Update on Pu and Actinide Transmutation in Fusion Reactors

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ARIES Project Meeting
University of California, San Diego
Room 584, Engineering Building EBII
Thursday, 2 December 1999

Outline

Progress on Performance Analysis:
- HTGR Type Transmutation Blanket
- Molten Salt Blanket

International Cooperation Activities

HTGR-Type Transmutation Blanket

Solid Blanket Concept

- Pu/Actinide Confined in Graphite/SiC Coated Particles
- Graphite Matrix
- Helium Cooled (Pb-Bi Eutectic Coolant Possible)

Multiple-Region Blanket Management

- Higher Burnup Rate Occurs at the Region Close to Plasma
- Removal of Close-to-Plasma Region When Reaching Desirable Burnup
- Irradiated Regions Moved Toward the Plasma
- Fresh Region Introduced Behind the Irradiated Regions

Studies Completed for the ST-VNS Based Transmutation Reactor

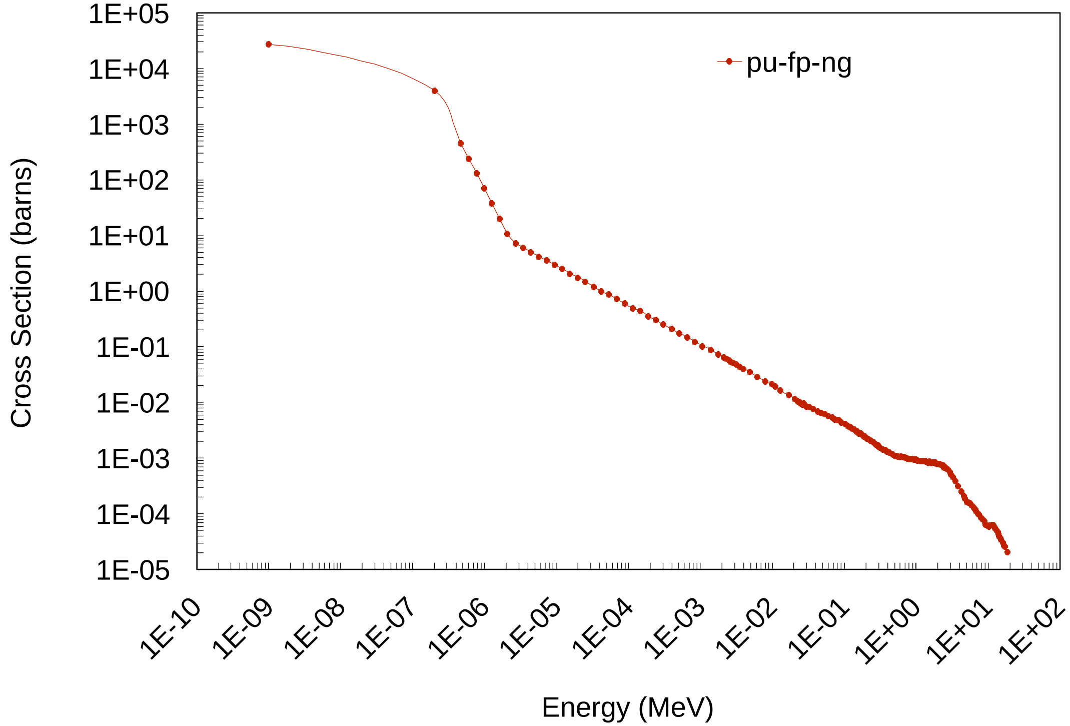
- 40 cm Transmutation Blanket Divided into 4 Regions (10 cm Each)
- Finished Calculations up to Replacement of 4 Regions (A Complete Cycle)
- The First Replacement Results Presented at SOFE99
- Remaining Results Being Analyzed

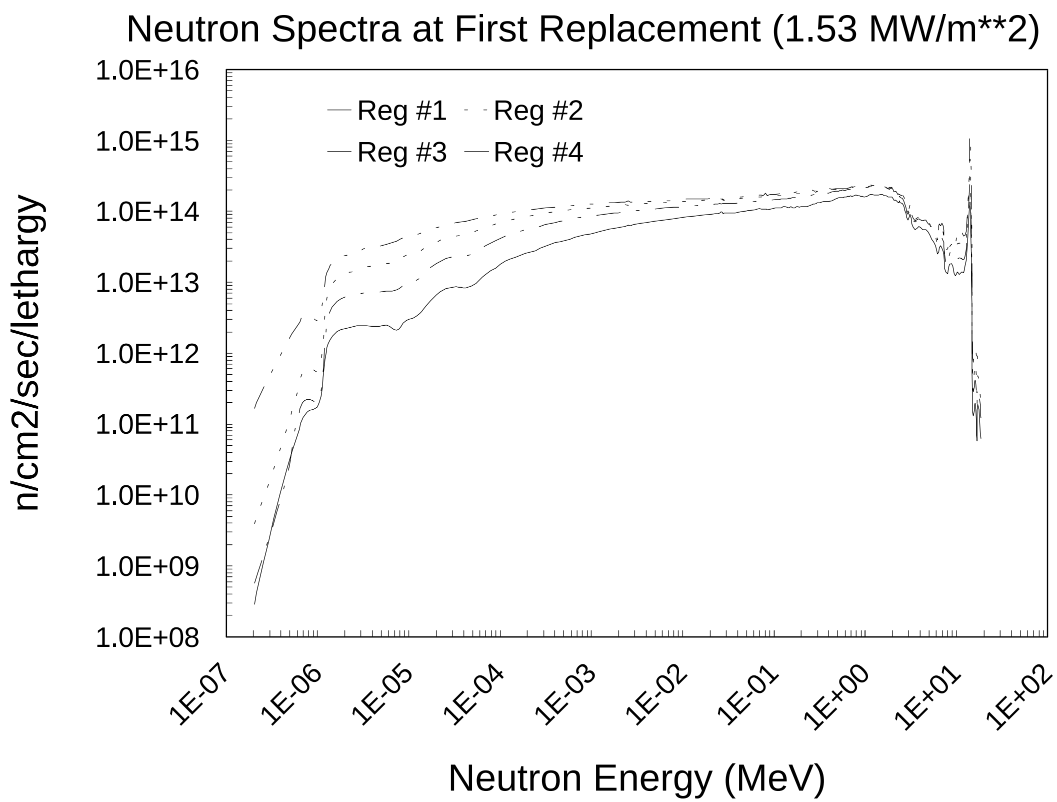
Table 1. Neutronics model of the ST-based plutonium burning reactor.

