Los Alamos Transmutation Research

- Heavy Liquid Metal Coolant Technology & Accelerator-Driven Materials Test Station

Ning Li*, Eric Pitcher
Los Alamos National Laboratory, USA

Sept. 28, 2006

Outline

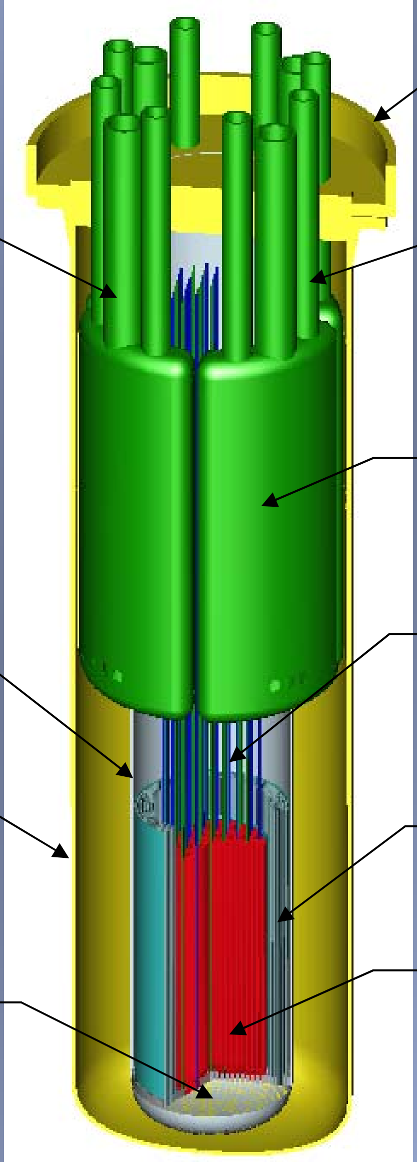
- Heavy Liquid Metal Coolant Technology
  - Facilities, materials testing and coolant technology development
  - Corrosion modeling and database
- Materials Test Station (MTS)
  - Mission
  - Design
  - Outlook

Heavy Liquid Metal Coolant Technology

Supporting AFCI and Gen IV Goals

- AFCI (Advanced Fuel Cycle Initiative):
  - Original goal: ADS spallation target and transmutation assembly - substantially met;
  - Extended goal: reactor-based systems and Gen IV
- Gen IV LFR (Generation IV Nuclear Energy Systems: Lead Fast Reactor):
  - Near to mid-term: long-life LBE/Pb-cooled cores - long-term corrosion performance under testing, modified materials and/or surface treatment necessary
  - Long-term: high temperature Pb-cooled systems - new classes of materials and coolant technology necessary
- GNEP (Global Nuclear Energy Partnership)
  - Sodium as coolant for Advanced Burner Reactor (ABR)
  - Will SMR (small and modular reactors) carry LFR?

Gen IV LFR: 20 MWe SSTAR Concept



CLOSURE HEAD

CO2 OUTLET NOZZLE (1 OF 8)

CO_2 INLET NOZZLE (1 OF 4)

Pb-TO-CO_2 HEAT EXCHANGER (1 OF 4)

CONTROL ROD DRIVELINES

FLOW SHROUD

REACTOR VESSEL

RADIAL REFLECTOR

ACTIVE CORE AND FISSION GAS PLENUM

FLOW DISTRIBUTOR HEAD

DELTA Loop (DEvelopment of Lead-alloy Technology and Applications)

- Design in 2000
  - 316L construction
  - ~100 kW power
  - Up to 15 m³/h forced circulation with a 20 HP pump, normally operated below 2 m/s LBE flow in test section
  - Oxygen controlled
- Loop construction finished in 2002
- Operation and testing since 2003

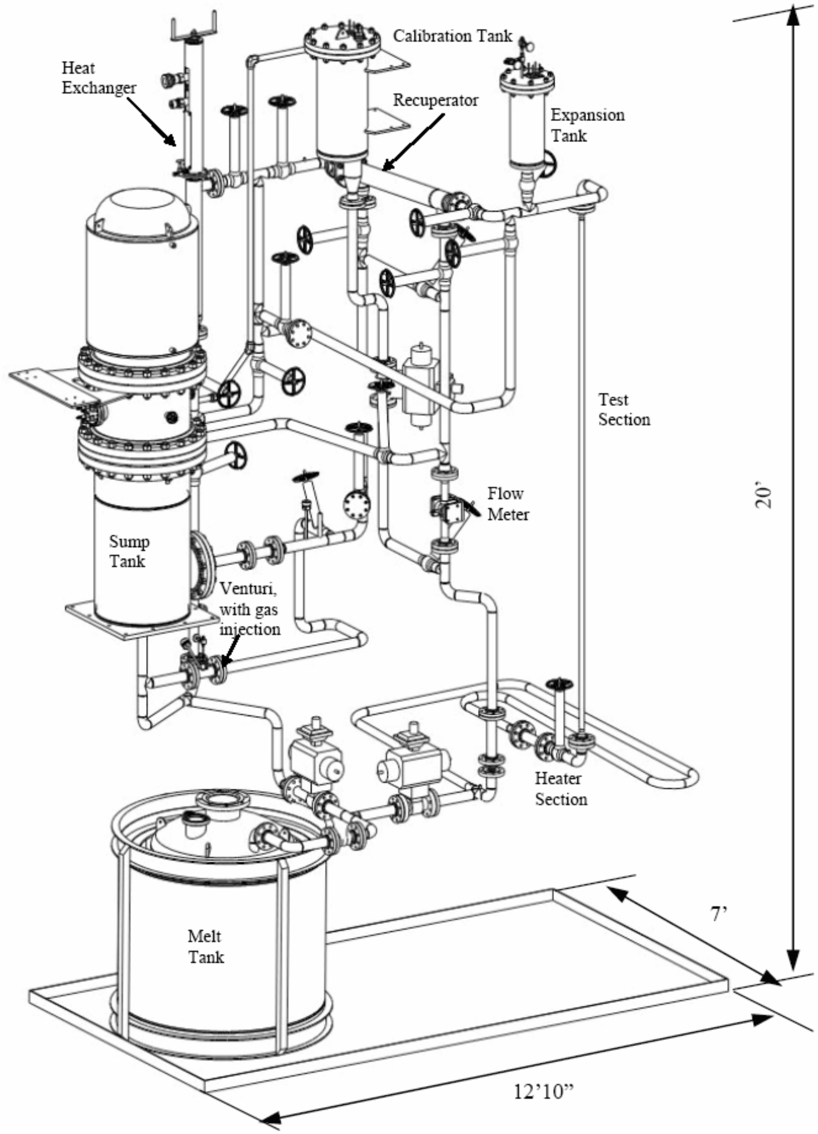
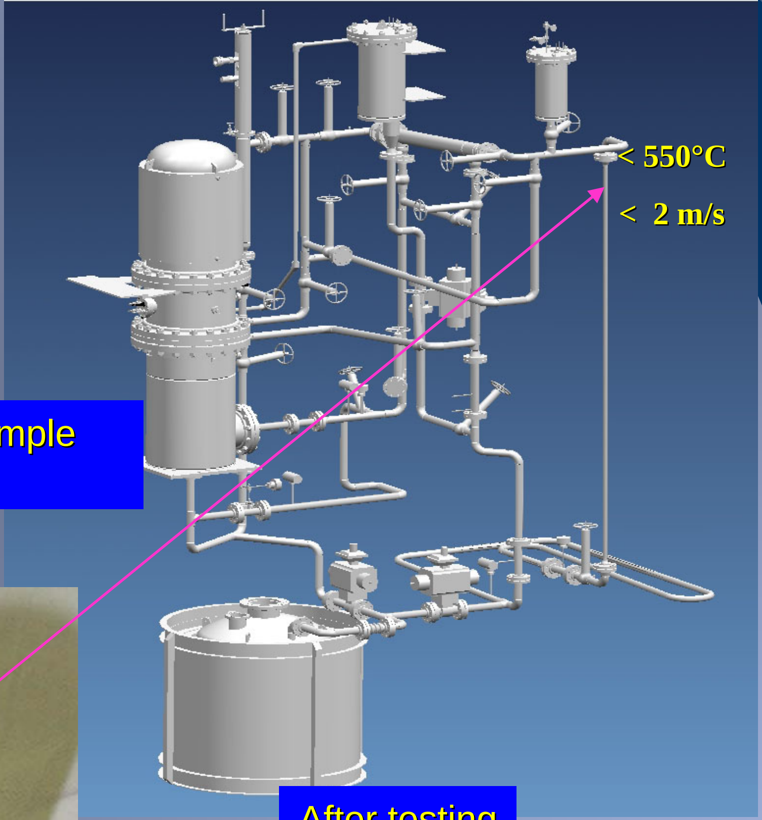


Fig. 1. Illustration of the DELTA Loop.

