin Paul, and Cary Yoshikawa).
- and seven indirectly through subgrants, at Fermilab, JLab, IIT, NCSU, LBNL and ODU (Drs. Katsuya Yonehara, Shahid Ahmed, Guimei Wang, Vasiliy Morozov, Frank Hunte, Dan Bowring).
- Muons, Inc. supports Ph. D. students working on our projects: Ms. Mahzad BastaniNejad and Ms. Ana Samolov at ODU, Ms. Melanie Turenne at NCSU, and Mr. James Maloney at NIU. Other potential Ph. D. students are considering working on our projects as thesis topics.
- Melanie and Ana have completed all requirements and will receive their Ph.D.s this year!

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512 GeV at Fermilab

Nothing like making difficult accelerators work well!

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Ultimate Goal – after the LHC: High-Energy High-Luminosity Muon Colliders

- precision lepton machines at the energy frontier
- achieved in physics-motivated stages that require developing inventions and technology, e.g.
  - MANX (a new version is in the works)
    - demonstrate HCC, HS, & EEX concepts (based on a prototype HCC segment)
  - high-intensity proton driver
    - simultaneous intense muon beams
  - stopping muon beams
    - useful 6D cooling w HCC, EEX
  - neutrino factory
    - HCC with RF, RLA in CW Proj-X
  - Z′ factory
    - low Luminosity collider, HE RLA
  - Higgs factory ← (we have some new ideas on this!)
    - extreme 6D cooling, low beta, super-detectors
  - energy-frontier muon collider
    - more cooling, lower beta

new ideas for MCs first seen in our SBIR-STTR projects:

- H_2-Pressurized RF Cavities
- Helical Cooling Channel
  - Continuous Absorber for Emittance Exchange
- Parametric-resonance Ionization Cooling
  - Correlated Optics
- Reverse Emittance Exchange with Absorbers
- RF Capture, Phase Rotation, Cooling in HP RF Cavities
- Bunch Coalescing
  - to overcome space charge limitations
- High Field HTS Solenoids for transverse cooling
- Helical Solenoid magnets
  - NbTi 4-coil HS models
  - YBCO 6-coil HS models
  - Fiber optics for HTS quench protection
- p-dependent HCC
  - precooler
  - MANX 6d Cooling Demo
  - improved mu2e design
- Pulsed Quadrupoles in SRF Linacs for RLAs
  - Multipass arcs – c.f. Morozov et al.

Muons, Inc.

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

Charles Bowman — ***ADNA & CLF Corps***

Rolland P. Johnson — ***Muons, Inc.,***

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. 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 methane and renewable carbon for the Fischer-Tropsch generation of diesel fuel.

The project requires

1) reducing accelerator construction and operating expenses,
2) integration of ORNL molten-salt reactor technology with an internal spallation target,
3) construction and test of a molten-salt to gas process heat transfer model device and
4) attracting private funding to build the first plant.

DOD could be the first customer

Muons, Inc.

A few preliminary comments:

- We believe ADSR needs close collaboration between accelerator and reactor people and have been very lucky to collaborate with Charlie Bowman of ADNA and CLF
  - 1992 patent: Apparatus for nuclear transmutation and power production using an intense ... Charles D. Bowman
- We have many other collaborators, including Bruce Vogelaar of Virginia Tech
- national labs - ANL, BNL, Fermilab, JLab, LANL, LBNL, ORNL, PNNL, and SLAC
- many universities - U of Chicago, Cornell, FSU, GWU, IIT, NCSU, NIU, and ODU

Muons, Inc.