Zone	Thickness (cm)	Material Composition
Center Post	37	70%Cu+30%H_2O
Structure	2	HT-9(Ferritic Steel)
Be-limiter	1	Be
Plasma	200	Void
Scrape-off	15	Void
Be-limiter	1	Be
Structure	2	HT-9
Blanket-1	10	60%C(0.075g/cc Pu*)+40%He
Blanket-2	10	60%C(0.15g/cc Pu)+40%He
Blanket-3	10	60%C(0.225g/cc Pu)+40%He
Blanket-4	10	60%C(0.3g/cc Pu)+40%He
T Breeding	20	5%HT-9+57%$LiAlO_2$+38%He
Reflector	40	90%C+10%He
Shield	20	SS316

*Initial composition of weapons plutonium: 93%Pu239, 5.7%Pu240, 0.28%Pu241, and 0.68%Pu242.

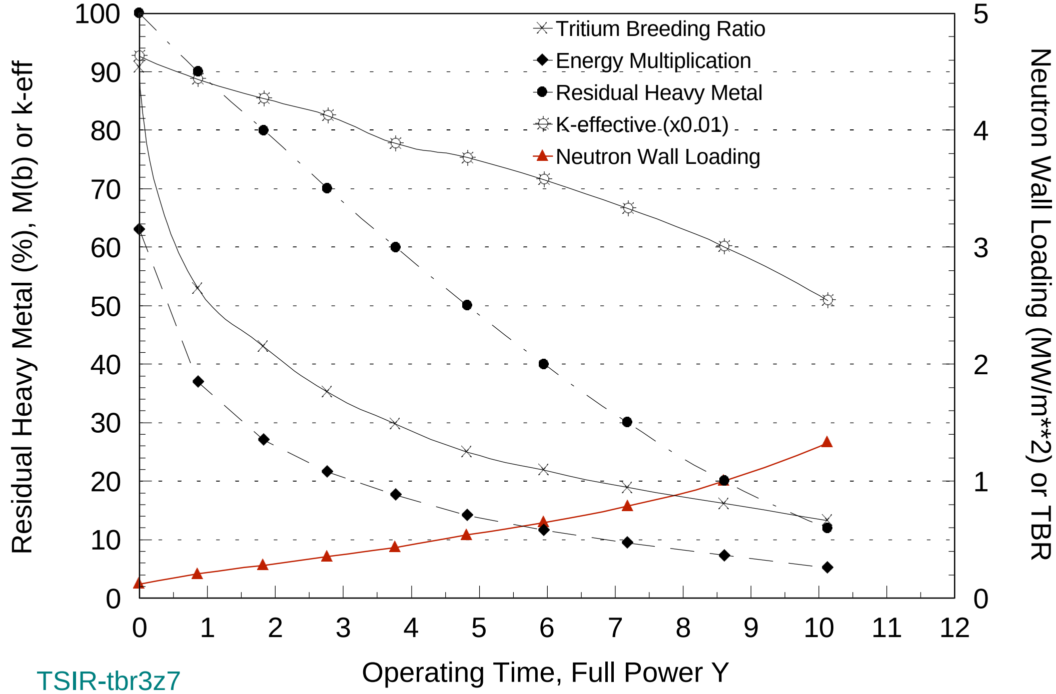
Fission Products Absorption Cross Section





Neutron Spectra at First Replacement (1.53 MW/m**2)
Reg #1
Reg #2
Reg #3
Reg #4
1.0E+16
1.0E+15
1.0E+14
1.0E+13
1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
n/cm2/sec/lethargy
1E-07
1E-06
1E-05
1E-04
1E-03
1E-02
1E-01
1E+00
1E+01
1E+02
Neutron Energy (MeV)

Plutonium Transmutation: [Initial k(eff)=0.926]
(STVNS: R=1.4 m; <30 W/cc region average)



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Plutonium Transmutation: [Initial k(eff)=0.926]
(STVNS: R=1.4 m; <100 W/cc region average)