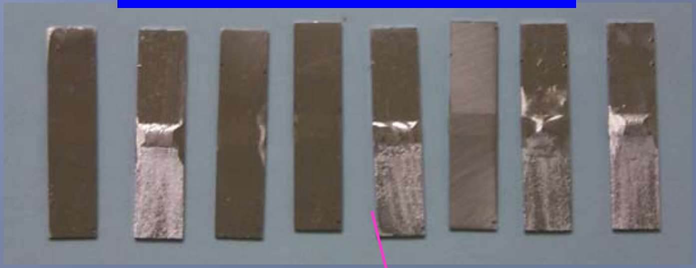
DELTA Loop in MPF-18, TA-53, LANL

DELTA Loop Test Program

- Large test matrix of materials, surface treatment, and alloy modifications
- Materials from other national labs, universities and international partners



Corrosion test specimens



Sample holders (slotted channels)

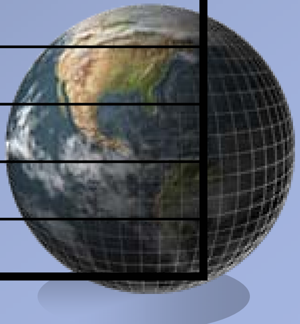
Assembled sample holders

After testing

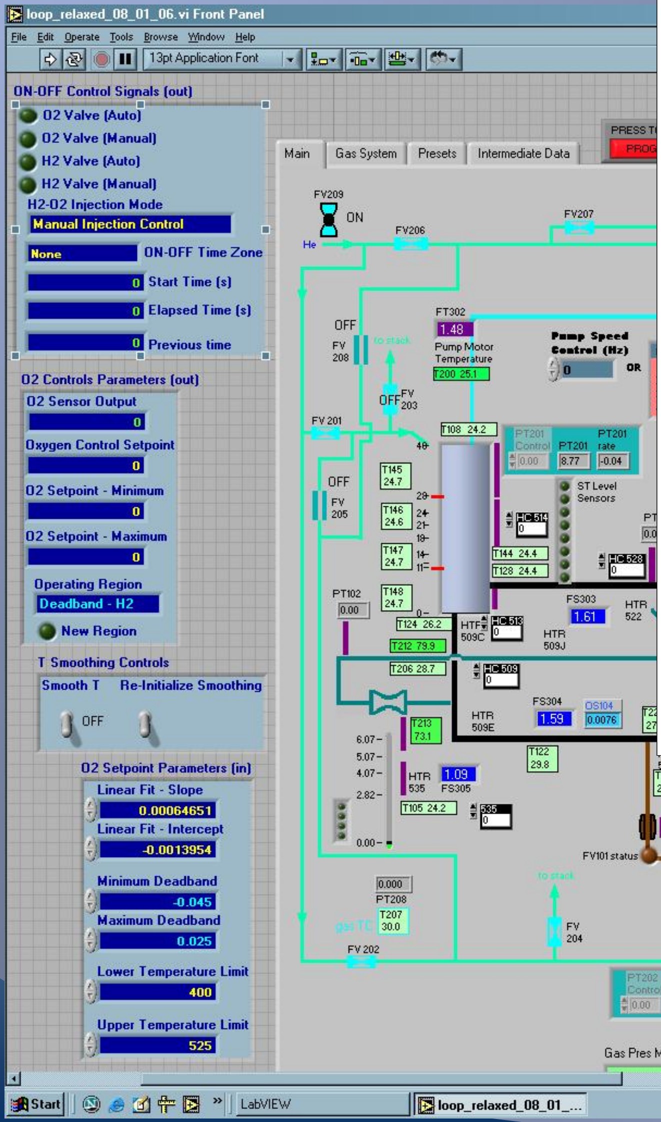
2005 DELTA Test Campaign

- T=540^{o}C, C_O=10^{-6}wt%, v=1m/s, t=200, 400, 600hrs
- Stress Corrosion Cracking specimens(HT-9, EP823 U-bends and C-rings)
- Corrosion specimens:

ODS steels	MA957	NF616, sputtered and implanted	NF616
	MA956		Si + Xe$^+$
	12YWT		Y + Xe$^+$
	14YWT		O$^+$
	PM2000		Ta + Xe$^+$
	(JNC)	HCM12A, sputtered and implanted	HCM12A
Amorphous coating on 316L	SAM40		Y + Xe$^+$
	SAM40X3		O$^+$
	HVOF		Ta + Xe$^+$
	C22 HVOF	Laser-peened	316L
Mo, W coating	MA957		EP823
	EP823		HT-9
	HT-9		T91
	9Cr-1Mo	High Cr	18-20%Cr



Stable Oxygen Control in DELTA via Automated Direct Gas Injection



ON-OFF Control Signals (out)

- ● O2 Valve (Auto)
- ● O2 Valve (Manual)
- ● H2 Valve (Auto)
- ● H2 Valve (Manual)

H2-O2 Injection Mode: Manual Injection Control

ON-OFF Time Zone: None

Start Time (s): 0

Elapsed Time (s): 0

Previous time: 0

O2 Controls Parameters (out)

O2 Sensor Output: 0

Oxygen Control Setpoint: 0

O2 Setpoint - Minimum: 0

O2 Setpoint - Maximum: 0

Operating Region: Deadband - H2

● New Region

T Smoothing Controls

Smooth T: OFF

Re-Initialize Smoothing

O2 Setpoint Parameters (in)

