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Z-Pinch Fusion Driven Systems for IFE, Transmutation, and GNEP

Gary E. Rochau
Deputy Program Manager for Z-IFE
Experiments and New Programs
Center for Nuclear and Risk Technologies
Sandia National Laboratories
Albuquerque, New Mexico USA
gerocha@sandia.gov (505)845-7543

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Z-IFE Team

Benjamin B. Cipiti, Jason T. Cook, Charles W. Morrow, Matthew C. Turgeon, Salvador B. Rodriguez, Cathy O. Farnum, Marcos A. Modesto-Beato, Michael F. Young, Samuel Durbin, Virginia D. Cleary, James D. Smith, Paul E. McConnell, Dannelle P. Sierra, Craig L. Olson, Gary E. Rochau, Wayne Meier, Ralph Moir, Per F. Peterson, Philippe M. Bardet, Chris Campen, James Franklin, Haihua Zhao3 Gerald L. Kulcinski, Mark Anderson, Jason Oakley, Ed Marriott, Jesse Gudmundson, Kumar Sridharan, Riccardo Bonazza, Virginia L. Vigil, Mohamed A. Abdou, Lothar Schmitz, Alice Ying, Tomas Sketchley, Yu Tajima, Said I. Abdel-Khalik, Brian Kern, M. Ghiaasiaan

Institutions Represented

Sandia National Laboratories
Lawrence Livermore National Laboratory
University of California, Berkeley
University of Wisconsin, Madison
University of California, Los Angeles
Georgia Institute of Technology

Scope

- Snapshot of a Z-Pinch Inertial Fusion Energy (Z-IFE) Power Plant
  - extends the single-shot z-pinch fusion program on Z
  - a repetitive, high-yield, power plant scenario
  - production of electricity
  - transmutation of nuclear waste
  - hydrogen production
  - desalination of water
  - no CO_2 production
  - no long-lived radioactive nuclear waste.
- A possible path to Z-IFE fusion energy
  - small fusion yields for neutron production
  - transmutation of nuclear waste from fission power plants
  - GNEP (Global Nuclear Energy Partnership).
  - sets the stage to large scale IFE systems.
- Road Map that inter-relates IFE, transmutation, and GNEP

Z-IFE Power Plant Baseline Parameters

Target Yield	3 GJ
Rep. Rate (per chamber)	0.1 Hz
Fusion Power per chamber	300 MWth
Number of Chambers	10

Chamber

Shape	Spherical or Ellipsoidal
Dimension	4 m internal radius
Material	F82H Steel
Wall Thickness	15-30 cm

Coolant

Coolant Choice	Flibe
Jet Design	Circular Array
Standoff (Target to First Jet)	0-2 m
Void Fraction	0.05 – 0.67
Curtain Operating Temperature	950 K
Average Curtain Coolant Flow	12 m^3/s
Heat Exchanger Coolant Flow	0.47 m^3/s
Heat Exchanger Temp. Drop	133 K
Pumping Power	1.3 MW/chamber
Heat Cycle	Rankine
Heat Exchanger Type	Shell and Tube

Tritium Recovery

Breeding Ratio	1.1
Tritium Recovered per Shot	0.017 g
Extraction Type	Countercurrent

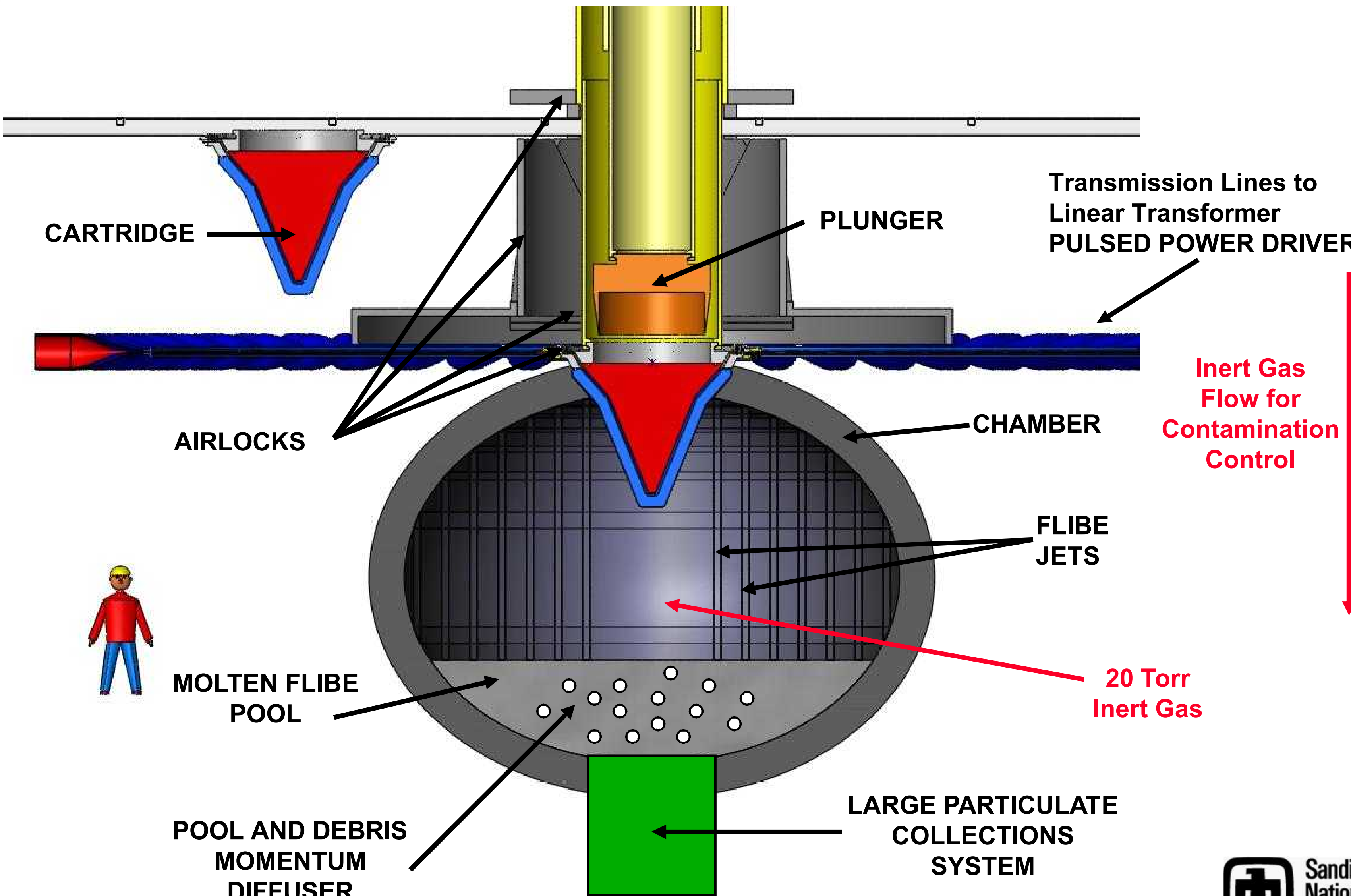
RTL

RTL Material	1004 Carbon Steel
Cone Dimensions	1 m Ø x 0.1 m Ø x 2 m h
Outer Cone Thickness	0.9 mm → 0.52 mm
Inner Cone Thickness	0.52 mm
Mass per RTL (2 cones)	50 kg → 34 kg