Goal – US government pays industry to take 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 in the US
  - 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

Carlo Rubbia

Comparing alternatives

AkerSolutions

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

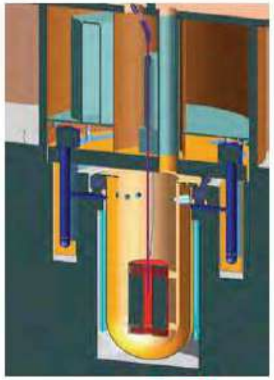
200 tonnes of Uranium

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 (fissile),
  - (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 fertile, 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 — β^- — β^- — *fissile*

- $n + {}^{238}U_{92} \rightarrow {}^{239}U_{92} \xrightarrow[24\ m]{} {}^{239}Np_{93} \xrightarrow[2.4\ d]{} {}^{239}Pu_{94}$ ← 30% LWR
- $n + {}^{232}Th_{90} \rightarrow {}^{233}Th_{90} \xrightarrow[22\ m]{} {}^{233}Pa_{91} \xrightarrow[27\ d]{} {}^{233}U_{92}$ ← 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 now provide extraordinary neutron flux
    - SRF is safer than BRs, which operate above criticality with fewer delayed neutrons and require enrichment and reprocessing
  - 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

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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 $UO_{2\ to}$ 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.

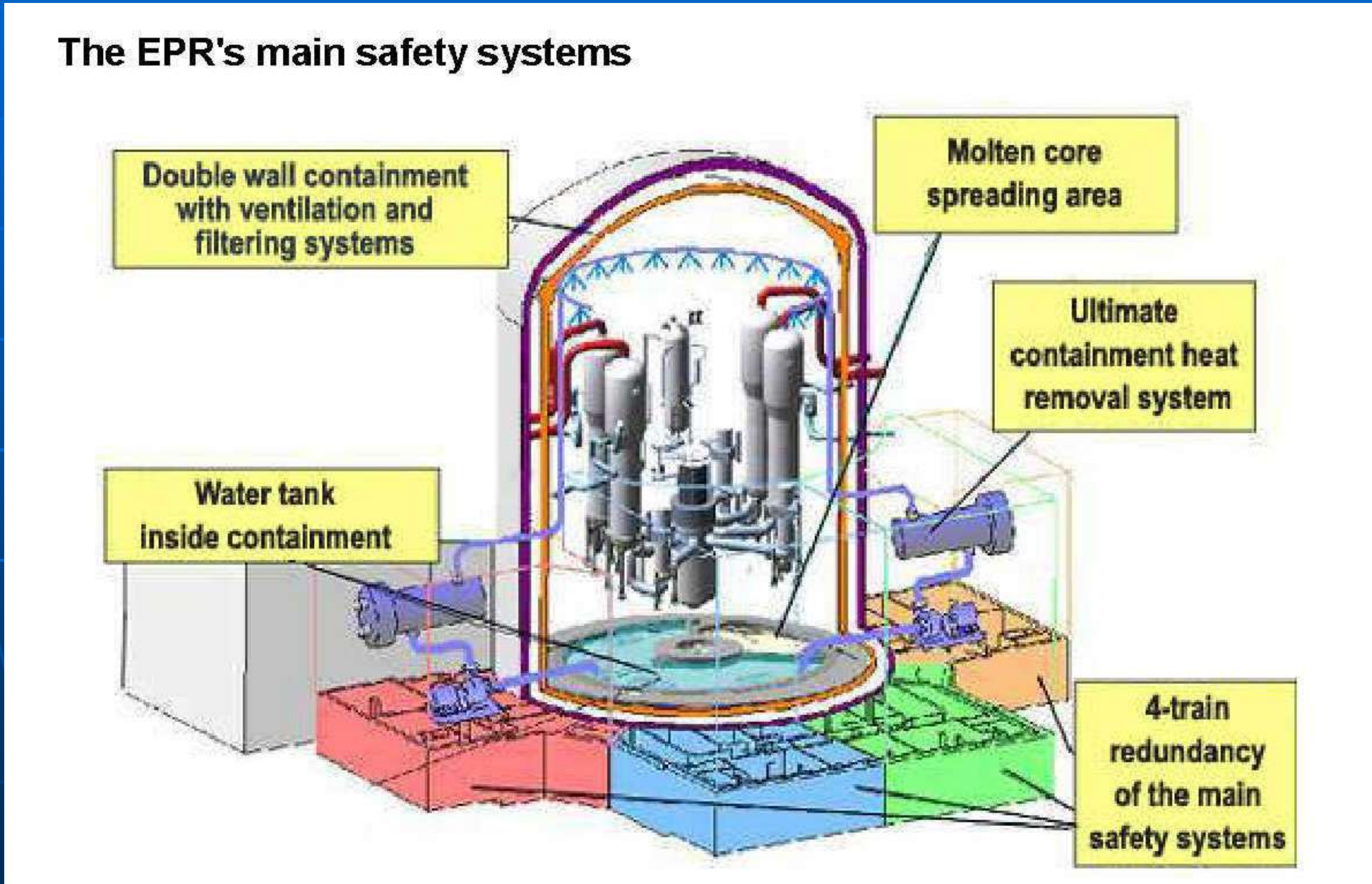
- For reactors, there are lots of layers of protection that have been invented and used to mitigate the problems that follow from solid fuel rod technology.
  - See latest iteration on next slide.