Linear Fit - Slope: 0.00064651

Linear Fit - Intercept: -0.0013954

Minimum Deadband: -0.045

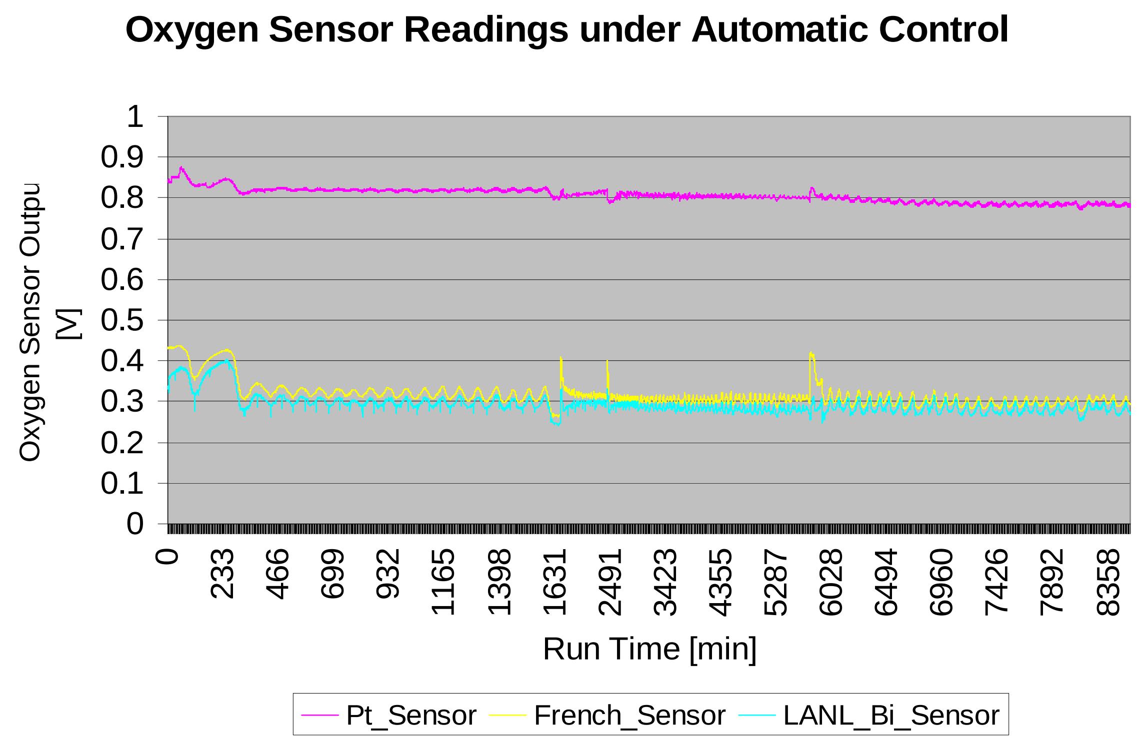
Maximum Deadband: 0.025

Lower Temperature Limit: 400

Upper Temperature Limit: 525

Status and Warnings

Venturi DOES NOT have a Freeze Plug!
Gas Valves are controlled by OPERATOR!
TC106<=150.0C! Check heaters!
TC112<=150.0C! Check heaters!
TC114<=150.0C! Check heaters!
TC116<=150.0C! Check heaters!


Oxygen Sensor Readings under Automatic Control

A Bypass in DELTA with a PbO Mass Exchanger to Control Oxygen Concentration in LBE

Investigate Effects of Oxygen Concentration in LBE on Heat Transfer and Wetting in DELTA

Fig. 4(a). Interior of the pipe after the first run at low oxygen concentration.

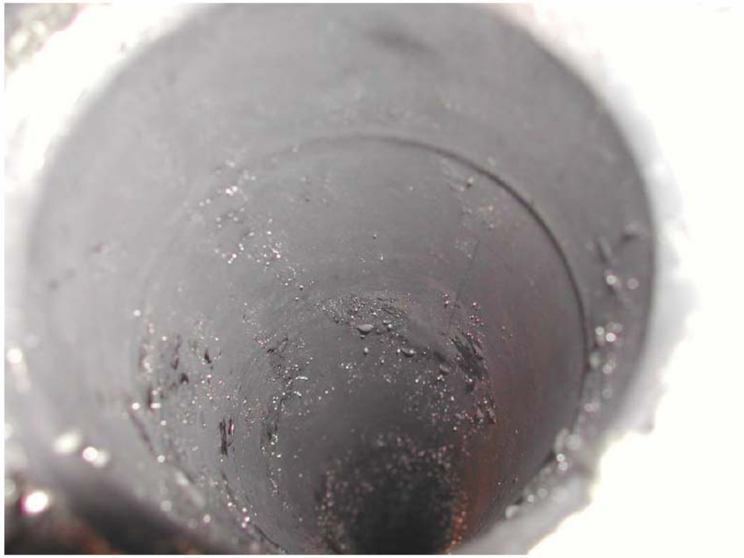
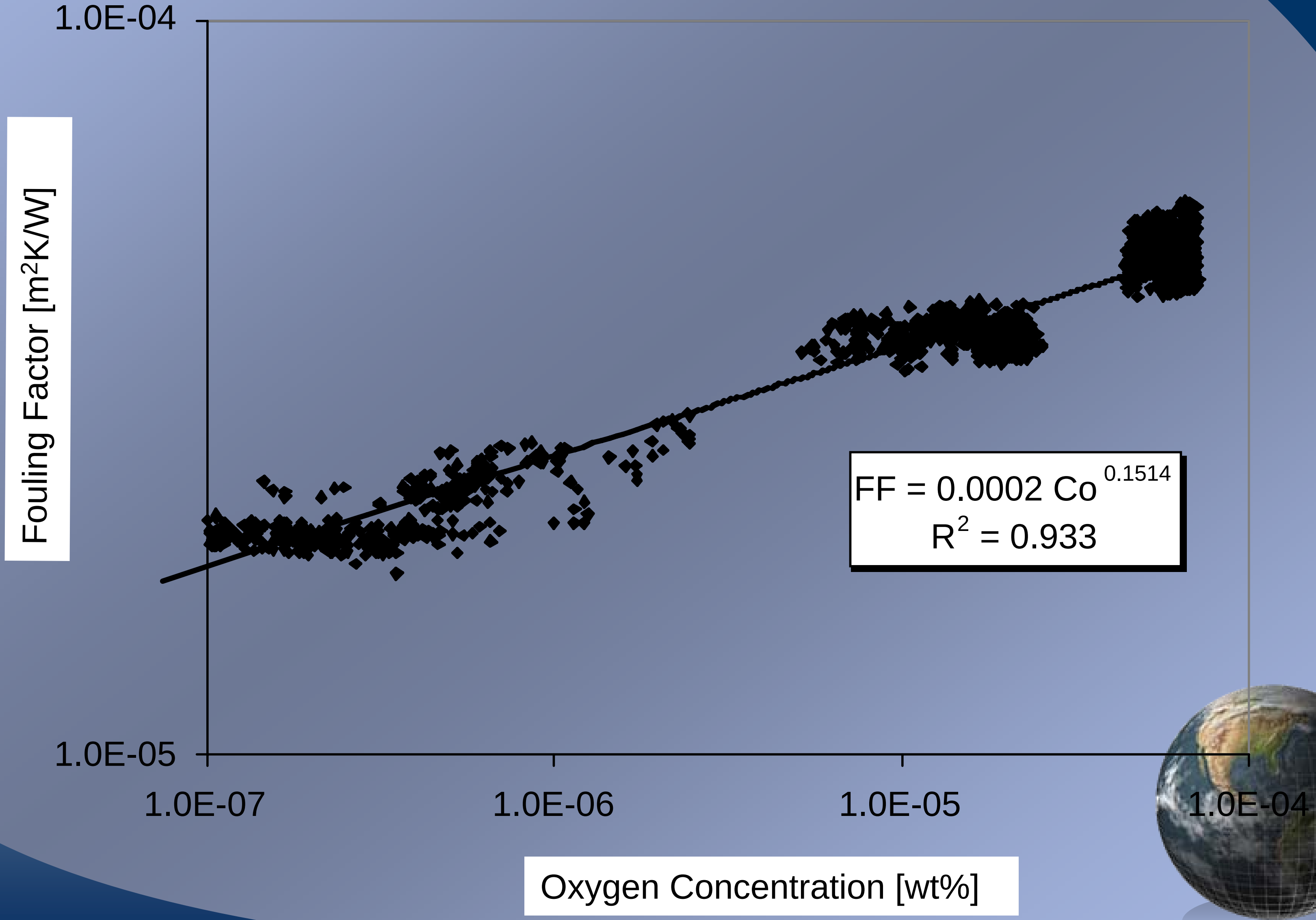


Fig. 4(b). Interior of the pipe after the second run at a higher oxygen concentration.