RTL Manufacturing

Furnace	Electric Arc
Production	Sheet Metal to Deep Draw
Energy Demand	184 MW for ten chambers

BASE Z-IFE UNIT



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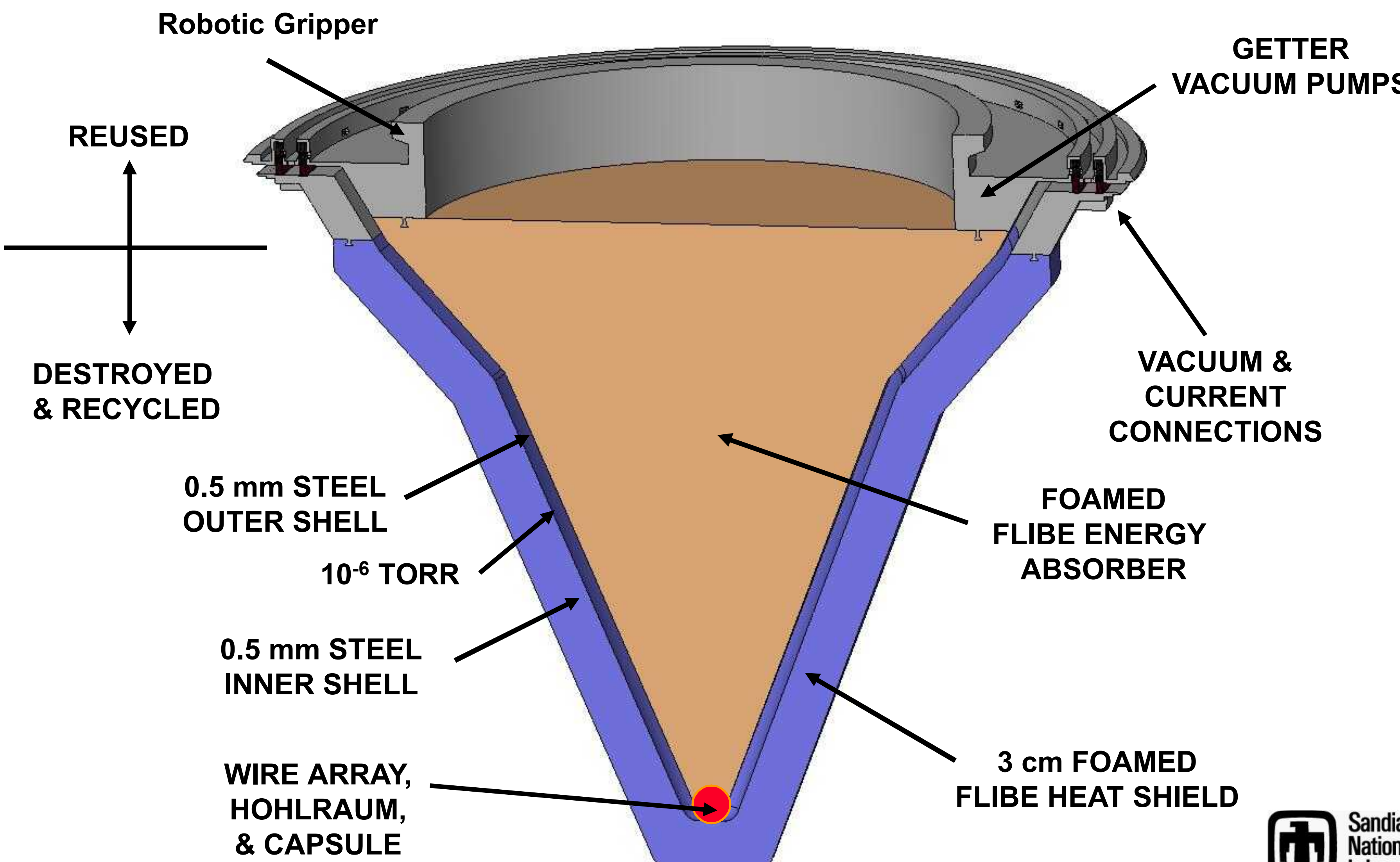
Not to Scale