- 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

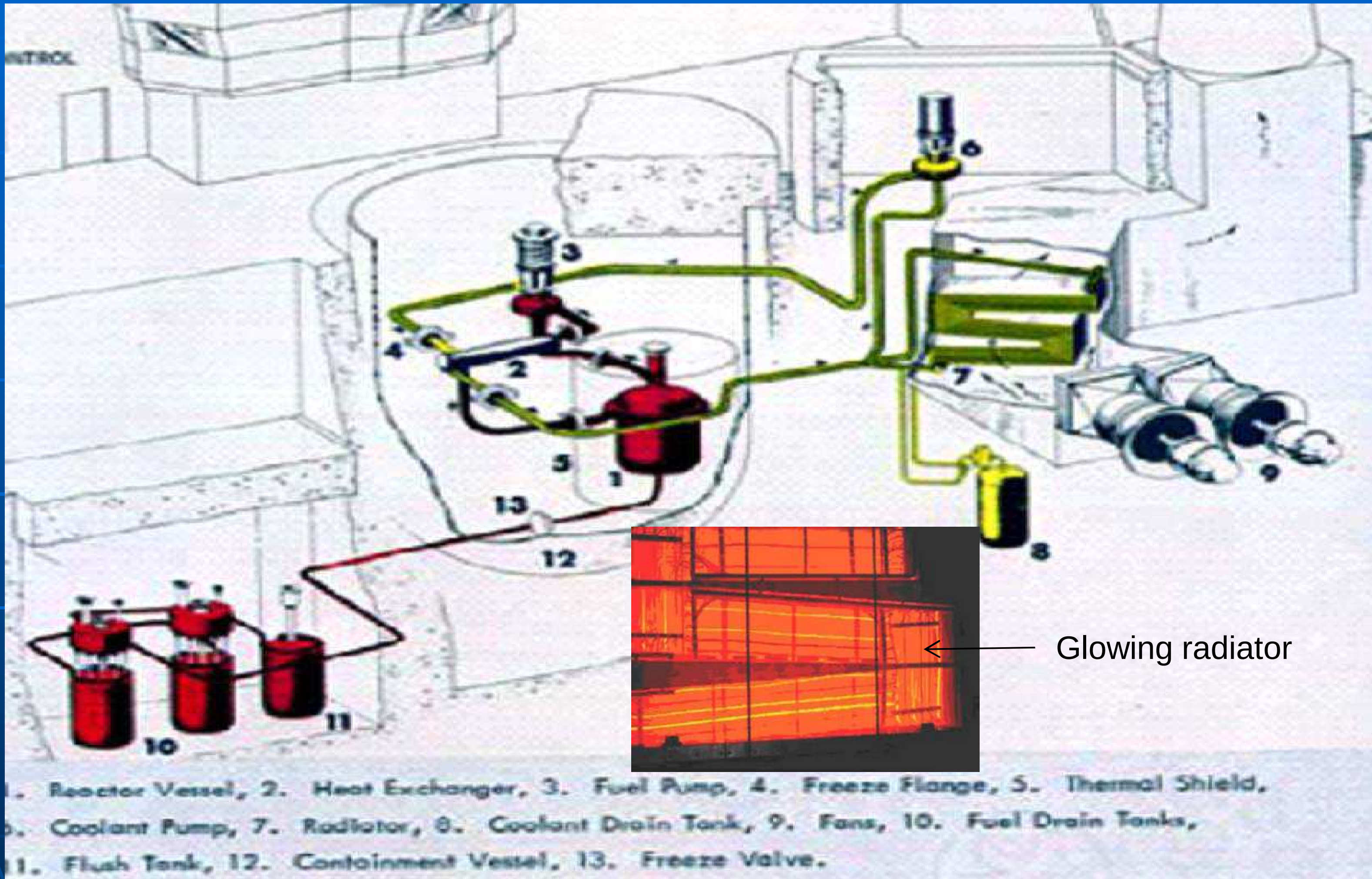
http://en.wikipedia.org/wiki/European_Pressurized_Reactor