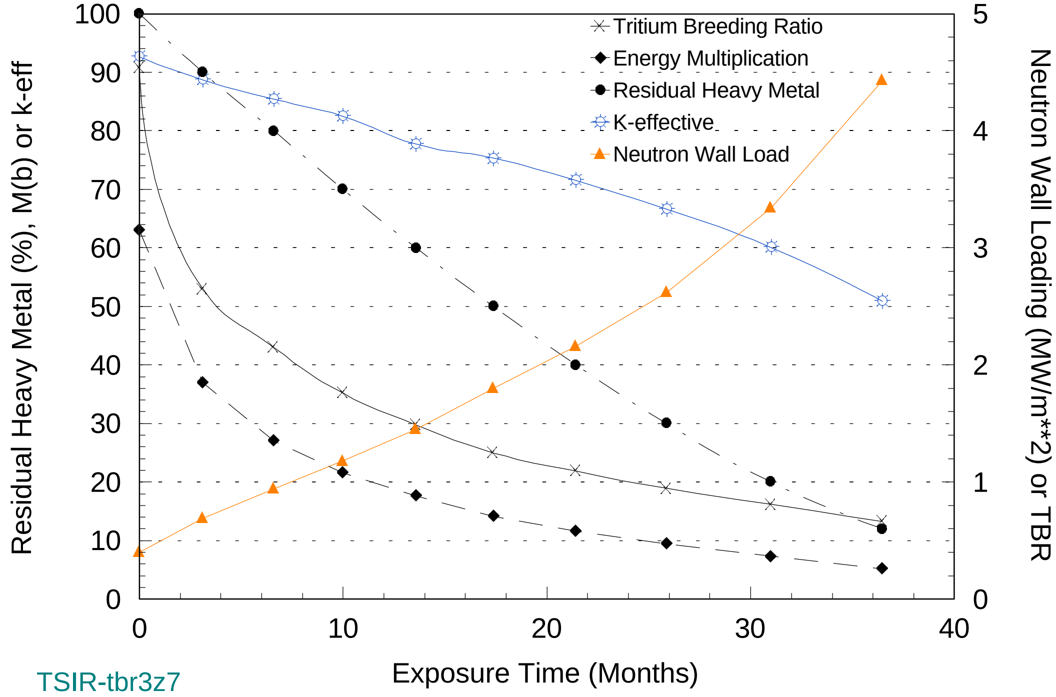


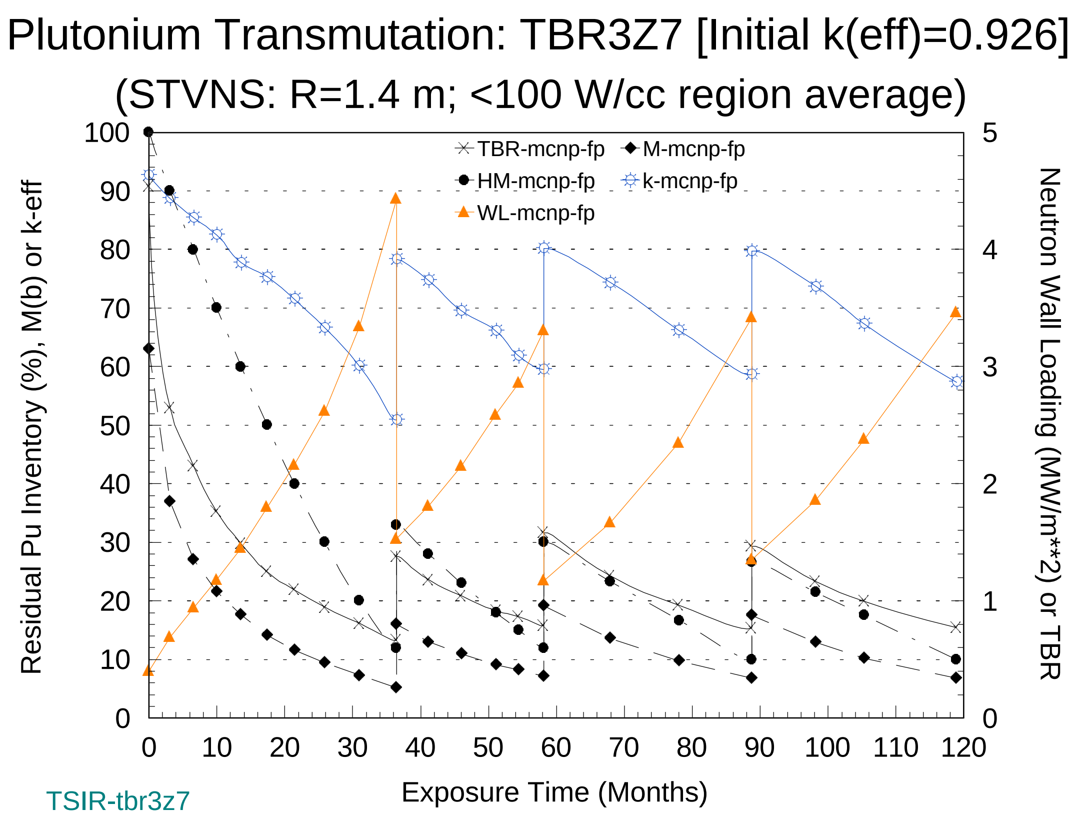
Table 2. Neutronics Parameters at Several Burn-up Stages in the PLUTO Blanket System (Blanket-1 Region)

Neutronics Parameters	Heavy Metal Burn-up Stage (1% ~ 10,000 MWD/MTHM)				
	10%	30%	50%	70%	88%
First Wall Integrated Fluence (MW-y/m**2)	0.14	0.68	1.6	3.1	6.2
Estimated DPA in HT-9	1.4	6.8	16	31	62
Fuel particle Fast Neutron Fluence+ $E_n \geq 0.1$ MeV (n/cm2)	7e+21 (1.4e+22)	2.4e+22 (4.8e+22)	4.4e+22 (8.8e+22)	7e+22 (1.4e+23)	1.1e+23 (2.2e+23)
Neutron Wall Loading (MW/m2)					
• **100 W/cc Power Density Averaged Over Cycle** (Initial – Discharge Stage)	0.55 (0.40-0.69)	0.8 (0.40–0.94)	1.1 (0.40-1.45)	1.5 (0.40-2.16)	2 (0.40-4.40)
• **30 W/cc Power Density Averaged Over Cycle** (Initial – Discharge Stage)	0.165 (0.133-0.23)	0.24 (0.133-0.313)	0.33 (0.133-0.483)	0.45 (0.133-0.72)	0.6 (0.133-1.47)
• **10 W/cc Power Density Averaged Over Cycle** (Initial – Discharge Stage)	0.055 (0.04-0.069)	0.08 (0.040-0.094)	0.11 (0.040-0.145)	0.15 (0.04-0.022)	0.2 (0.04-0.044)

+Region (10 cm) averaged value. The values given in the parentheses are the maximum.

Plutonium/Actinide Inventory at First Discharge Cycle
(ST-VNS Based Pu/Actinide Transmutation Reactor)

Parameter	Pu/Actinide Loading Region				
	#1	#2	#3	#4	Average
Initial Heavy Metal (Pu) Loading, MT	0.775	1.55	2.33	3.1	(Blanket) 7.75
Residual Inventory at Discharge, %					
Fission Products	88	67	48	28	48
Heavy Metal	12	33	52	72	52
(Pu)	(5.3)	(31)	(51)	(71)	(50)
Pu Isotopic Composition, %					
Pu-239	21.2	29.0	51.1	74.1	61.0
Pu-240	<0.1	36.9	35.9	22.0	27.8
Pu-241	32.0	27.2	11.3	3.6	9.2
Pu-242	46.8	6.9	1.7	0.3	2.0