RTL Configuration



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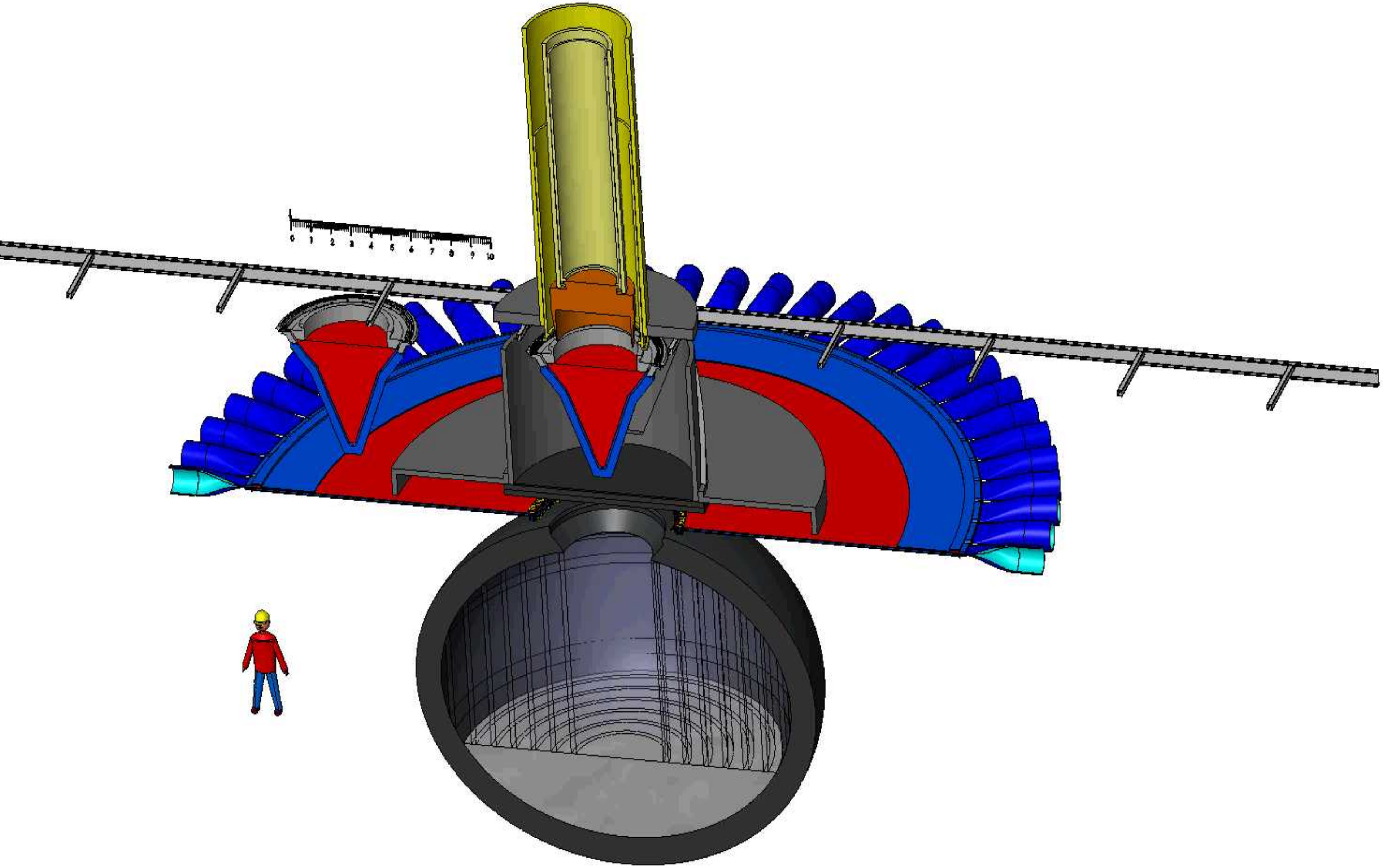
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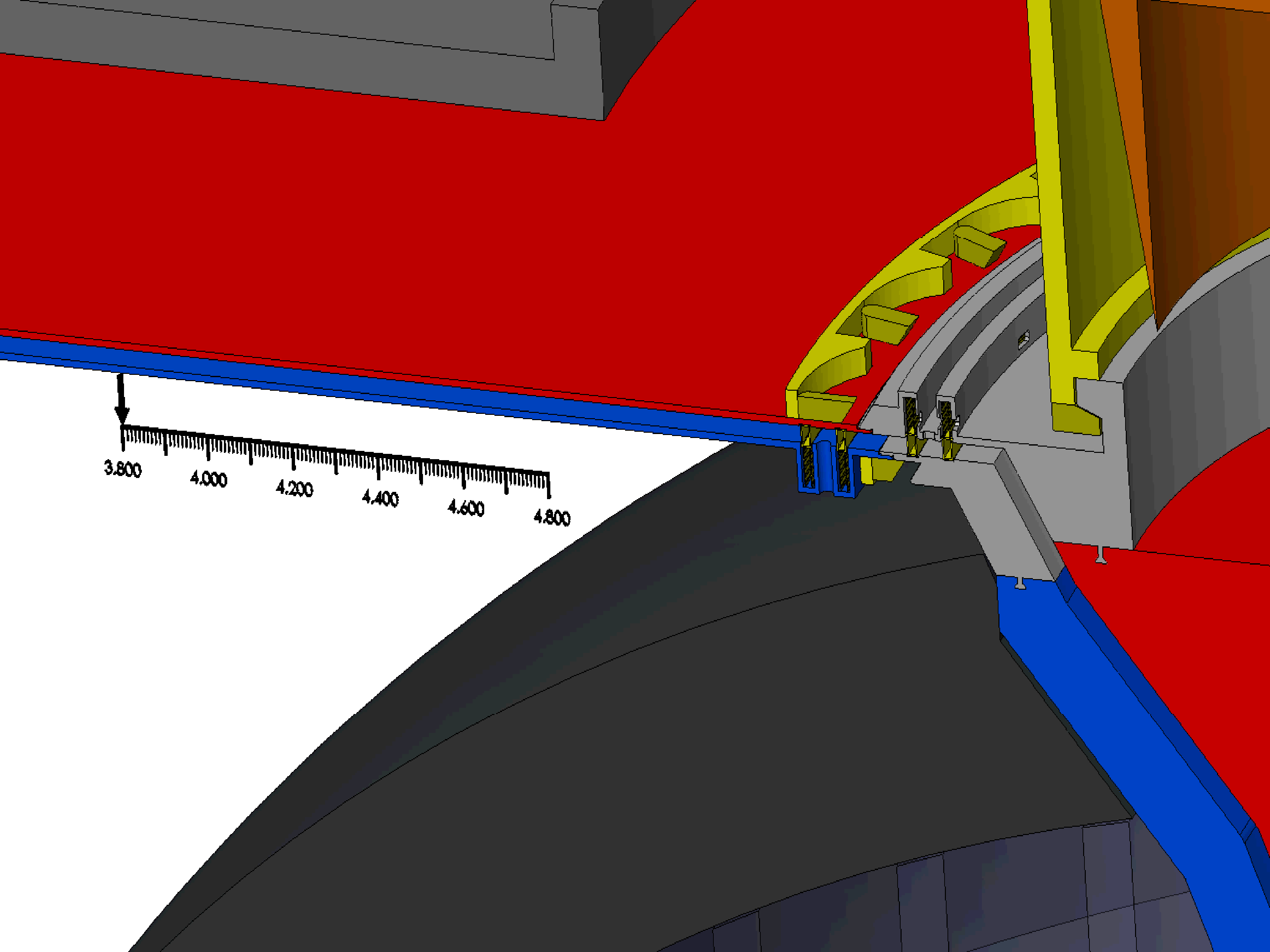
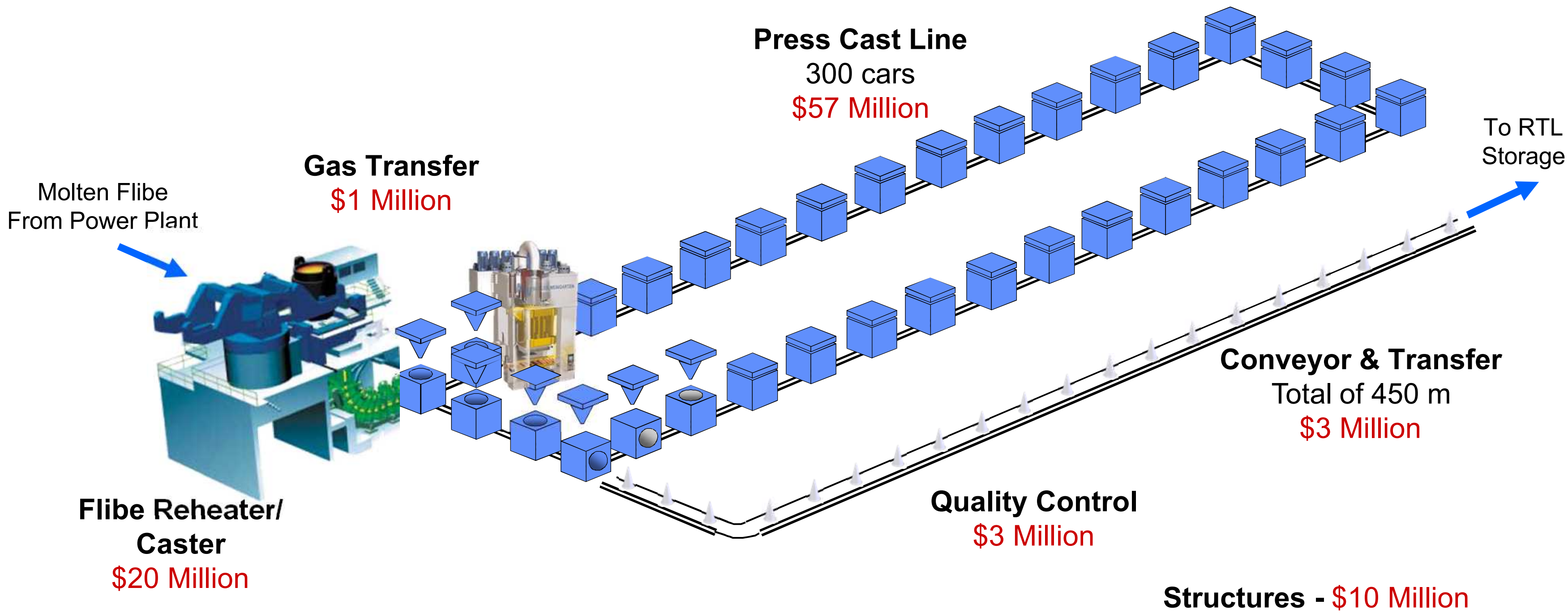