- 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



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.

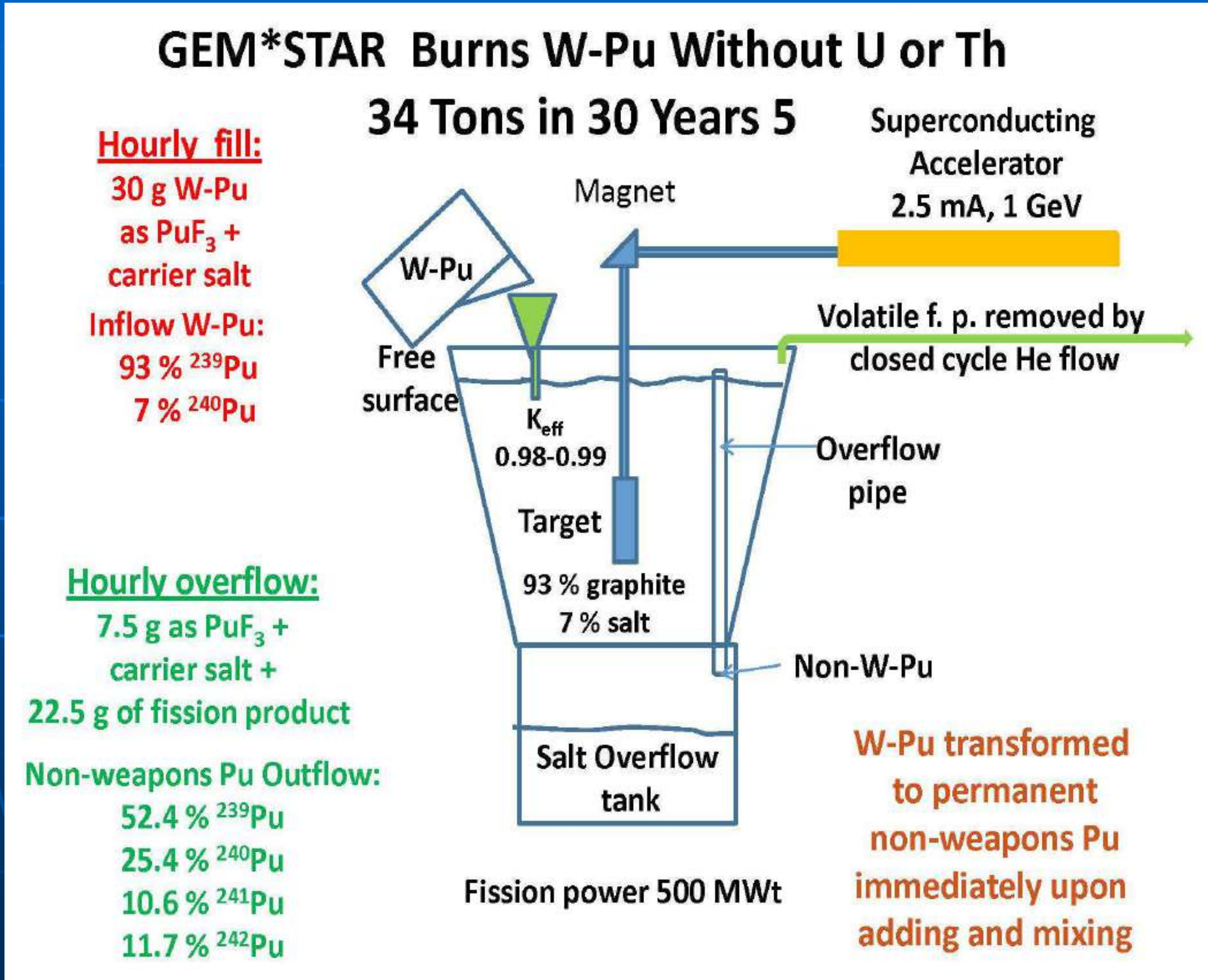
Operation with 235U (33% enrichment) in the fuel salt began in June 1965, and by March 1968 nuclear operation amounted to 9,000 equivalent full-power hours. The goal of demonstrating reliability had been attained - over the last 15 months of 235U operation the reactor had been critical 80% of the time. 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