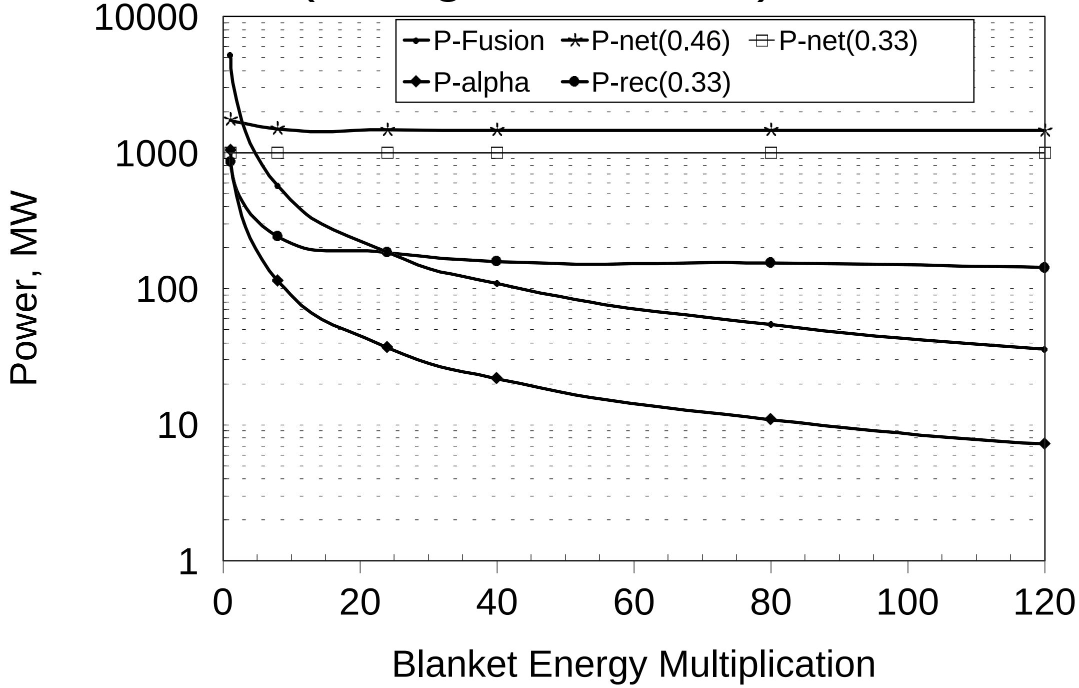

Plutonium Transmutation: TBR3Z7 [Initial k(eff)=0.926]
(STVNS: R=1.4 m; <100 W/cc region average)
TBR-mcnp-fp
M-mcnp-fp
HM-mcnp-fp
k-mcnp-fp
WL-mcnp-fp
Residual Pu Inventory (%), M(b) or k-eff
Neutron Wall Loading (MW/m**2) or TBR
Exposure Time (Months)
0
10
20
30
40
50
60
70
80
90
100
110
120
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
TSIR-tbr3z7

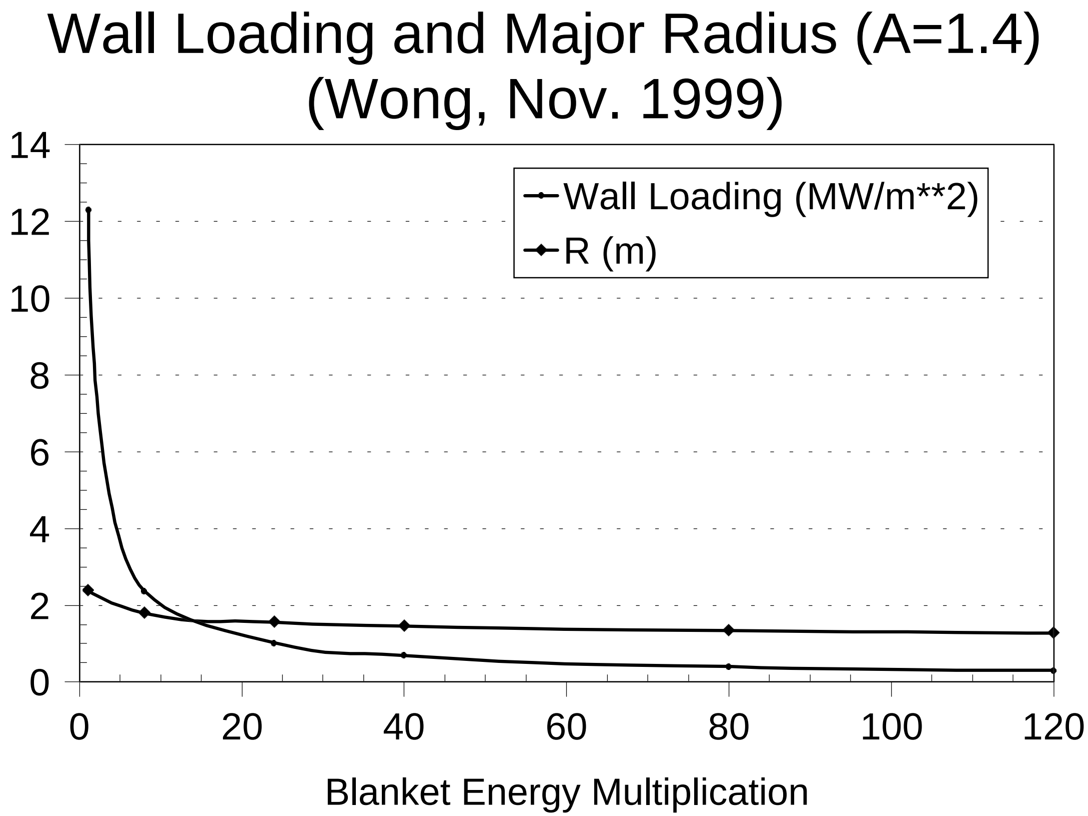
Systems Analysis

Preliminary Systems Analysis was performed
(C. Wong, GA)