3.800
4.000
4.200
4.400
4.600
4.800

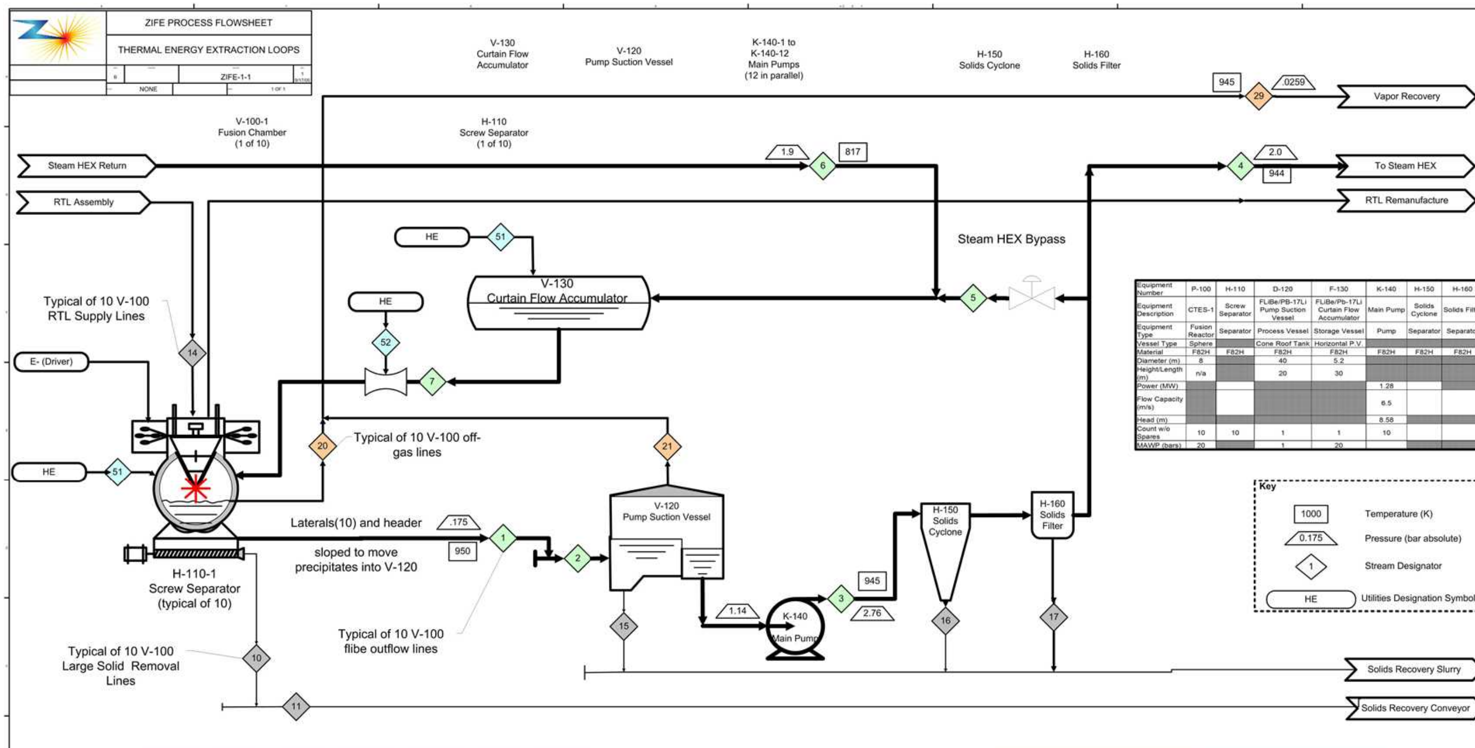
Cast Flibe RTL Manufacturing Plant



TOTAL DIRECT CAPITAL: $94 Million
ELECTRICITY USE: 5 MWe

Process Flow Diagrams

Energy Recovery Loop



Equipment Number	P-100	H-110	D-120	F-130	K-140	H-150	H-160
Equipment Description	CTES-1	Screw Separator	FLiBe/PB-17Li Pump Suction Vessel	FLiBe/Pb-17Li Curtain Flow Accumulator	Main Pump	Solids Cyclone	Solids Filter
Equipment Type	Fusion Reactor	Separator	Process Vessel	Storage Vessel	Pump	Separator	Separator
Vessel Type	Sphere		Cone Roof Tank	Horizontal P.V.			
Material	F82H	F82H	F82H	F82H	F82H	F82H	F82H
Diameter (m)	8		40	5.2			
Height/Length (m)	n/a		20	30			
Power (MW)					1.28		
Flow Capacity (m/s)					6.5		
Head (m)					8.58		
Count w/o Spares	10	10	1	1	10		
MAWP (bars)	20		1	20			