A first example of an ADSR may be the destruction of 34 tons of weapons grade plutonium in the US and 34 tons in Russia



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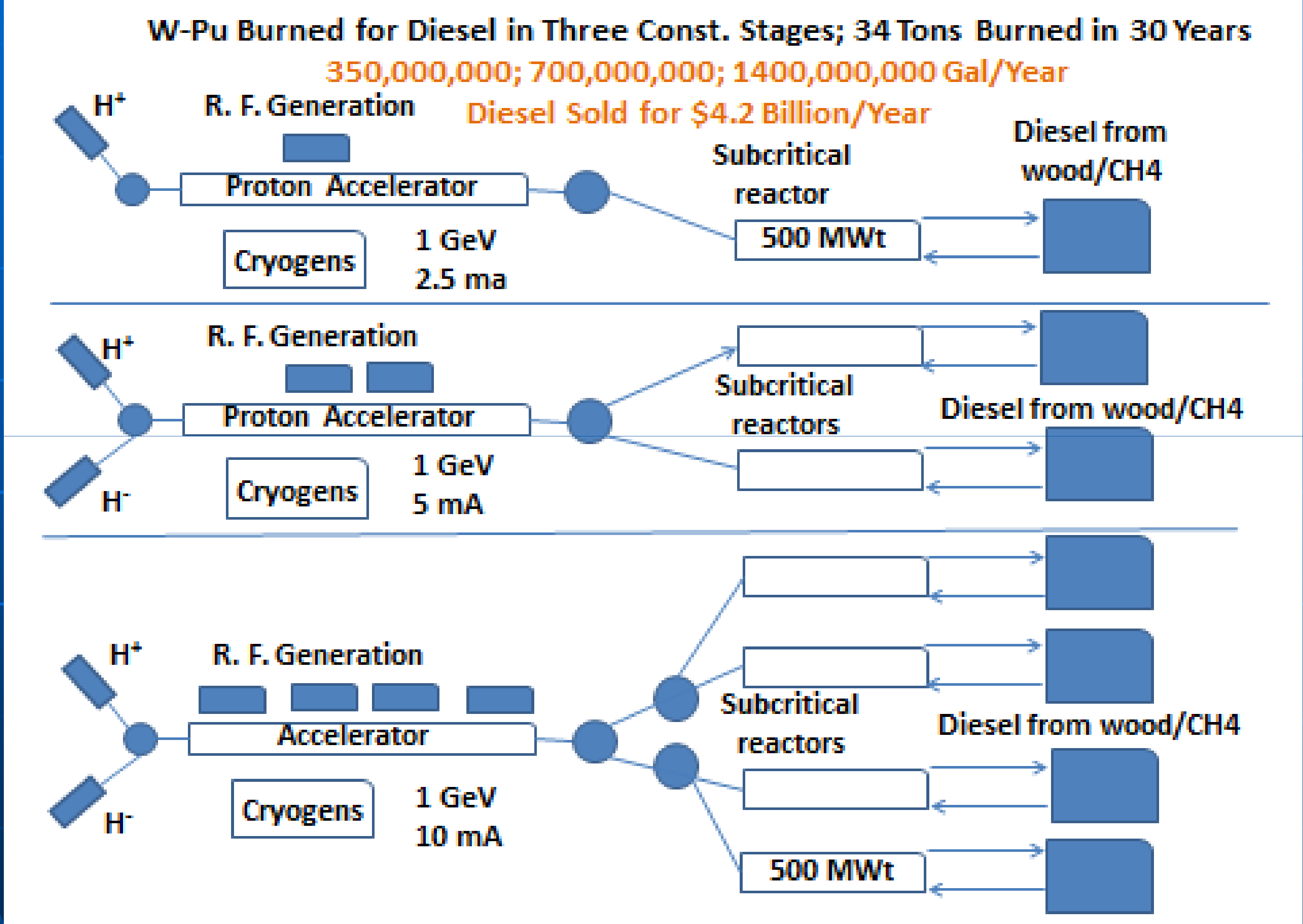
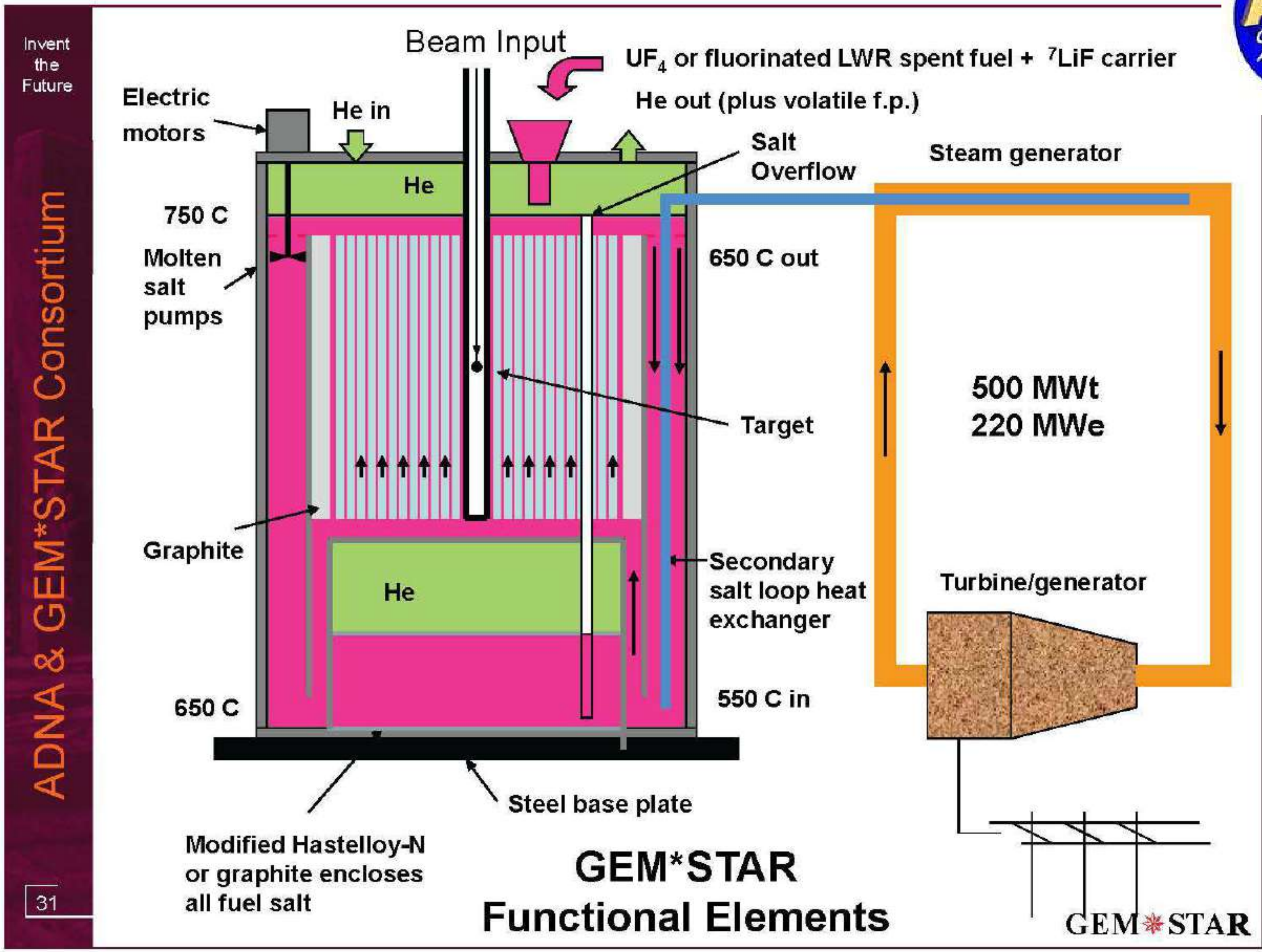
In the US, natural gas can be turned into diesel for very large profits – here is a staged approach