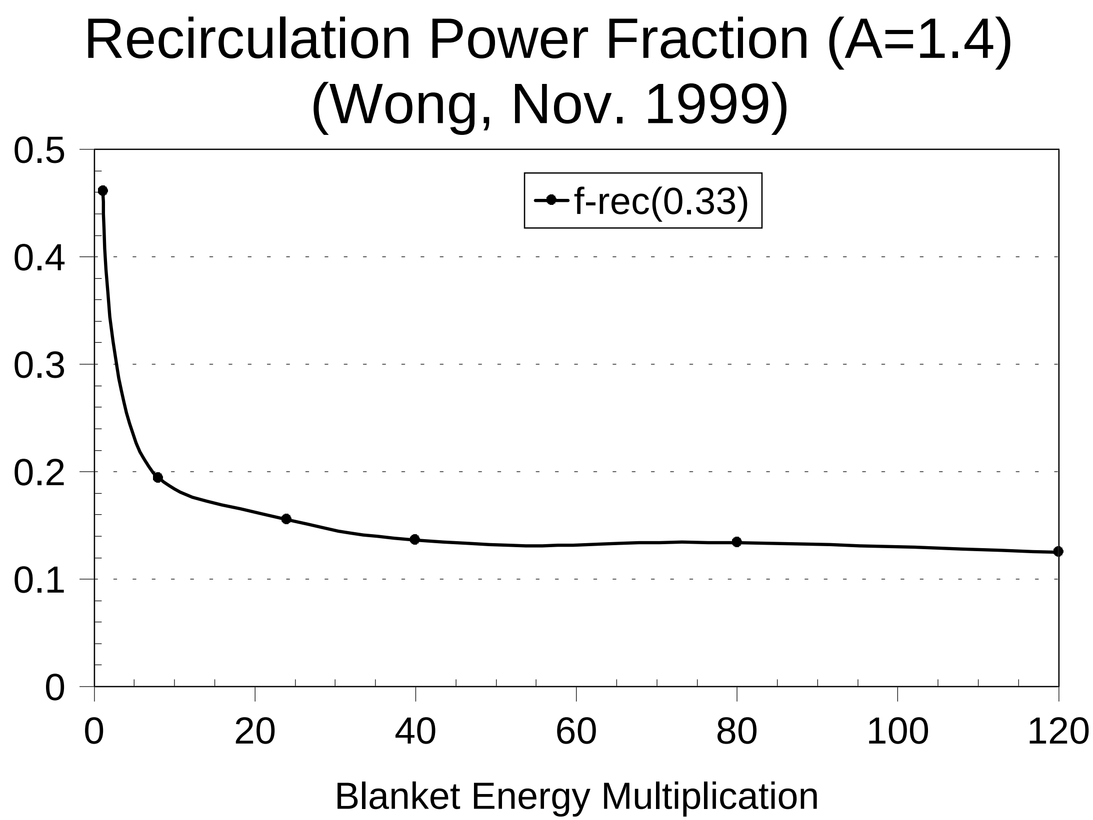
- As Function of Energy Multiplication, M(B)
- A=1.4 ST VNS Based Power Plant
- Thermal Efficiency = 33%
- 1000 MWe Net Output
- Comparing COE, Fusion Power, Major Radius, Wall Loading, and Actinide Consumption Rate

Power Balance (A=1.4)
(Wong, Nov. 1999)

