SUB-CRITICAL TRANSMUTATION REACTORS WITH TOKAMAK FUSION NEUTRON SOURCES

W. M. Stacey[1], J. Mandrekas[1] and E. A. Hoffman[2]
C. de Oliveira[1], J. Lackey[1], D. Tedder1 & Student Design Projects[1]

[1]**Fusion Research Center**
Georgia Institute of Technolog
Atlanta, GA 30332, USA

[2]**Nuclear Engineering Div.**
Argonne National Lab.
Argonne, IL 60439, USA

- **A SERIES OF DESIGNS HAVE BEEN DEVELOPED FOR SUB-CRITICAL REACTORS, DRIVEN BY TOKAMAK D-T NEUTRON SOURCES, FOR THE TRANSMUTATION OF SPENT NUCLEAR FUEL**

- **EMPHASIS IS ON INTERMEDIATE-TERM (2040) APPLICATION**

- **REACTOR DESIGNS ARE BASED ON NUCLEAR, SEPARATION AND FUELS TECHNOLOGY UNDER DEVELOPMENT IN DOE GEN-IV, AFCI AND NGNP PROGRAMS**

- **TOKAMAK NEUTRON SOURCE DESIGN IS BASED ON ITER PHYSICS AND TECHNOLOGY DESIGN BASES**

INTRODUCTION

- AT THE PRESENT LEVEL OF NUCLEAR POWER PRODUCTION IN USA, A NEW YUCCA MOUNTAIN HIGH LEVEL WASTE REPOSITORY (HLWR) WILL BE NEEDED EVERY 30 YEARS.

- SUBSTANTIAL R&D ACTIVITY SINCE EARLY 1990s DEVOTED TO CLOSING THE NUCLEAR FUEL CYCLE BY TRANSMUTATION OF SPENT NUCLEAR FUEL (SNF), WITH OBJECTIVE OF REDUCING HLWR REQUIREMENTS.

- POTENTIAL ADVANTAGES IDENTIFIED FOR SUB-CRITICAL TRANSMUTATION REACTORS WITH NEUTRON SOURCES. MANY STUDIES OF ACCELERATOR-SPALLATION NEUTRON SOURCES (ATW), VERY FEW OF FUSION NEUTRON SOURCES.

- SNF SEPARATIONS TECHNOLOGY PACING--CRITICAL AND ATW SUB-CRITICAL TRANSMUTATION REACTORS COULD BE ONLINE BY 2030.

- A FUSION TRANSMUTATION REACTOR COULD BE DESIGNED ON THE BASIS OF 1) ADAPTATION OF NUCLEAR & SEPARATIONS TECHNOLOGY BEING DEVELOPED IN USDOE GEN-IV, AFCI AND NGNP PROGRAMS AND 2) ITER DESIGN BASIS PHYSICS AND TECHNOLOGY. OPERATION OF ITER (OR SIMILAR FACILITY) AND COMPONENT TEST FACILITIES NEEDED FOR ACHIEVING HIGH (50%) AVAILABILITY ARE PACING—A FUSION-DRIVEN SUB-CRITICAL TRANSMUTATION REACTOR COULD BE ONLINE BY 2040.