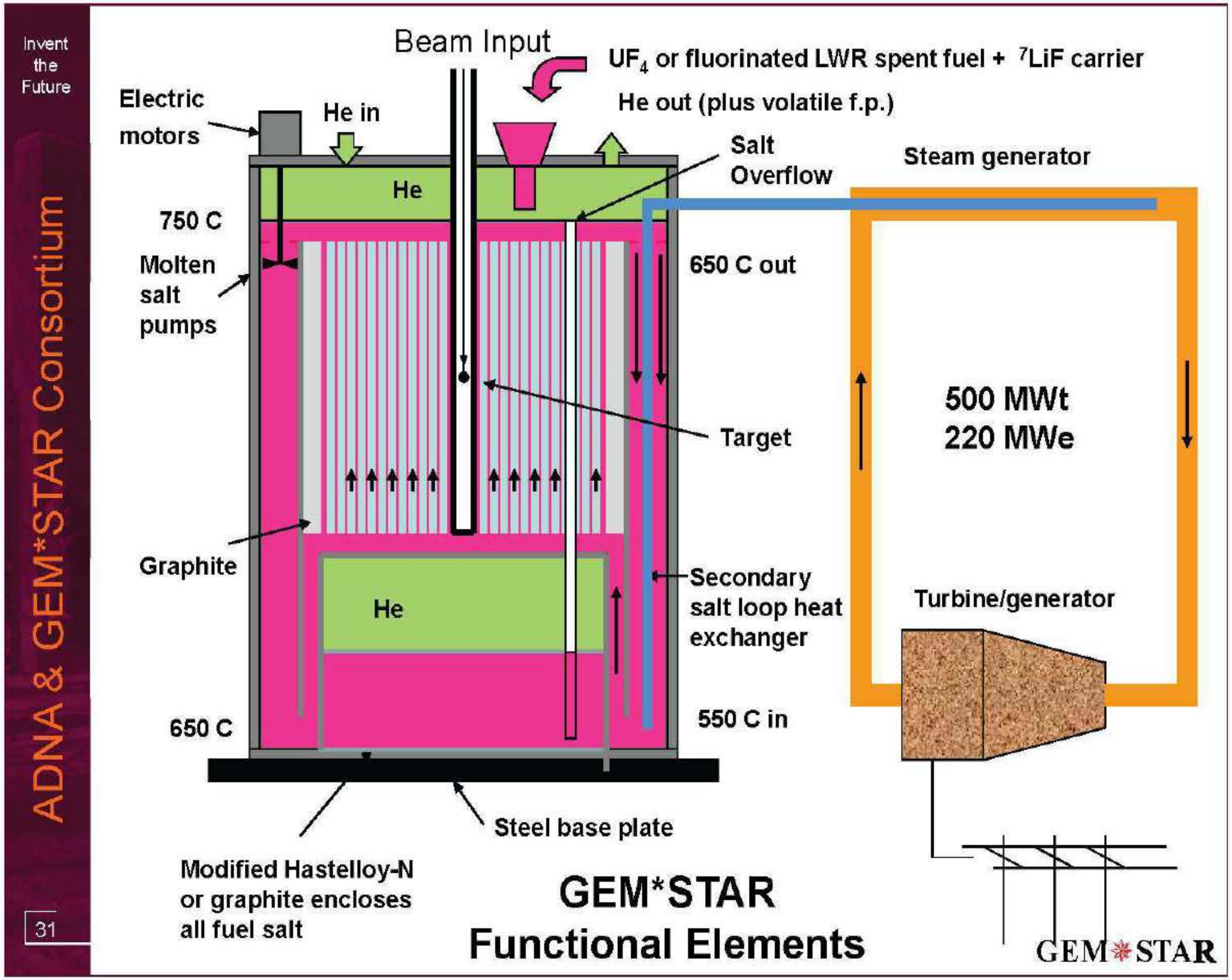


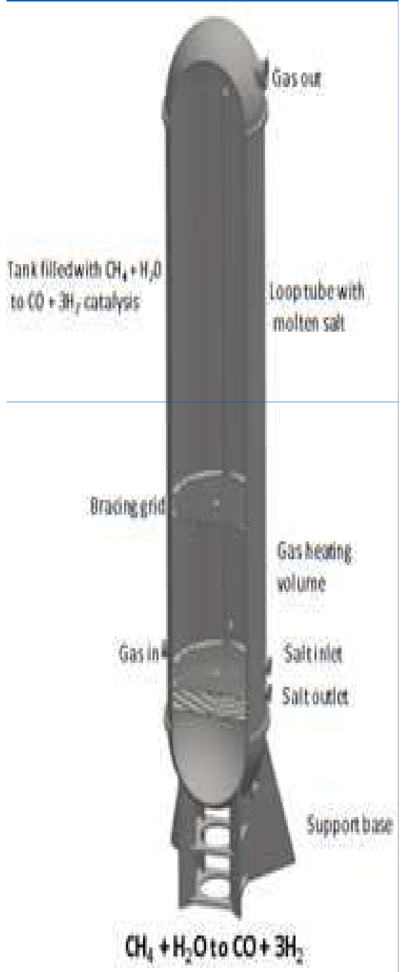
The Superconducting Particle Accelerator Forum (SPAFOA) from ILC days
Has many industrial partners that we are partnering with for ADSR.

SNS ORNL Linac



Invent the Future
ADNA & GEM*STAR Consortium
Beam Input
UF$_4$ or fluorinated LWR spent fuel + ^{7}LiF carrier
He out (plus volatile f.p.)
Electric motors
He in
He
Salt Overflow
Steam generator
750 C
Molten salt pumps
650 C out
Target
500 MWt
220 MWe
Graphite
Secondary salt loop heat exchanger
Turbine/generator
He
650 C
550 C in
Steel base plate
Modified Hastelloy-N or graphite encloses all fuel salt
GEM*STAR
Functional Elements
GEM*STAR
31


Invent
the
Future
ADNA & GEM*STAR Consortium
31
Beam Input
UF_4 or fluorinated LWR spent fuel + ^7LiF carrier
He out (plus volatile f.p.)
Electric
motors
He in
He
Salt
Overflow
Steam generator
750 C
Molten
salt
pumps
650 C out
Target
500 MWt
220 MWe
Graphite
He
Secondary
salt loop heat
exchanger
Turbine/generator
650 C
550 C in
Steel base plate
Modified Hastelloy-N
or graphite encloses
all fuel salt
GEM*STAR
Functional Elements
GEM*STAR


Gas out
Tank filled with $CH_4 + H_2O$ to $CO + 3H_2$ catalysis
Loop tube with molten salt
Bracing grid
Gas heating volume
Gas in
Salt inlet
Salt outlet
Support base
$CH_4 + H_2O$ to $CO + 3H_2$

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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
- many process heat applications like Diesel fuel production

ADSR 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.

The next generation of nuclear reactors will be subcritical,

Which is made possible by powerful proton accelerators.

They will be intrinsically safe because of molten salt fuel

There will be many of them,

because

The sun does not always shine

The wind does not always blow and

The nuclear fuel is almost inexhaustible

there is enough for 1000 years of electrical power already out of the ground.