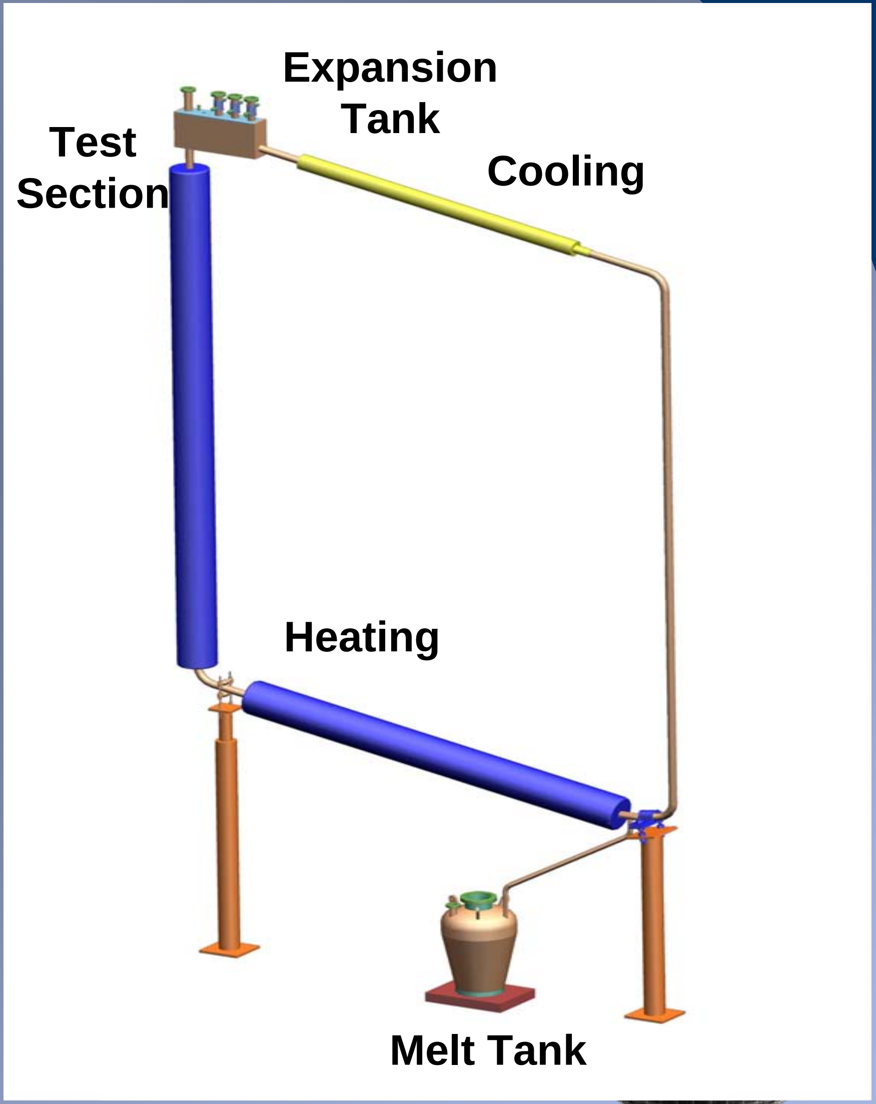
Fig. 4(c). Interior of the pipe after the third run at the highest oxygen concentration, showing significant oxidation and evidence of non-wetting.

Fouling Factor: Increasing Oxygen Concentration Reduces Heat Transfer



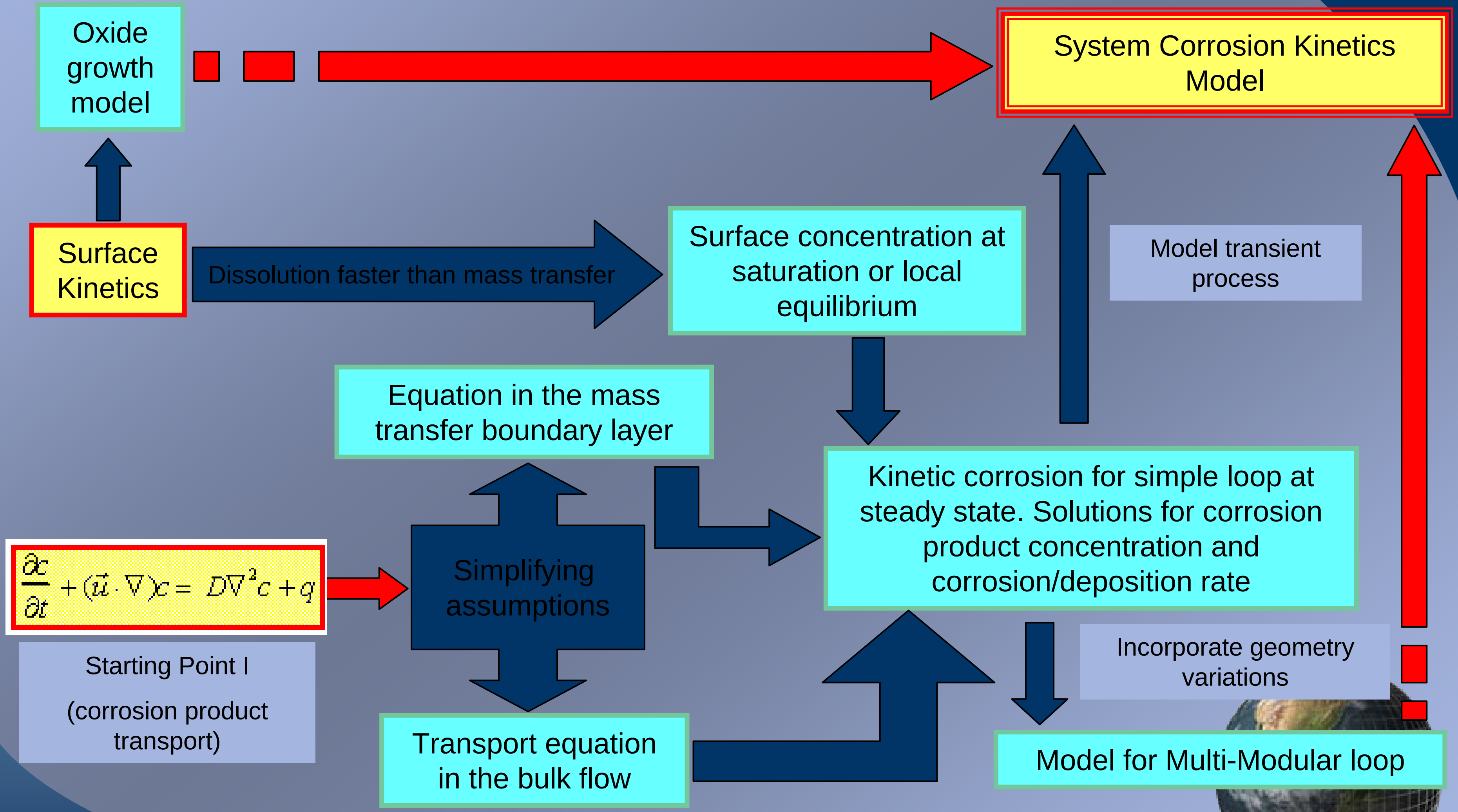
Lead Correlation Stand to Test Materials in Pb for Temperatures up to 650-700^{o}C

- Design
  - ODS steel (MA956 – 4.5%Al) construction
  - 0.25m/s natural circulation
  - Oxygen controlled
- Loop construction finished
- Auxiliary systems to be added



Lead Correlation Stand (LCS) in Support and Containment Structure (Next to DELTA)

A Framework to Systematically Model Oxidation and Corrosion of Steels in Lead-Alloys



Oxide growth model

System Corrosion Kinetics Model

Surface Kinetics

Dissolution faster than mass transfer

Surface concentration at saturation or local equilibrium

Model transient process

Equation in the mass transfer boundary layer

Kinetic corrosion for simple loop at steady state. Solutions for corrosion product concentration and corrosion/deposition rate

$$\frac{\partial c}{\partial t} + (\vec{u} \cdot \nabla)c = D\nabla^2 c + q$$

Simplifying assumptions

Starting Point I

(corrosion product transport)