SUB-CRITICAL REACTOR DESIGNS

COMMON OBJECTIVES--- $k_{eff} \leq 0.95$, LWR SUPPORT RATIO ≥ 3

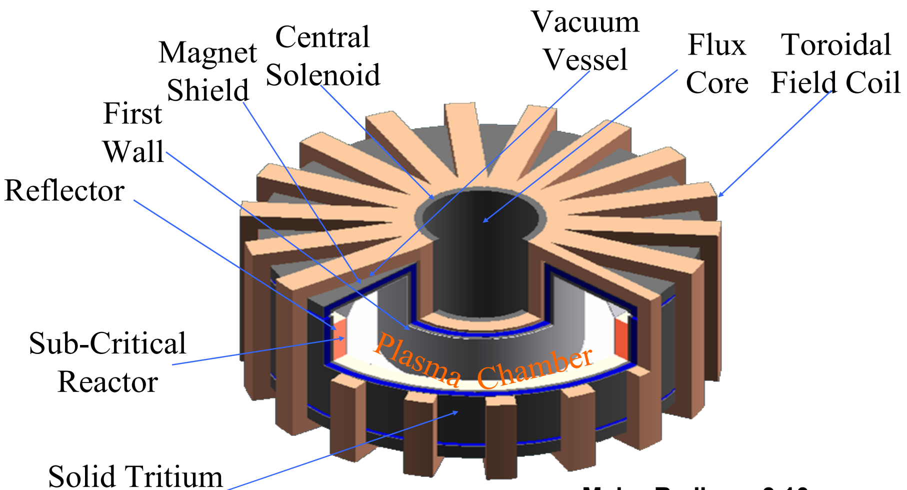
FTWR

- **---ANL METAL FUEL, LIQUID METAL COOLED FAST REACTOR DESIGN ADAPTED TO TRU-ZR FUEL & LIPB COOLANT**
- **---REPEATED PYRO PROCESSING & RECYCLING » 99% BURNUP**
- **---VARIANTS**
  - **FTWR—ITER PHYSICS, LN_2 COOLED CU MAGNETS, $Q_E = 1$**
  - **FTWR-SC---ITER PHYSICS, SC MAGNETS, $Q_E > 1$**
  - **FTWR-AT---AT PHYSICS, SC MAGNETS, $Q_E > 1$**

GCFTR

- **---HE COOLED FAST REACTOR**
- **---NGNP COATED PARTICLE FUEL ADAPTED TO TRU-ZR**
- **--- ≥ 90% BURNUP W/O REPROCESS COATED PARTICLE FUEL**
- **---ITER PHYSICS, SC MAGNETS, $Q_E > 1$**

FTWR Schematic



- **Major Radius – 3.10 m**
- **Minor Radius – 0.89 m**
- **Magnet Radius – 1.81 m**

Tokamak Fusion Transmutation of Waste Reactor

- ANNULAR REACTOR LOCATED OUTBOARD OF PLASMA CHAMBER
- REFLECTOR SURROUNDS PLASMA CHAMBER-REACTOR
- SHIELD SURROUNDS REFLECTOR INSIDE TF COILS

Reference Materials Composition of FTWR and GCFTR

Component	**FTWR**	**GCFTR**
Reactor		
Fuel	TRU-Zr metal in Zr matrix	TRU TRISO/SiC matrix (option BISO/Zirc-4 matrix)
Clad/structure	FeS/FeS	Zirc-4/FeS
Coolant	LiPb	He
Trit. Breeder	LiPb	LiO_2
Reflector	FeS, LiPb	FeS, He
Shield	FeS, LiPb, B_4C, ZrD_2, W	W, B_4C, He
Magnets	NbSn,NbTi/He (OFHC/LN_2)	NbSn, NbTi/He
First-Wall	Be-coated FeS, LiPb	Be-coated FeS, He
Divertor	W-tiles on Cu-CuCrZr, LiPb	W-tiles on Cu – CuCrZr, He

Dimensions (m) of FTWR and GCFTR Designs

Parameter	**FTWR**[a]	**FTWR-SC**[b]	**FTWR-AT**[c]	**GCFTR**[d]	**GCFTR-2**[d]
Neutron Source					
Maj. Radius[e], R_0	3.10	4.50	3.86	4.15	3.70
Fluxcore, R_{fc}	1.24	1.10	0.65	0.66	0.66
CS+TF, Δ_{mag}	0.57	1.68	1.20	1.50	1.13
Refl+Shld, Δ_{rs}	0.40	0.65	0.90	0.86	0.82
Plasma, a_{plasma}	0.89	0.90	1.10	1.04	1.08
Core					
In Radius R_{in}	4.00	5.40	5.00	5.25	4.84
Width, W	0.40	0.40	0.40	1.12	1.12
Height, H	2.28	2.28	2.28	3.00	3.00

[a] ITER physics, LN2 Cu magnets, PbLi/TRU-metal reactor;

[b] ITER physics, ITER SC magnets, PbLi/TRU-metal reactor;

[c] AT physics, SC magnets, PbLi/TRU-metal reactor;

[d] ITER physics, ITER SC magnets, He/TRU-TRISO reactor;