Stream	1	2	3	4	5	6	7	10	11	15	16	17	18	20	21	29	20	23	25
Description	V-100-1 Outflow	Flibe Main Header	Main Pumps Discharge	to Steam HEX	Bypass	from Steam HEX	Curtain Flow	V-100-1 Large Solids	Large Solids Conveyor	V-120 Slurry Outflow	Cyclone Slurry	FLiBe Filtrate	RTL In	V-100-1 Vapor	V-120 Vapor	Vapor Recovery Hdr	V-100-1 He	Eductor He	V-130 He
Pressure (bars)	2	2.0000	2.76	2	1.90	1.90	0.0270	2.76	1.03	1.47	ients must be n	1.47	n/a	0.027	2.000	1.90	n/a	1.90	2.00
Temperature (K)	950	950	950	949	949	800	938	950	950	950	949	949	n/a	950	950	950	950	949	949
Mass Flow FLiBe (kg/s)	1.66E+04	1.66E+05	1.65E+05	8.65E+03	8.65E+03	8.65E+03	4.70E+03	2.04E+02	2.04E+03	1.02E+03	9.20E+02	1.02E+02	4.09E+02	6.92E-12	-	6.92E-11	-	-	-
Mol Rate FLiBe (mol/s)	5.03E+05	5.03E+06	5.03E+06	2.62E+05	2.62E+05	2.62E+05	1.42E+05	6.20E+03	6.20E+04	-	2.79E+04	3.10E+03	1.24E+04	2.10E-10	-	2.10E-09	-	-	-
Mass Flow T2 (kg/s)	1.17E-06	1.17E-05	1.16E-05	6.12E-07	6.12E-07	6.12E-07	3.30E-07	1.44E-08	1.44E-07	7.19E-08	6.47E-08	7.19E-09	-	1.64E-04	-	1.64E-03	-	-	-
Mol Rate T2 (mol/s)	1.94E-04	1.94E-03	1.93E-03	1.02E-04	1.02E-04	1.02E-04	5.50E-05	2.40E-06	2.40E-05	1.20E-05	1.08E-05	1.20E-06	-	2.73E-02	-	2.73E-01	-	-	-
Mass Flow D2 (kg/s)	5.01E-07	5.01E-06	4.98E-06	2.63E-07	2.63E-07	2.63E-07	1.42E-07	6.18E-09	6.18E-08	3.09E-08	2.78E-08	3.09E-09	-	7.05E-05	-	7.05E-04	-	-	-
Mol Rate D2 (mol/s)	1.25E-04	1.25E-03	1.25E-03	6.58E-05	6.58E-05	6.58E-05	3.55E-05	1.55E-06	1.55E-05	7.73E-06	6.95E-06	7.73E-07	-	1.76E-02	-	1.76E-01	-	-	-
Mass Flow He (kg/s)	1.12E-04	1.12E-03	1.11E-03	5.89E-05	5.89E-05	5.89E-05	3.18E-05	1.38E-06	1.38E-05	6.92E-06	6.23E-06	6.92E-07	-	3.28E-03	-	3.28E-02	3.30E-03	1.65E-04	-
Mol Rate He (mol/s)	2.80E-02	2.80E-01	2.79E-01	1.47E-02	1.47E-02	1.47E-02	7.94E-03	3.46E-04	3.46E-03	1.73E-03	1.56E-03	1.73E-04	-	8.20E-01	-	8.20E+00	8.23E-01	4.13E-02	-
Mass Flow Steel (kg/s)	1.87E+00	1.87E+01	9.35E+00	-	-	-	-	1.87E+00	1.87E+01	9.35E+00	8.41E+00	9.35E-01	3.74E+00	-	-	-	-	-	-
Mol Rate Steel (mol/s)	3.35E+01	3.35E+02	1.67E+02	-	-	-	-	3.35E+01	3.35E+02	1.67E+02	1.51E+02	1.67E+01	6.70E+01	-	-	-	-	-	-
Total Mass Rate (kg/s)	**1.66E+04**	**1.66E+05**	**1.65E+05**	**1.65E+05**	**8.65E+03**	**1.56E+05**	**4.70E+03**	**2.05E+02**	**2.05E+03**	**1.02E+03**	**9.20E+02**	**1.02E+02**	**4.09E+02**	**3.52E-03**	**1.66E+04**	**3.52E-02**	**3.30E-03**	**1.65E-04**	-
Total Mol Rate (mol/s)	**5.03E+05**	**5.03E+06**	**5.03E+06**	**5.03E+06**	**2.62E+05**	**4.77E+06**	**1.42E+05**	**6.20E+03**	**6.20E+04**	**1.75E-03**	**2.79E+04**	**3.10E+03**	**1.24E+04**	**8.65E-01**	**5.03E+05**	**8.65E+00**	**8.23E-01**	**4.13E-02**	-