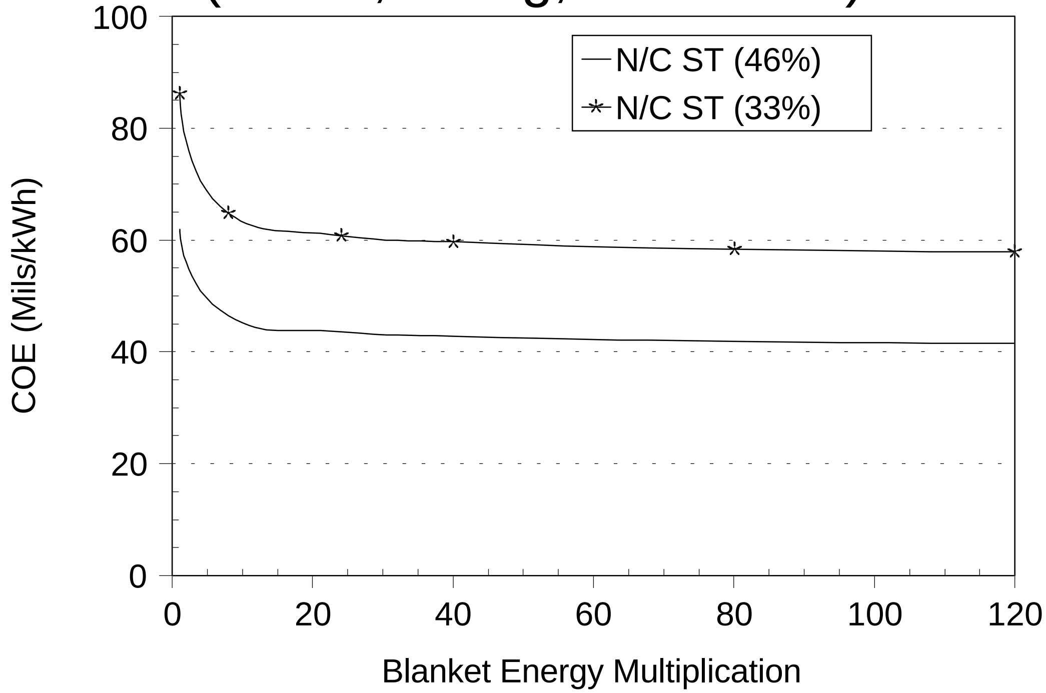


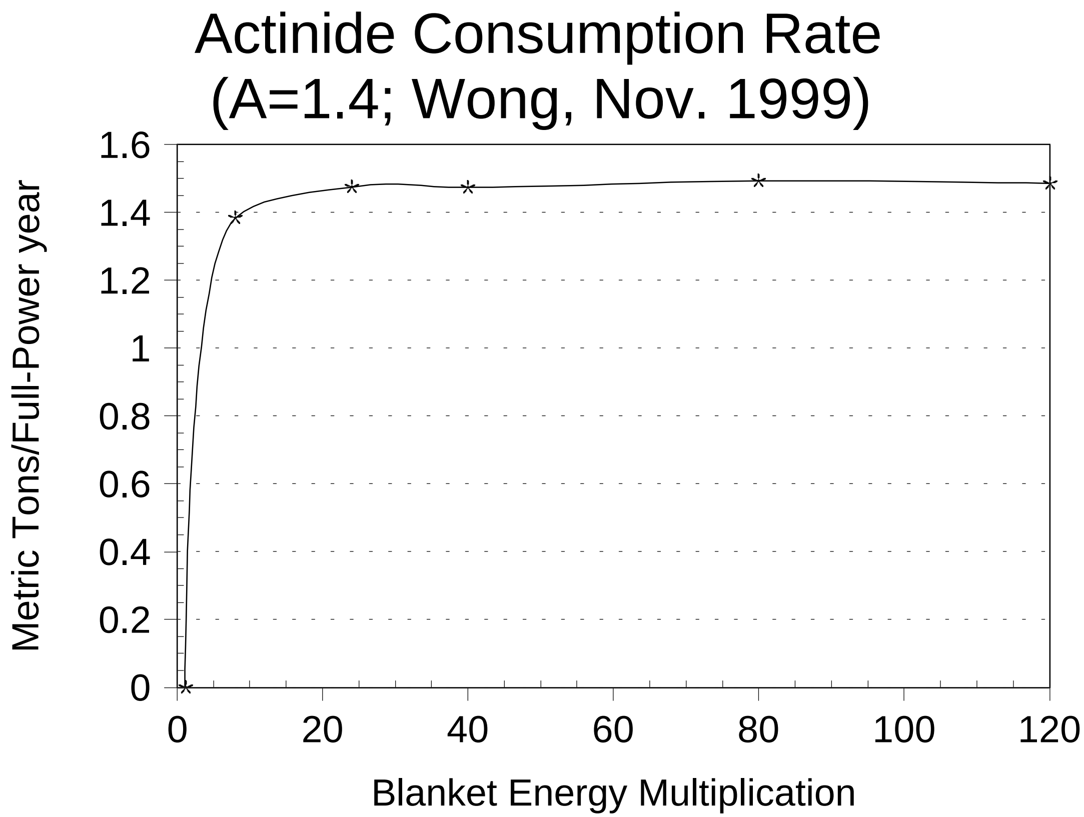


Wall Loading and Major Radius (A=1.4)
(Wong, Nov. 1999)
Wall Loading (MW/m**2)
R (m)
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
Blanket Energy Multiplication


Recirculation Power Fraction (A=1.4)
(Wong, Nov. 1999)
f-rec(0.33)
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
Blanket Energy Multiplication

Cost of Electricity Normalized to 1 GWe Net
(A=1.4; Wong, Nov. 1999)





Actinide Consumption Rate
(A=1.4; Wong, Nov. 1999)
Metric Tons/Full-Power year
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
Blanket Energy Multiplication

Conclusions

- Cost of Electricity May Not Improve Beyond Blanket Energy Multiplication ~15
- A 30% Lower COE is Obtainable in a Transmutation Plant
- ~20 ST-VNS Based Transmutation Plants Will Be Needed to Destroy 870 Tons of Pu/Actinides from the LWR Spent Fuel in the U.S.:
  - 40 Years at 75% Availability
  - 1 – 1.4 GWe Net Output Each
  - COE = $0.04 – 0.06/kWh
- Pu/Actinide Inventory Crucial to Waste Reduction Factor
  - 99% Reduction:
- Solid Blanket without Reprocessing Not Acceptable
- In Plant Pu/Actinide Inventory < 8.7 Tons

Molten Salt Blanket Concept

Molten Salt Blanket Being Investigated for the IFE Based Transmutation Reactor

- Simple Geometry and Blanket Configuration

- Initial, Peak, and Equilibrium Performance

- Energy Balance

Initial Investigation Assumes Self-Cooled FliBe Molten Salt with 0.5 Molar% Pu/Actinide Fluoride

Neutronics Model: zone dimension and material compositions

Zone No. (i) /Name	Radius (cm) R(i) – R(i+1)	Thickness (cm)	Material Composition
0/Cavity	0 - 200	200	Void
1/Liquid Wall	200 - 201	1	Flibe*
2/Metalic Wall	201 – 201.3	0.3	SS316 (50%)
3/Graphite	201.3 – 202.3	1	Graphite
4/Transmutation	**202.3 – 217.3**	**15**	**Flibe** (0.5 molar % Pu+MA)**
5/Transmutation	**217.3 – 232.3**	**15**	**Flibe** (0.5 molar % Pu+MA)**
6/Transmutation	**232.3 – 247.3**	**15**	**Flibe** (0.5 molar % Pu+MA)**
7/Transmutation	**247.3 – 262.3**	**15**	**Flibe** (0.5 molar % Pu+MA)**
8/Reflector	262.3 – 282.3	20	Graphite
9/Back Structure	282.3 – 287.3	5	SS316 (50%)

*0.1% Li-6 in lithium. **0.6% Li-6 in lithium.

Flibe density: 8.5156e+22 atoms/cc (2 g/cc).

Pu+MA in Flibe: 1.87e+20 atoms/cc (0.5 molar % in flibe) (0.074 g/cc).

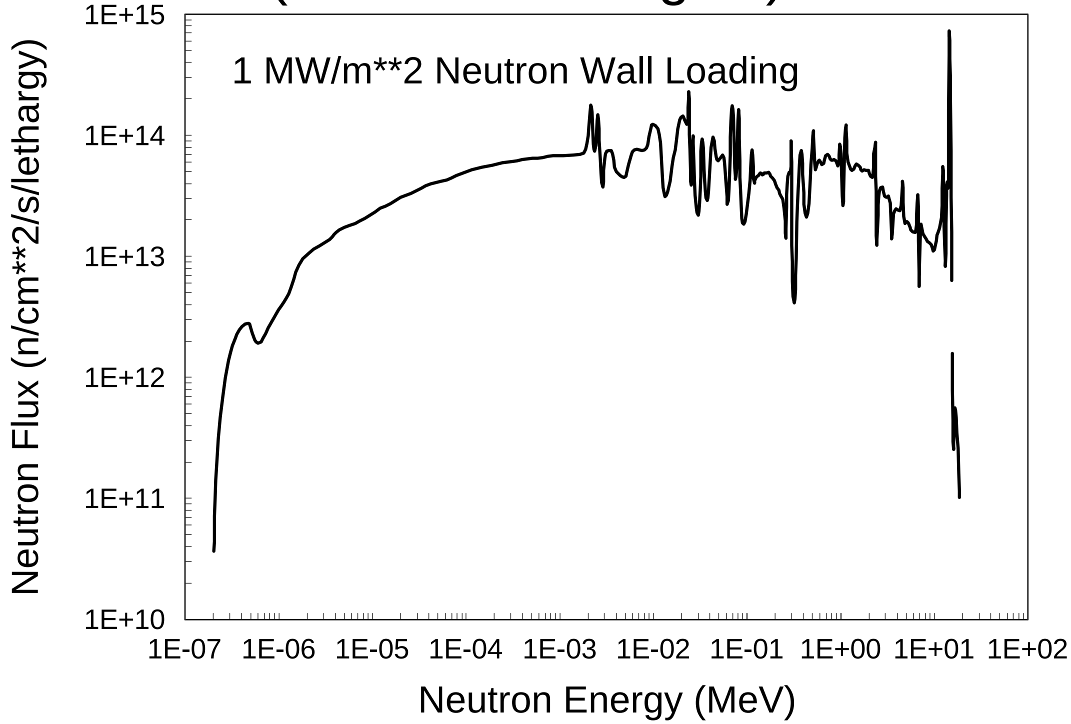
Total volume of the transmutation zone: 4xPi*(R8**3-R4**3)/3 = 4.09e+07 cc.