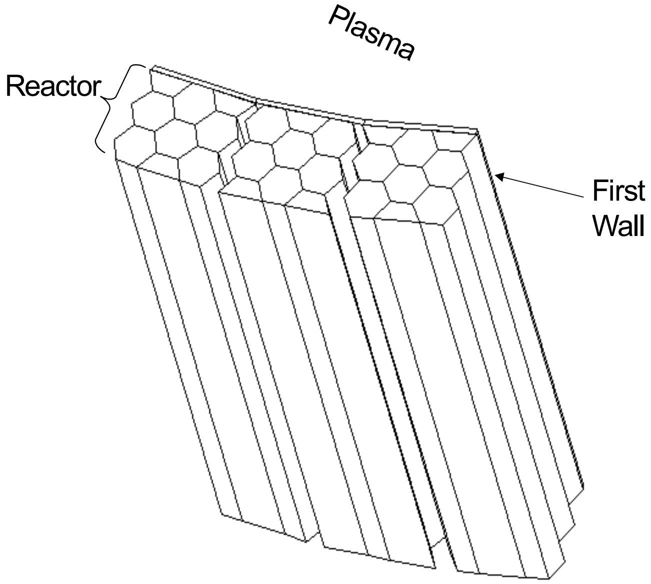
[e] Includes gap, first-wall, scrape-off layer and items below.

Tokamak Neutron Source Parameters for Transmutation Reactors

Parameter	**FTW**[a]	**FTW-SC**[b]	**FTWR-AT**[c]	**GCFTR**[d]	**GCFTR-2**[d]	**ITER**
Fusion power, P_{fus} (MW)	≤ 150	≤ 225	≤ 500	≤ 180	≤ 180	410
Neut. source, S_{fus}(10^{19} #/s)	≤ 5.3	≤ 8.0	≤ 17.6	≤ 6.4	≤ 6.4	14.4
Major radius, R (m)	3.1	4.5	3.9	4.2	3.7	6.2
Aspect ratio, A	3.5	5.0	3.5	4.0	3.4	3.1
Elongation, κ	1.7	1.8	1.7	1.7	1.7	1.8
Current, I (MA)	7.0	6.0	8.0	7.2	8.3	15.0
Magnetic field, B (T)	6.1	5.7	5.7	6.3	5.7	5.3
Safety factor, q_{95}	3.0	3.1	3.0	3.0	3.0	
Confinement, H_{IPB98}(y,2)	1.1	1.0	1.5	1.0	1.0	1.0
Normalized beta, β_N	≤ 2.5	≤ 2.5	4.0	2.0	2.0	1.8
Plasma Power Mult., Q_p	≤ 2.0	≤ 2.0	4.0	2.9	3.1	10
Bootstrap current frac., f_{bs}[e]	0.40	0.50	> 0.90	0.35	0.31	
CD eff., γ_{cd} (10^{-20} A/Wm^2)[e]	0.37	0.23	0.28	0.5	0.61	
Neut. flux, Γ_n (MW/m^2)	≤ 0.8	≤ 0.8	≤ 1.7	≤ 0.9	≤ 0.6	0.5
Heat flux, q_{fw} (MW/m^2)	≤ 0.34	≤ 0.29	≤ 0.5	≤ 0.23	≤ 0.23	0.15
Availability (%)	≥ 50	≥ 50	≥ 50	≥ 50	≥ 50	