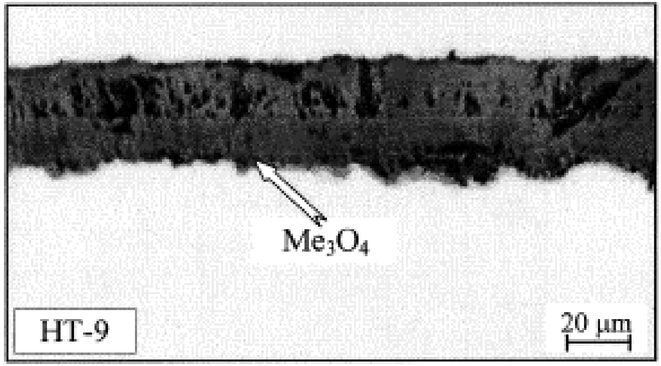
Incorporate geometry variations

Transport equation in the bulk flow

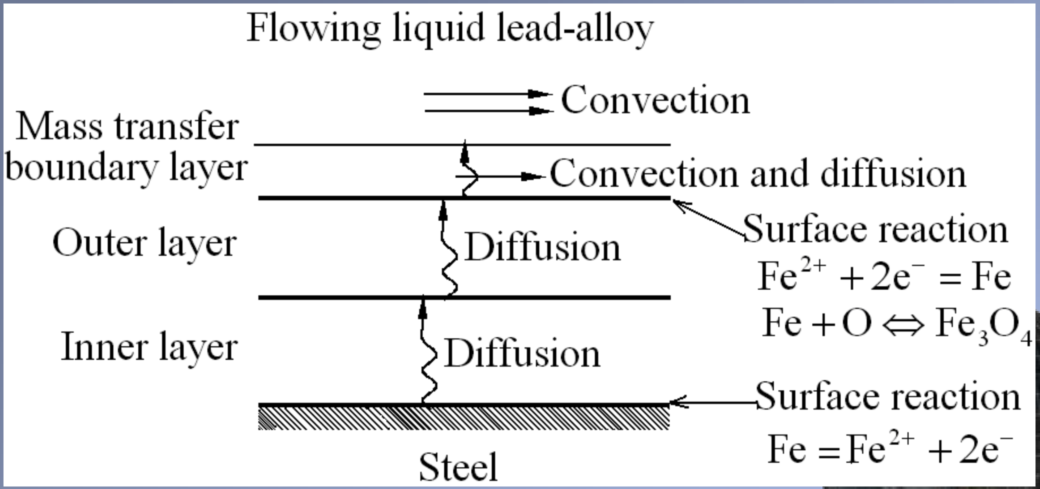
Model for Multi-Modular loop

Modeling Oxidation/Corrosion Based on First Principles and Experimental Findings

- Oxide scale:
  experimentally observed structures

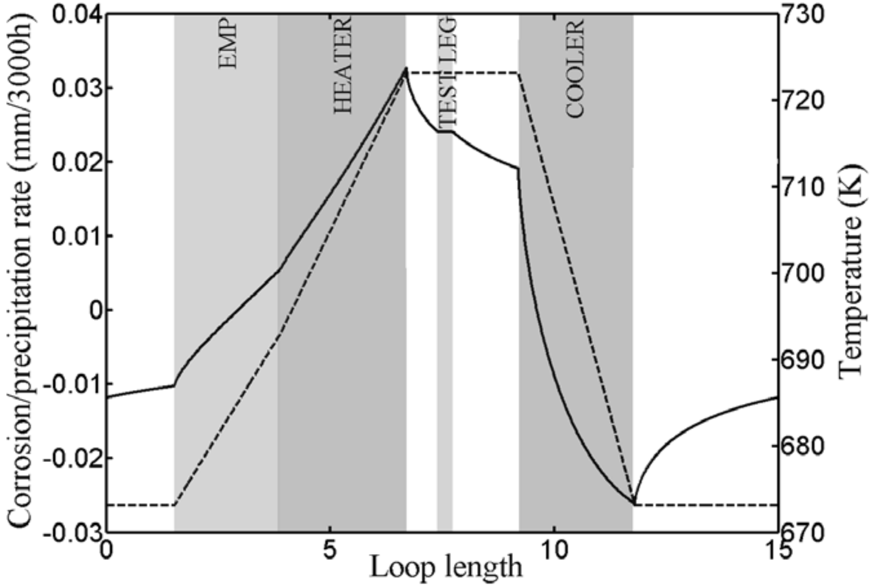


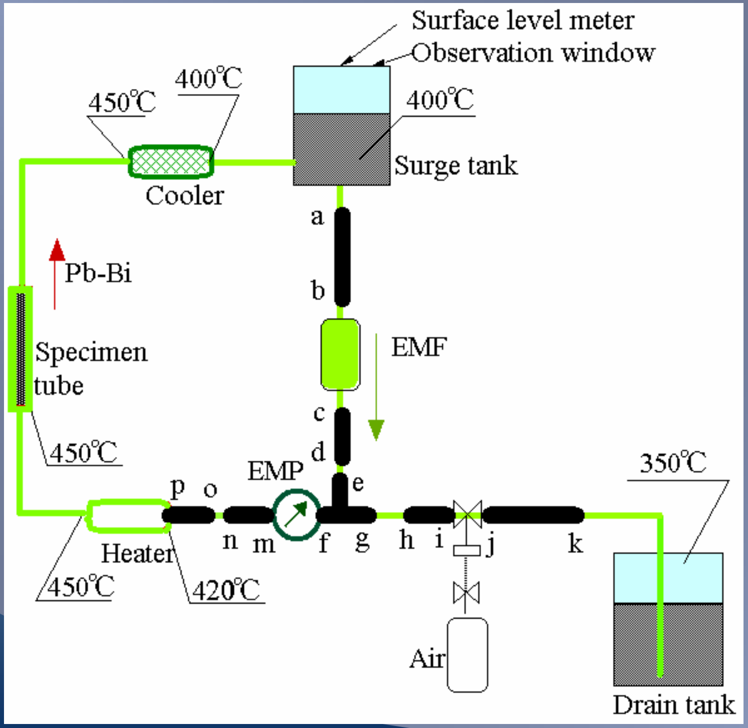
- Mass transfer in liquid metals:
  turbulence model



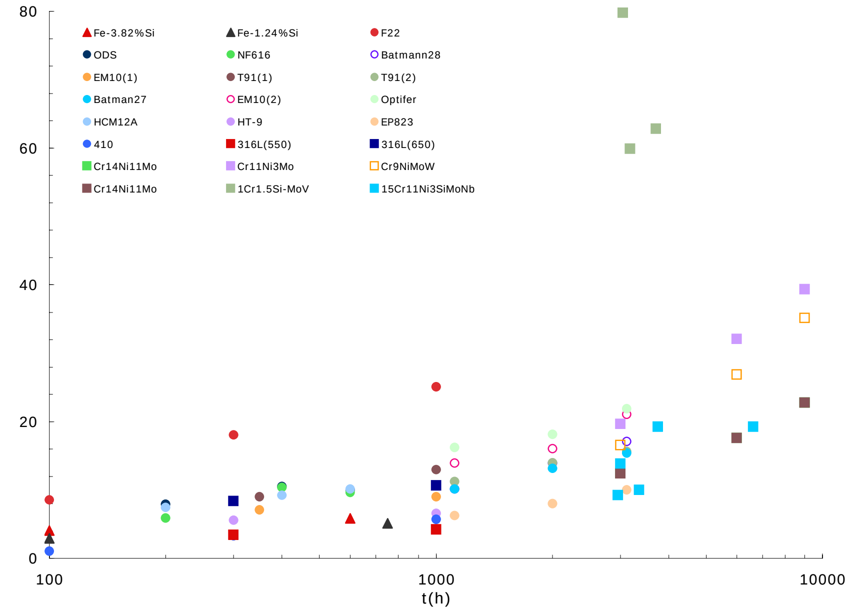
Benchmarking of Corrosion Model against JLBL-1 (JAERI Lead-Bismuth Loop) Experiment