Total blanket flibe inventory: 81.7 MT.

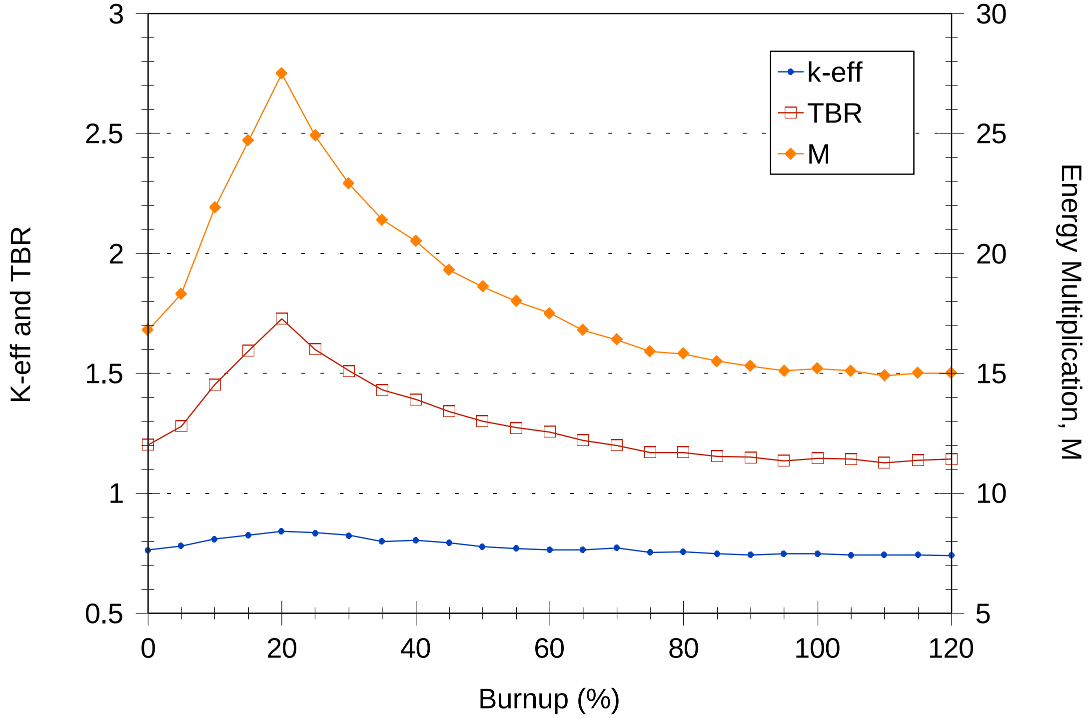
Total blanket Pu/MA inventory: 3.04 MT.

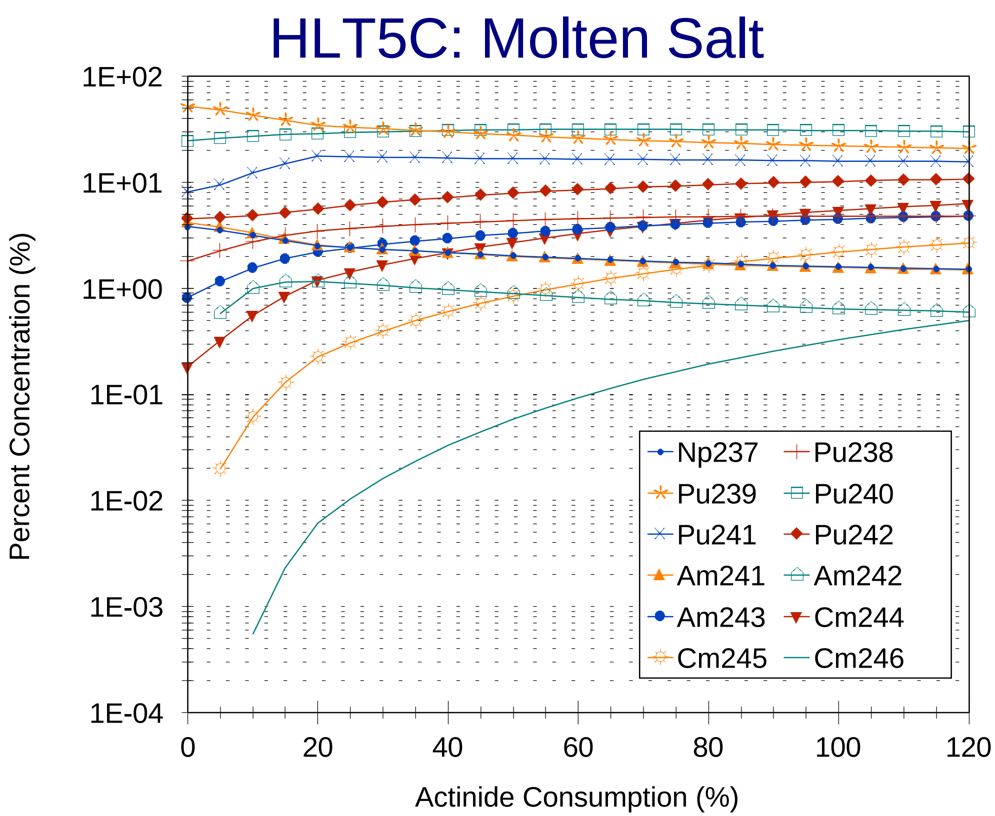
First wall surface area: 4*Pi*R1**2=50.3 m**2.