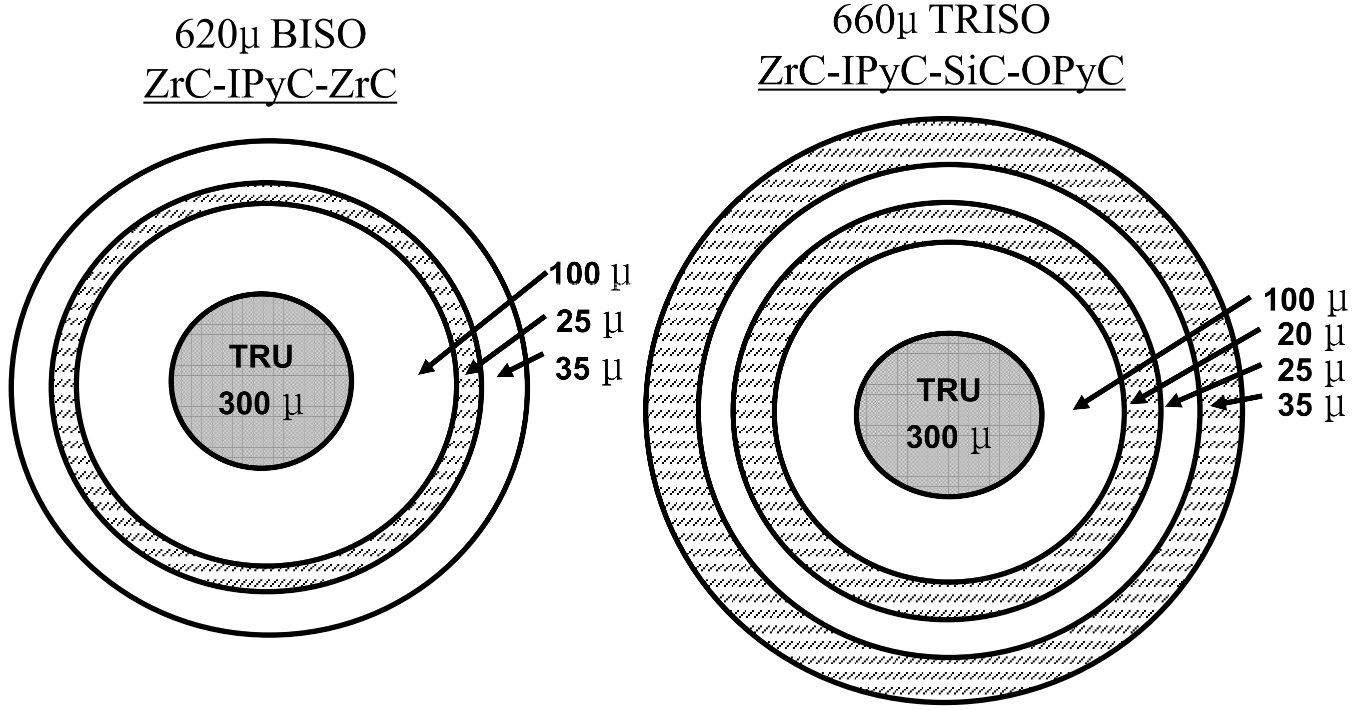
[a] ITER physics, LN2 Cu magnets, PbLi/TRU-metal reactor;
[b] ITER physics, ITER SC magnets, PbLi/TRU-metal reactor;
[c] AT physics, SC magnets, PbLi/TRU-metal reactor;
[d] ITER physics, ITER SC magnets, He/TRU-TRISO reactor;
[e] calc. fbs from ITER scaling, then determine needed γcd.

Transmutation Reactor Configuration Outboard of Plasma Chamber



FTWR Fuel Assembly Design

Pin Diameter (cm)		0.635
Clad thickness (cm)		0.05588
Pitch		Triangular
Pitch to Diameter		1.727
Pins per assembly		217
Structure Pins		7
Fuel Smear density		85%
Hexagonal Assembly Pitch		16.1
Assembly Length (cm)		228
Assemblies		470
Pumping Power (MW)		130
Volume %	Fuel	17.01
	Structure	10.44
	Coolant	69.55
Materials	Fuel	TRU-10Zr/Zr
	Structure	FeS
	Coolant	Li17Pb83



GCFTR BISO and TRISO coated TRU fuel particles

OPERATIONAL PRESSURE LIMIT DUE TO FISSION GAS BUILDUP MUST REMAIN BELOW COMPRESSIVE YIELD STRENGTH ≈ 350 MPA.

FISSION GAS PRESSURE AT NOMINAL 560OC IS 155 MPA @ 90% BURNUP AND 180 MPA @ 99% BURNUP.

OPERATIONAL PRESSURE LIMIT CORRESPONDS TO LIMITS ON FUEL CENTERLINE TEMPERATURES DURING ACCIDENTS OF ≈ 1700OC @ 90% BURNUP AND ≈ 1500OC @ 99% BURNUP, RELATIVE TO NOMINAL 560OC.

RADIATION DAMAGE EFFECTS ??

Performance Parameters of FTWR and GCFTR

Parameter	**FTWR**	**GCFTR**
TRU burnup objective, % FIMA	99.4 (repeated reprocess)	> 90 (no reprocess)
TRU transmutation rate, kg/EFPY	1100	1100
SNF transmutation rate, MTU/FPY	102	99.3
Fission thermal power, MW_{th}	3000	3000
Electric power, MW_e	1200	1024
Net electric power, MW_e	0	719
Electrical power amplification, Q_e	1.0	3.4