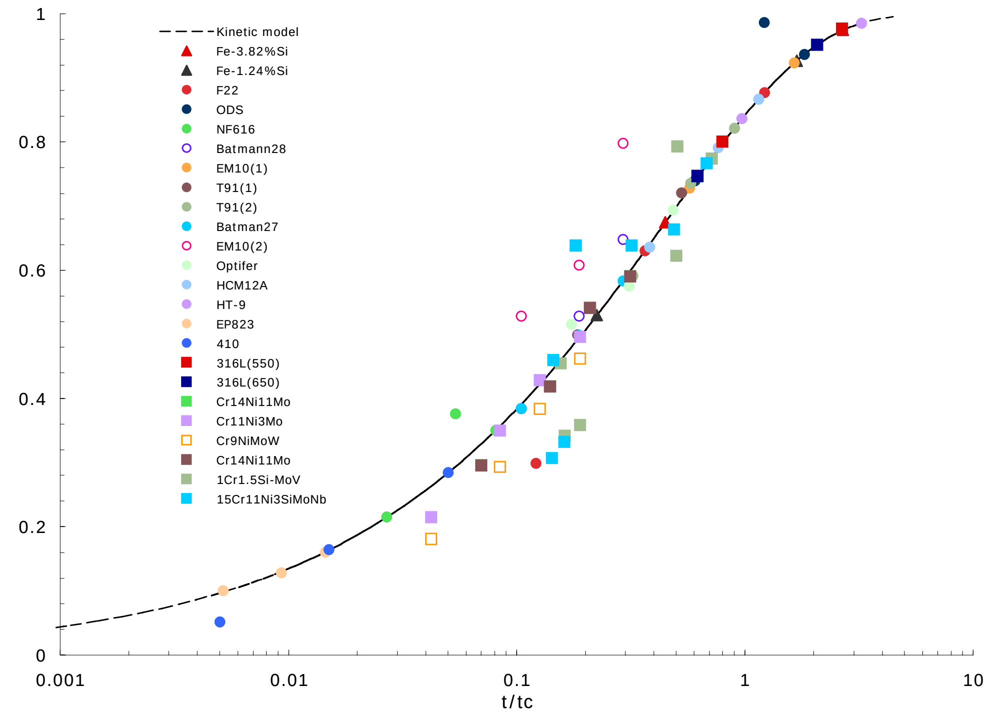
- Calculated dissolution/precipitation rate for iron (solid line) and the temperature profile (dashed line) for JLBL-1 loop.
- Deposition zone (thick back line) in JLBL-1 experiment. The corrosion rate is between 0.03-0.1 mm at the highest temperature leg.





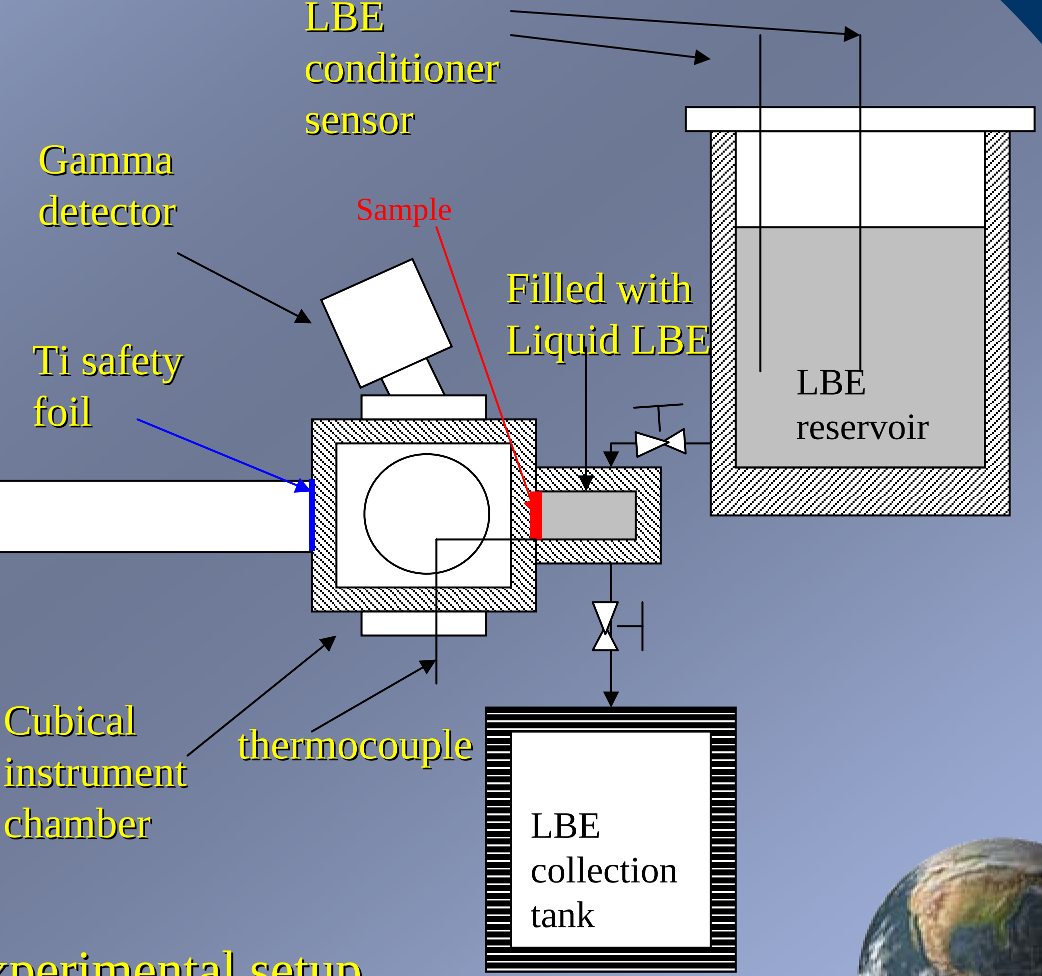
Universal Scaling of Reported LBE Loop Test Data based on the System Kinetic Model





Irradiation and Corrosion Experiment (ICE)

Ion Beam Materials Laboratory



LBE conditioner sensor

Gamma detector

Sample

Filled with Liquid LBE

Ti safety foil

LBE reservoir

5 MeV p+ beam

Cubical instrument chamber

thermocouple

LBE collection tank

Schematic sketch of the experimental setup.

ICE Device and Shielded Platform

LBE reservoir

Window/sample

ICE chamber

Shielded Platform

Extensive Collaborations

- University
  - UNLV (TC-1, materials, corrosion testing, sensors, etc)
  - MIT (Si effects, oxygen sensor seals)
  - U Wisconsin (testing fusion alloys and modifications)
  - Idaho Accelerator Center (oxygen sensor irradiation)
  - U Illinois U-C (corrosion probes)
  - U Michigan (irradiation effects on corrosion)
  - TAMU (nano-engineered coatings and materials)
  - Penn State U (oxide microstructure)
  - UC Santa Barbara (ODS steels)
- International
  - OECD/NEA HLMC Handbook project
  - EU (DEMETRA, MEGAPIE)
  - CEA (coolant technology, materials testing, oxygen sensors)
  - SNU/KAERI (fuel cladding materials, oxygen sensors)
  - JAERI (ADS), JNC/TITech (FR)
  - IPPE (ISTC projects on TC-1, PbO-based oxygen control, oxygen sensors)

Lead-Alloy Coolant Technology and Materials Readiness Level Assessment (2005)

- For peak temperature < 550^{o}C, and for short to medium lifetime at high temperatures, technology readiness level (TRL) is at early stages of “Proof-of-Performance”.
- For long-life core (20-30 years), and for high performance and higher temperature (up to 750^{o}C), TRL is at “Proof-of-Principle”.
- For temperature higher than 800^{o}C (e.g. for hydrogen production), TRL is at “Proof-of-Concept”.

Accelerator-Driven Materials Test Station (MTS)

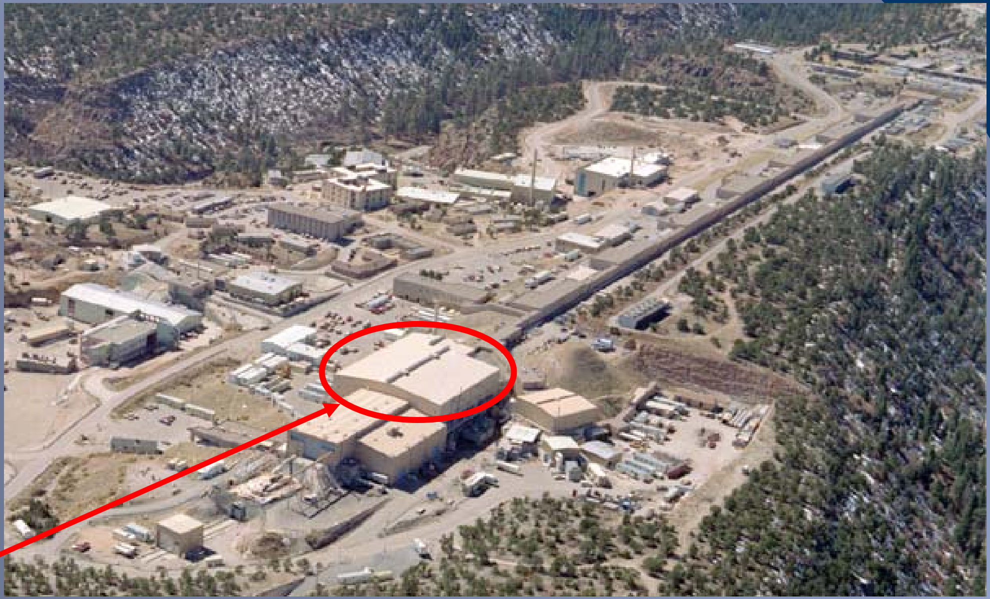
The MTS is a fast spectrum irradiation facility supporting fuels and materials development for the Global Nuclear Energy Partnership