Neutron Spectra In the Molten Salt Zone (First 15 cm Region)



HLT5C-Performance





HLT5C: Molten Salt
Percent Concentration (%)
1E+02
1E+01
1E+00
1E-01
1E-02
1E-03
1E-04
0
20
40
60
80
100
120
Actinide Consumption (%)
Np237
Pu238
Pu239
Pu240
Pu241
Pu242
Am241
Am242
Am243
Cm244
Cm245
Cm246

Nuclear Performance: Molten Salt Blanket
(IFE Transmutation Reactor: Chamber Radius: 2 m)

Nuclear Parameters	Fusion Power (MW)			
	30	60	120	180
Neutron Wall Loading (MW/m2)**	**0.5**	**1**	**2**	**3**
Initial Operation: M(B)=17				
Thermal Power, MW	408	816	1630	2450
Ave. Blanket Power Density, W/cc	**10**	**20**	**40**	**60**
FPY Actinide Consumption, MT*	**0.18**	**0.35**	**0.71**	**1.06**
***(Percent Blanket Inventory/FPY)**	**(5.9%)**	**(12%)**	**(23%)**	**(35%)**
Peak Operation: M(B)=28				
Thermal Power, MW	670	1340	2670	4030
Ave. Blanket Power Density, W/cc	**16**	**33**	**66**	**98**
FPY Actinide Consumption, MT*	**0.29**	**0.58**	**1.16**	**1.75**
	(9.5%)	**(19%)**	**(38%)**	**(58%)**
Equilibrium Operation: M(B)=15				
Thermal Power, MW	360	720	1440	2160
Ave. Blanket Power Density, W/cc	**8.8**	**18**	**35**	**53**
FPY Actinide Consumption, MT*	**0.16**	**0.31**	**0.62**	**0.94**
	(5%)	**(10%)**	**(20%)**	**(30%)**

Nuclear Performance of Transmutation Blanket

Without Removal of Fission Products and Replacement of Actinides

(Molten Salt Blanket in IFE Configuration)

Performance Parameter	Actinide Burnpup in the Blanket		
	0%	**5%**	**10%**
K-eff	**0.763**	**0.753**	**0.705**
M	**17**	**16**	**13**
TBR	**1.20**	**1.16**	**1.04**

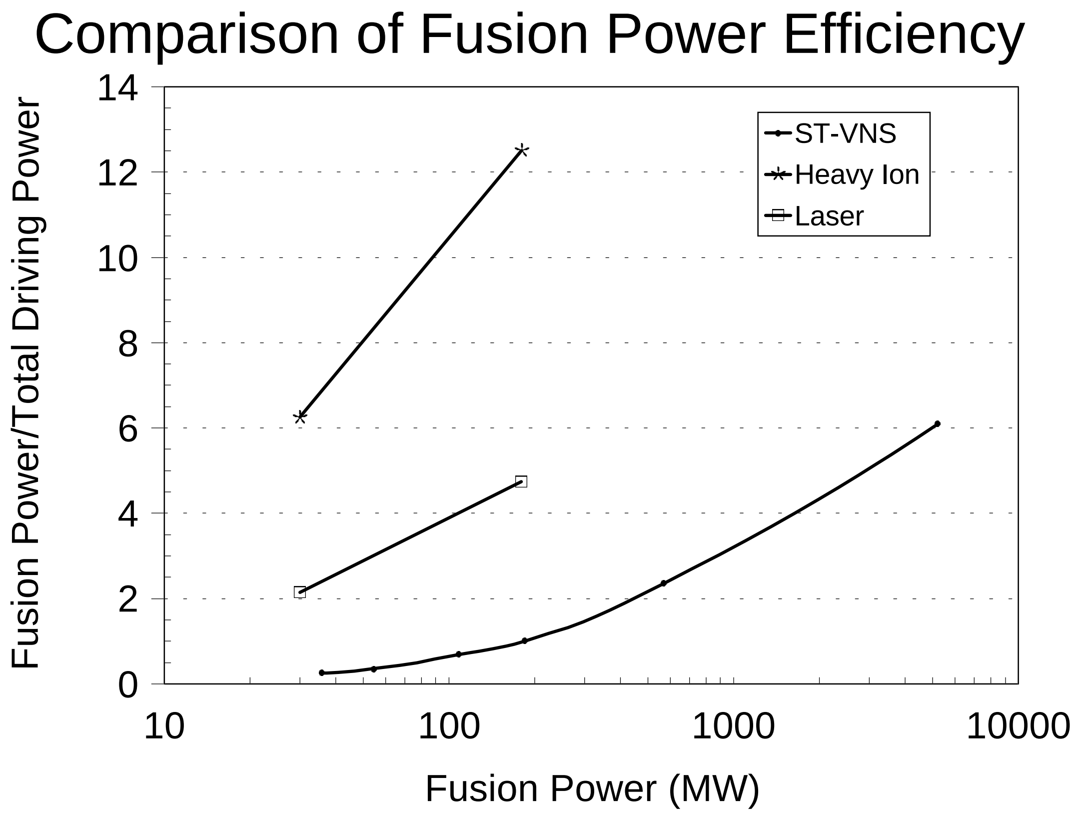
- Performance of a Transmutation Blanket can be Significantly Reduced due to Accumulation of Fission Products.

- Tolerance Level of Fission Products is to be Determined by the Adequacy of Tritium Breeding Ratio in the Blanket.

- For the IFE Transmutation Reactor, a 5 to 10% Fission Products Level May be Allowed.

IFE Driver Efficiency
(Ralph Moir, Nov. 1999)

IFE Driver Type	Heavy Ion		Laser	
Fusion Power, MW	30	180	30	180
E_d, MJ	1.2	3.6	0.7	1.9
Gain	25	50	42	95
Yield, MJ	30	180	30	180
Efficiency	25%	25%	5%	5%
Pulse Rate, Hz	1	1	1	1
Driver Power, MW	4.8	14.4	14	38
Fusion Power/Driver Power	6.25	12.5	2.14	4.74


Comparison of Fusion Power Efficiency
Fusion Power/Total Driving Power
Fusion Power (MW)
ST-VNS
Heavy Ion
Laser
0
2
4
6
8
10
12
14
10
100
1000
10000

IFE Attractive for Actinide Transmutation

- Simple Geometry
- Blanket Change-out Relatively Easy
- Higher Fusion Power Efficiency at Low Fusion Power

(Fusion Power: 30 to 180 MW):

Ratio of Fusion Power to Driving Power

- Heavy-Ion: 6 to 12
- Laser: 2 to 5
- ST-VNS: 0.25 to 1

International Cooperation Activities on Fusion Based Transmutation Study - As of November 1999

US/Russia:
- Russian Team Preparing the ISTC Proposal
- US/Russia Workshop Planned for FY2000

US/Japan:
- Discussed Concepts at NIFS and JAERI/Naka
- JAERI/Naka Interest in Studying the Subject
- US/Japan Benchmark Study?