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Conditions at 250 μs

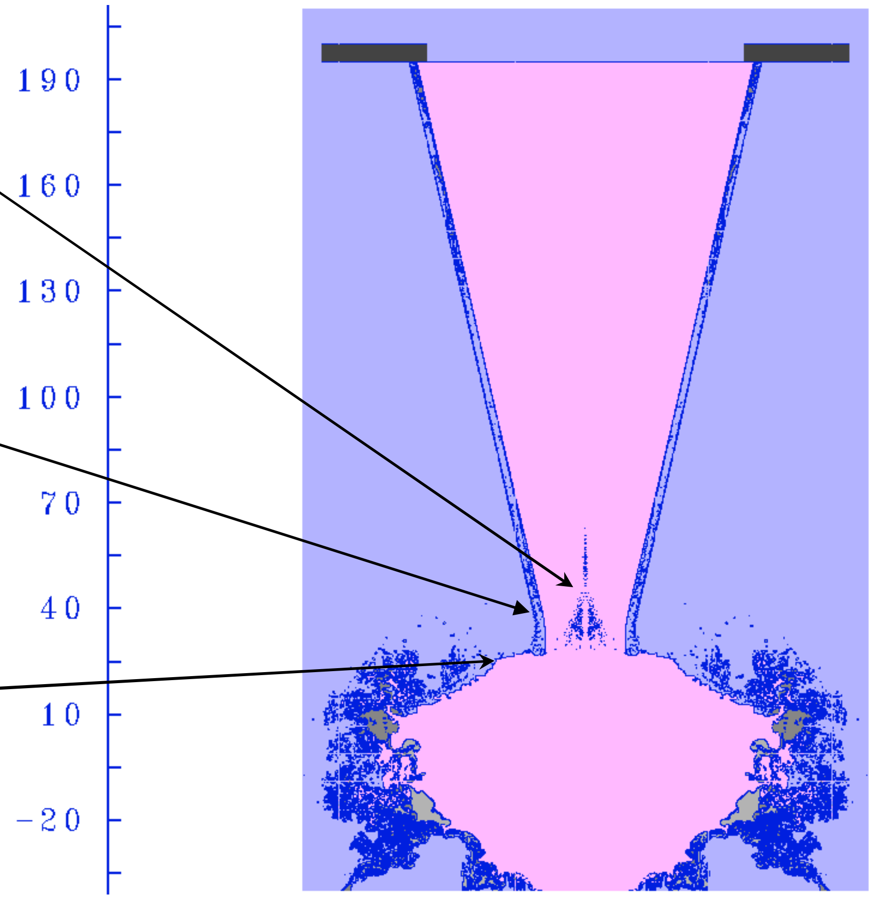
Fractures internal to the flibe (spall) resulting from the radial pressure release converging on the axis

Radial Velocity Pinches RTL closed

Radial velocity = 500 m/s

Strain rate = 2500 /s

Est'd ave Frag size = 6 cm



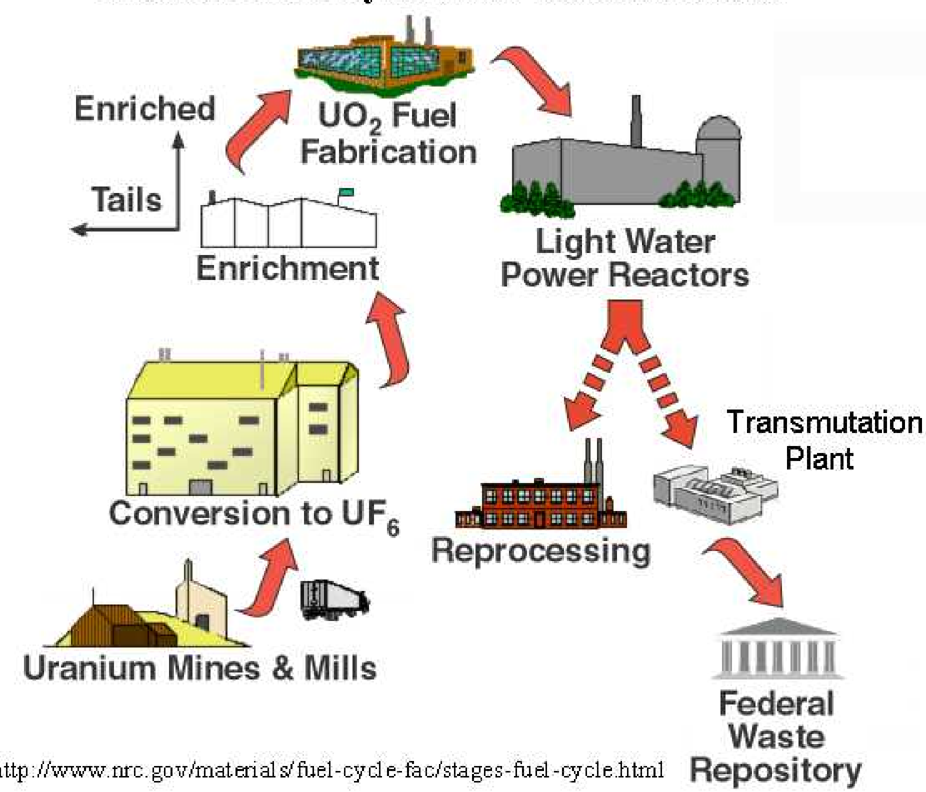
CTH Simulation

Immediate Science Issues to be Addressed

- High Yield Inertial Confinement Fusion in the laboratory
- Increasing energy density and efficiency of pulsed power systems
- Understanding the mitigation of high intensity x-rays and the resulting shrapnel generation
- Material science of FLiBe as an engineered solid material as well as a large volume coolant
- Intermediate applications of fusion neutrons to provide a basis for large scale designs