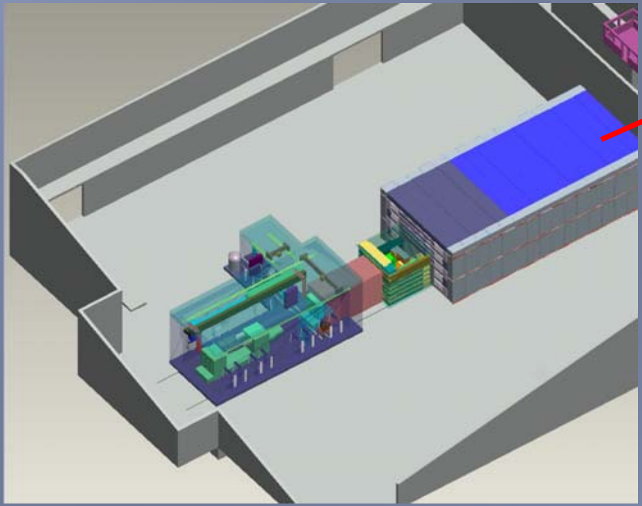
- The U.S.A. has no fast neutron spectrum irradiation facility
- There are a limited number of viable facilities abroad:
  - PHENIX (France, due to close by end of this decade)
  - JOYO (Japan)
  - BOR-60 (Russia)
- The AFCI program has been successful in securing irradiation services abroad, but the process
  - is time consuming
  - has risks associated with approvals outside of U.S. control
- The MTS will provide a near term fast spectrum domestic irradiation capability until the Advanced Burner Test Reactor is available circa 2019

MTS will be located in the 3,000 m^2 LANSCE “Area A” experiment hall

Existing assets include:

- **800-MeV, 1.35-mA proton linac**
- **30-T crane**
- **6 MW secondary cooling**
- **Ktons of shield blocks**
- **12 MW electrical service**



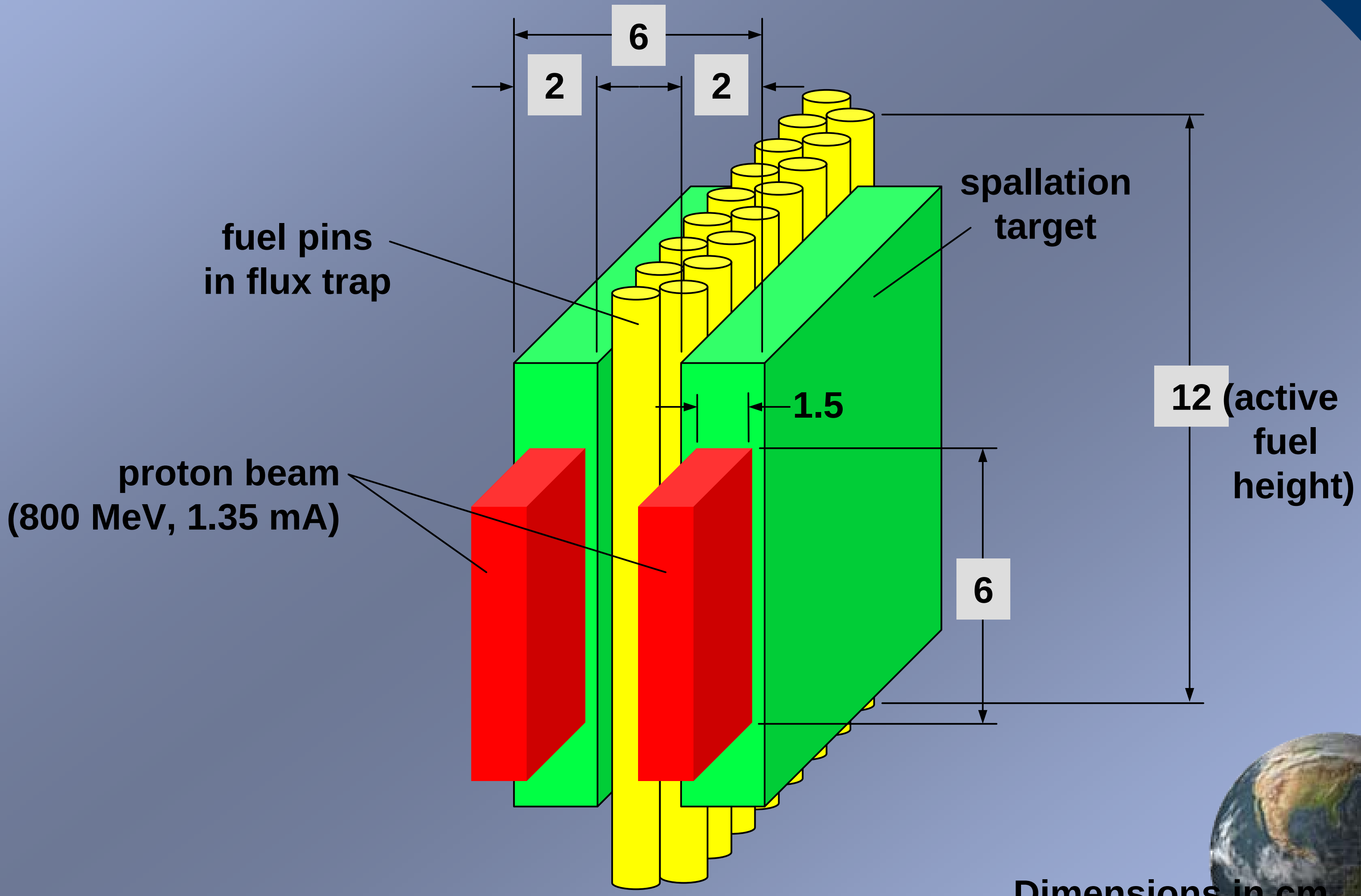


The LANSCE accelerator and Area A have a replacement cost of $1B. Utilization of this unique resource significantly reduces MTS capital costs.

The MTS irradiation environment meets programmatic objectives

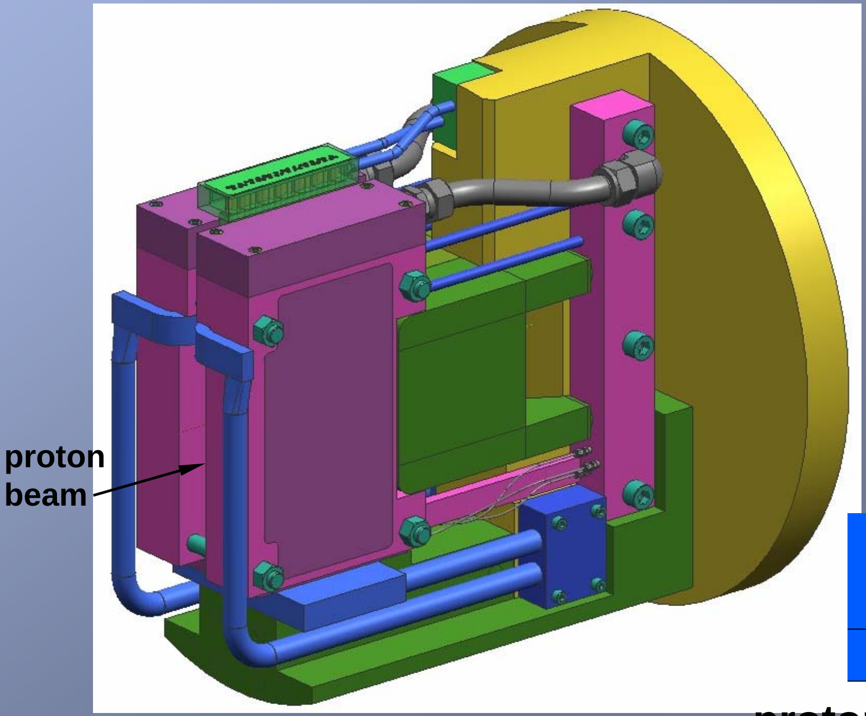
Criterion	Design Requirement	Current Design
Neutron spectrum	Similar to that of a fast reactor	Meets requirement
Peak fast (>0.1 MeV) neutron flux	$\geq 1\times10^{15}$ n.cm^{-2}.s^{-1}	1.3×10^{15} n.cm^{-2}.s^{-1}
Irradiation volume	Sufficient to achieve 360 W/cm linear heating in 20 cm of highly enriched fuel	Exceeds requirement by factor of 10
Availability	≥3%/y burnup and ≥10 dpa/y in Fe in the peak flux region	4%/y burnup and 18 dpa/y in Fe
Prototypic fast reactor environment	Ability to accommodate liquid metal coolants	Meets requirement