Deployment

≈ 100 LWRs PRODUCE ≈ 2000 MTU/YR

1 FTWR/GCFTR BURNS ≈ 100 MTU/EFPY OF SNF

HENCE, ≈ 20/A FTWRs OR GCFTRs WOULD SUPPORT PRESENT USA NUCLEAR POWER LEVEL, WHERE A ≡ AVAILABILITY

Radiation Damage

Fast (>0.1 MeV) Neutron Fluence (n/cm2) in GCFTR

	GCFTR	**Limit**
Reactor		
Clad over 5x600 EFPD residence	4.2×10^{22}	Zircalloy-4 ?
Structure over 30 EFPY lifetime	1.9×10^{23}	FeS $1.5\text{-}3.0 \times 10^{23}$ (80-150 dpa)
Fuel pellet @ 90% FIMA	4.1×10^{23}	?
Fuel pellet @ 99% FIMA	8.2×10^{23}	?
First-Wall	7.5×10^{23}	FeS $1.5\text{-}3.0 \times 10^{23}$ (80-150 dpa)
Divertor	5.8×10^{23}	Erosion
Superconducting Magnet		
Nb^3Sn @ 30 EFPY	1×10^{19}	1×10^{19}
Insulation @ 30 EFPY	6.7×10^{8} rad	Ceramic 10^{10} rad, org. 10^{9} rad

Component replacement

- CLAD FOR FUEL ELEMENTS NEEDS TO LAST FOR A 5-BATCH FUEL CYCLE (4X1022n/cm2), THEN REPLACED
- FUEL ASSY. STRUCTURE MAY NEED TO BE REPLACED ONCE OVER 30 EFPY LIFETIME
- COATED FUEL PELLETS NEED TO LAST ≥ 4.1X1023 n/cm2 TO ACHIEVE ‘NO REPROCESSING” GOAL
- FIRST-WALL MUST BE REPLACED 2-4 TIMES OVER 30 EFPY LIFETIME
- DIVERTOR EROSION WILL REQUIRE SEVERAL REPLACEMENTS OVER 30 EFPY LIFETIME
- MAGNETS ARE 30 EFPY LIFETIME COMPONENTS

Requirements for a Tokamak Neutron Source, Electric Power Reactor and DEMO

Parameter	Transmutation	Electric Power[a]	DEMO[b]
Confinement $H_{IPB98}(y,2)$	1.0	1.5-2.0	1.5-2.0
Beta β_N	< 2.5	> 5.0	> 4.0
Power Amplification Q_p	< 3	≥ 50	> 10
Bootstrap Current Fraction f_{bs}	0.2-0.5	0.9	0.7
Neutron wall load (MW/m^2)	≤ 1.0	> 4.0	> 2.0
Fusion Power (MW)	≤ 200	3000	1000
Pulse length/duty factor	long/steady-state	long/steady-state	long/steady-state
Availability (%)	> 50	90	50

- REQUIREMENTS FOR A TOKAMAK NEUTRON SOURCE FOR A TRANSMUTATION REACTOR ARE LESS DEMANDING THAN FOR A TOKAMAK DEMO AND MUCH LESS DEMANDING THAN FOR A TOKAMAK ELECTRIC POWER REACTOR

- R&D REQUIRED FOR A TOKAMAK NEUTRON SOURCE FOR A TRANSMUTATION REACTOR IS ALSO REQUIRED FOR A TOKAMAK DEMO

CONCLUSIONS

- TRANSMUTATION OF SPENT NUCLEAR FUEL, WITH THE OBJECTIVE OF REDUCING HLW REPOSITORY REQUIREMENTS, IS A PLAUSIBLE ‘NEAR-TERM’ MISSION FOR FUSION THAT IS DIRECTLY ON THE PATH TO FUSION ELECTRIC POWER.

- A SUB-CRITICAL TRANSMUTATION REACTOR WITH A TOKAMAK D-T FUSION NEUTRON SOURCE COULD BE ONLINE BY 2040.

- THE REQUIREMENTS FOR THE TOKAMAK NEUTRON SOURCE ARE MODEST [$R \approx 4$ m, $Pfus < 200$ MW, $H \approx 1$, $Qp \approx 3$, $\beta N \leq 2$, $fbs \approx 0.3 - 0.5$, $\gamma CD \approx 0.5$, $\Gamma n \leq 1$], EXCEPT FOR AVAILABILITY > 50%, COMPARED TO THE REQUIREMENTS FOR A DEMO.

- THE REQUIRED REACTOR TECHNOLOGY (NUCLEAR, FUELS, SEPARATIONS, etc.) THAT IS BEING DEVELOPED IN THE DOE NUCLEAR ENERGY PROGRAM CAN BE ADAPTED TO ACCOMMODATE TRITIUM BREEDING AND PURE TRANSURANIC FUELS.