A Possible Intermediate Fusion Neutron Application

Nuclear Fuel Cycle with Transmutation

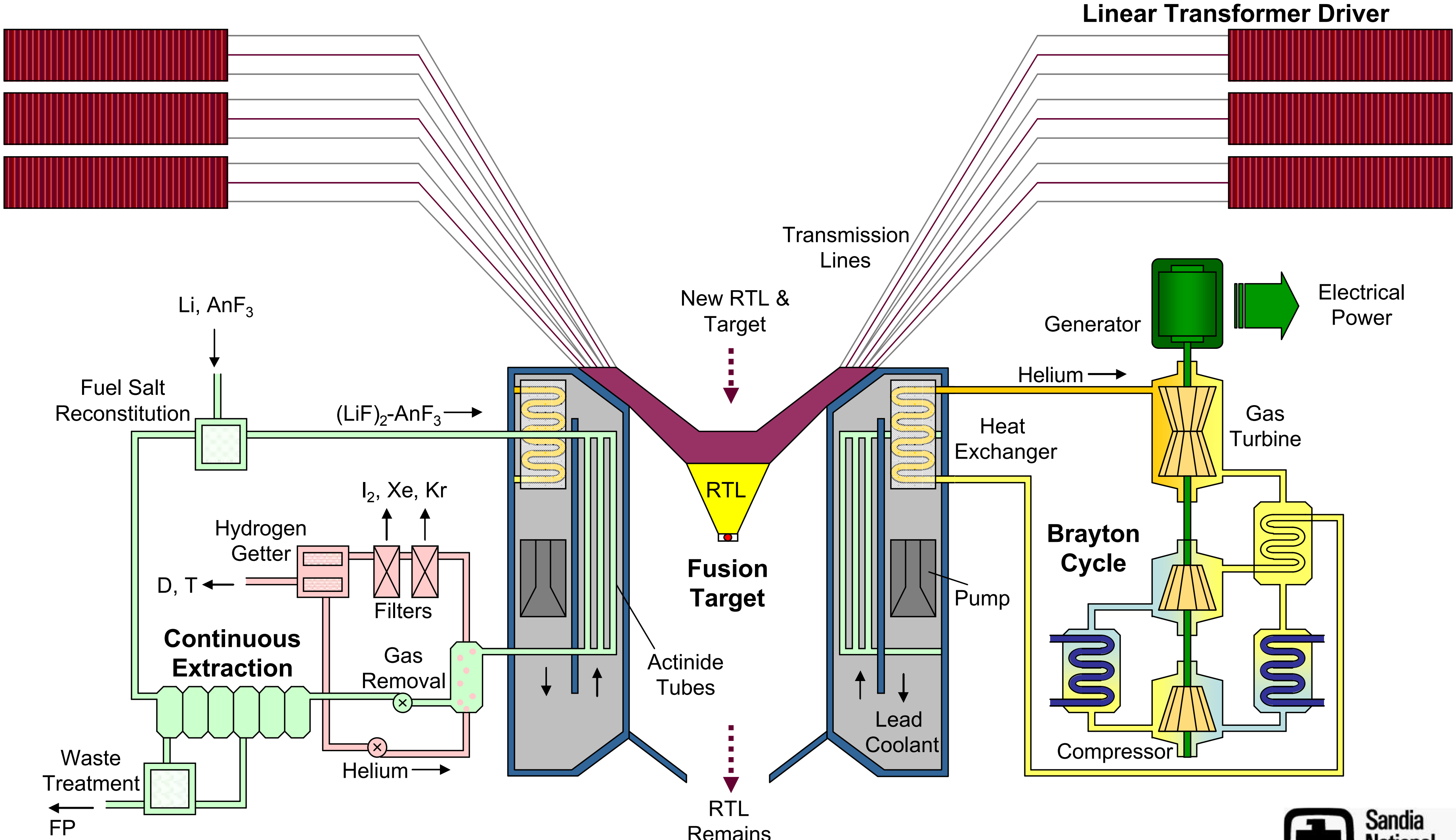


http://www.nrc.gov/materials/fuel-cycle-fac/stages-fuel-cycle.html

Why Use Fusion for Transmutation?

- The transmutation of TRU (Pu, Np, Am, Cm) can drastically decrease the heat load and proliferation risk of waste destined for a repository
- A sub-critical blanket driven by fusion can operate in a "burn only" mode—so it can be more efficient than a fast reactor
- The fusion yield requirements are much lower than those required for fusion energy (30 MW as opposed to 3000 MW)
- 14.7 MeV neutrons can burn up all minor actinides without buildup

In-Zinerator Power Plant Concept: A Fusion-Fission Hybrid



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Transmutation Yield Requirements

- **Full Scale TRU Burner**
  - 20 transmuters required to burn TRU as fast as the current LWR fleet can produce it:

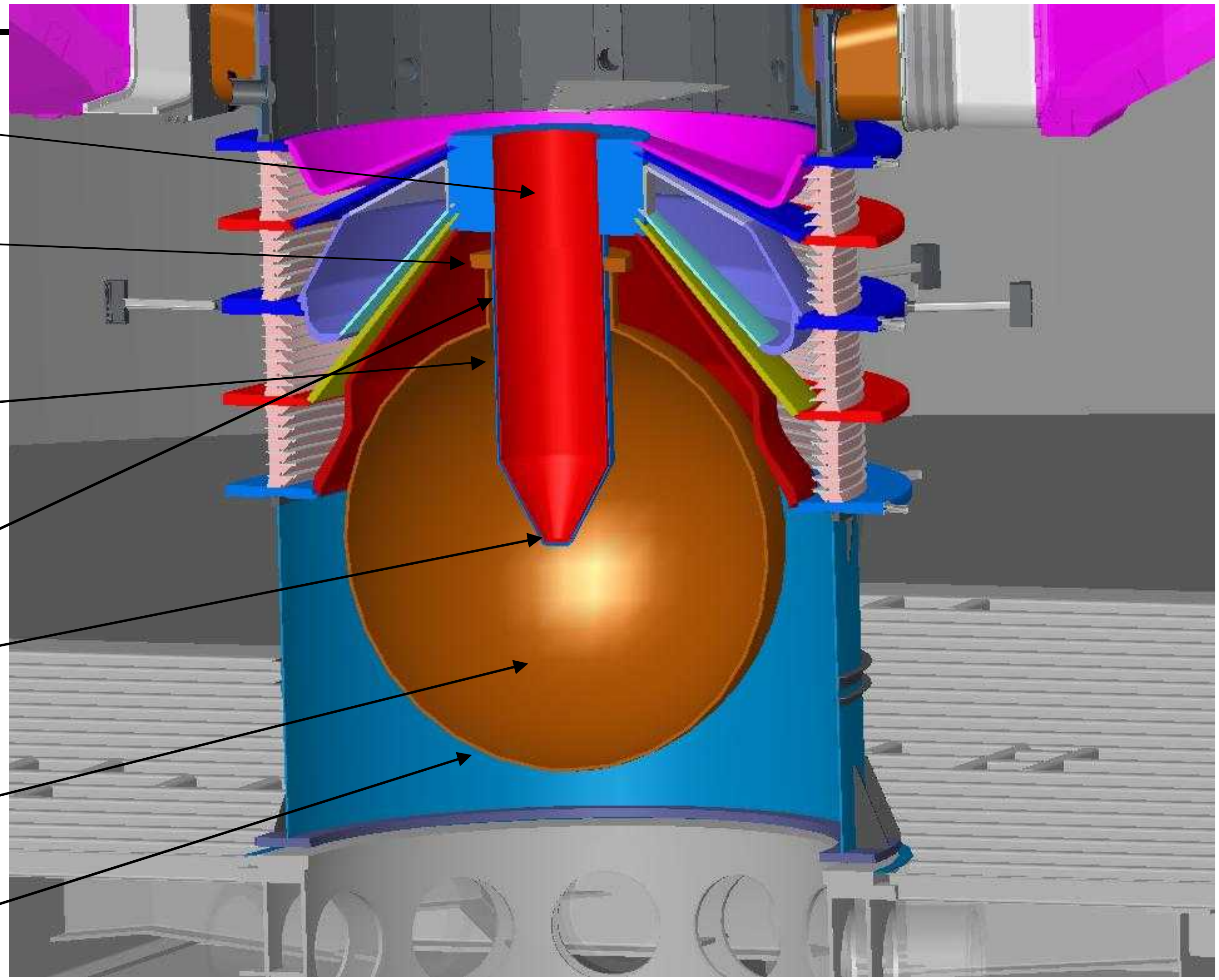
    200 MJ target fired every 10 seconds
- **Full Scale Am/Cm Burner**
  - 2 transmuters required to burn Am/Cm as fast as the current LWR fleet can produce it (assumes Pu/Np burned in LWRs):

    240 MJ target fired every 10 seconds

Z Initiated Power Systems: ZIPS

- Goal: Determine steps to achieve early demonstration of high-energy and rep-rated shots
- Challenges
  - Contain the radioactive gases
  - Survive the blast of x-rays, pressure, and shrapnel
  - Engineer a system that can be rep-rated
- Potential solution for first-step demo
  - Low-pressure gas to absorb x-ray pulse and convert the 100-ns pulse to milliseconds at the wall
  - MITL “snout” to provide standoff
  - Explosive closure to protect permanent MITL
- Goal of 1 shot per hour would enhance ZR utility

Potential Option for Integration with ZR



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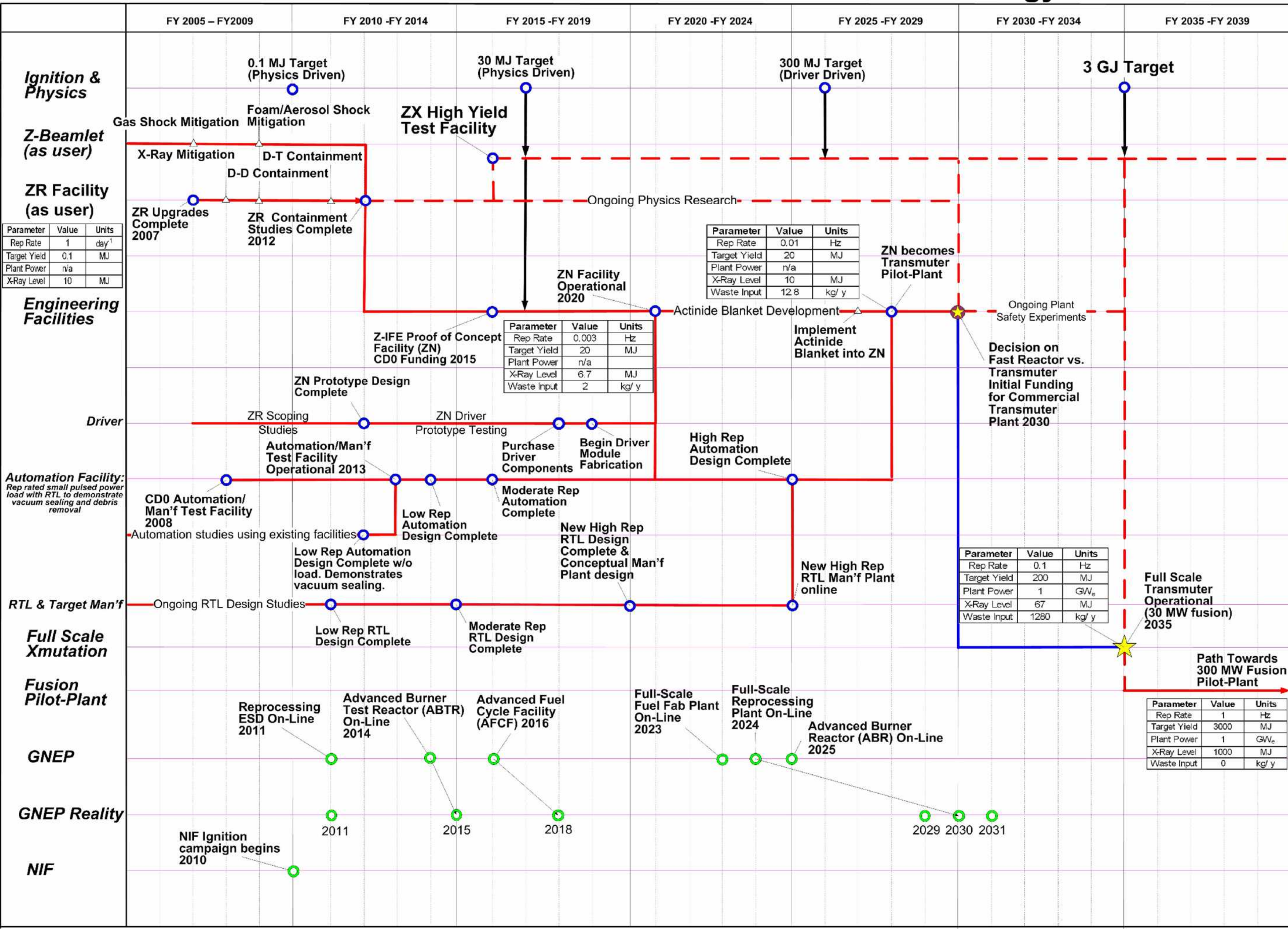
Z-Pinch Transmutation and Inertial Fusion Energy



Parameter	Value	Units
Rep Rate	1	day⁻¹
Target Yield	0.1	MJ
Plant Power	n/a	
X-Ray Level	10	MJ

Parameter	Value	Units
Rep Rate	0.003	Hz
Target Yield	20	MJ
Plant Power	n/a	
X-Ray Level	6.7	MJ
Waste Input	2	kg/ y

Parameter	Value	Units
Rep Rate	0.01	Hz
Target Yield	20	MJ
Plant Power	n/a	
X-Ray Level	10	MJ
Waste Input	12.8	kg/ y

Parameter	Value	Units
Rep Rate	0.1	Hz
Target Yield	200	MJ
Plant Power	1	GW_e
X-Ray Level	67	MJ
Waste Input	1280	kg/ y

Parameter	Value	Units
Rep Rate	1	Hz
Target Yield	3000	MJ
Plant Power	1	GW_e
X-Ray Level	1000	MJ
Waste Input	0	kg/ y

Issues to be Resolved

- ZR should work toward a fusion burn with a yield on the order of 0.1 MJ.
- A pulsed power/fusion energy program required to create the higher yields
  - Transmuter = 200-250 MJ
  - Power plant = 3-30 GJ
- Repetitive neutron pulses
  - Every 1 to 10 seconds depending on the fusion yield
  - Extensive target and mass production capabilities must be developed.
  - A simple and light weight recyclable transmission line (RTL)
  - state-of-the-art automation for placing and removing the RTL
  - Pumping the vessel and driver components to ensure the electric pulse integrity.

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Conclusions

- A conceptual design of a z-pinch driven inertial confinement fusion driven power plant is evolving that is:
  - Potentially economical
  - Minimizes waste streams
  - Utilizes existing materials data bases
  - Capable of containing up to 20 gigajoule yields
  - Heavily dependent on robotic technology in high radiation fields
  - Leverages existing technology when high yield has been achieved