The MTS spallation target is split, with a “flux trap” irradiation zone located in between

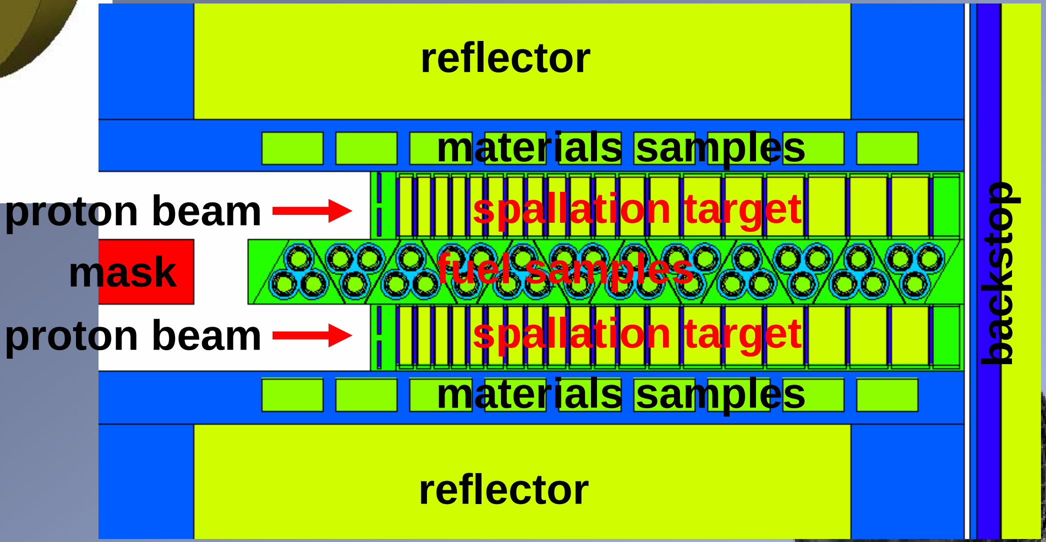


Dimensions in cm.

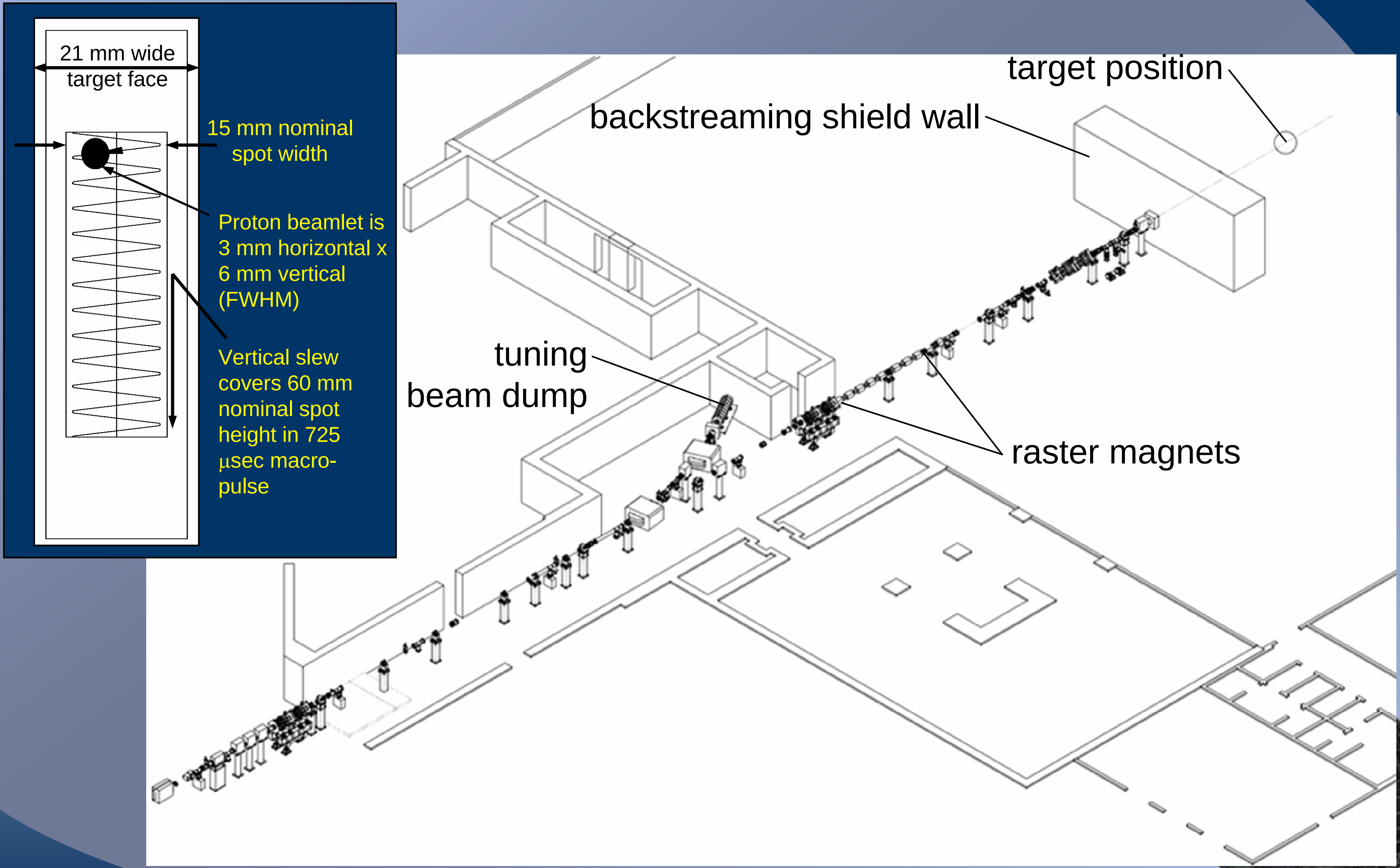
The target assembly consists of a series of nested inserts



Horizontal cross section at mid-plane



The MTS beam line design includes a raster system that produces nearly uniform current density on target



21 mm wide target face

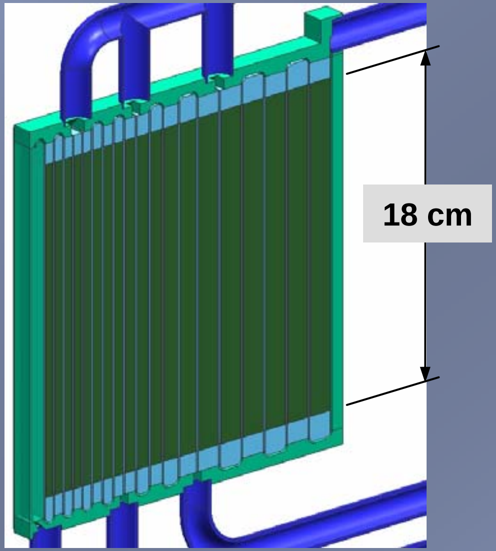
15 mm nominal spot width

Proton beamlet is 3 mm horizontal x 6 mm vertical (FWHM)

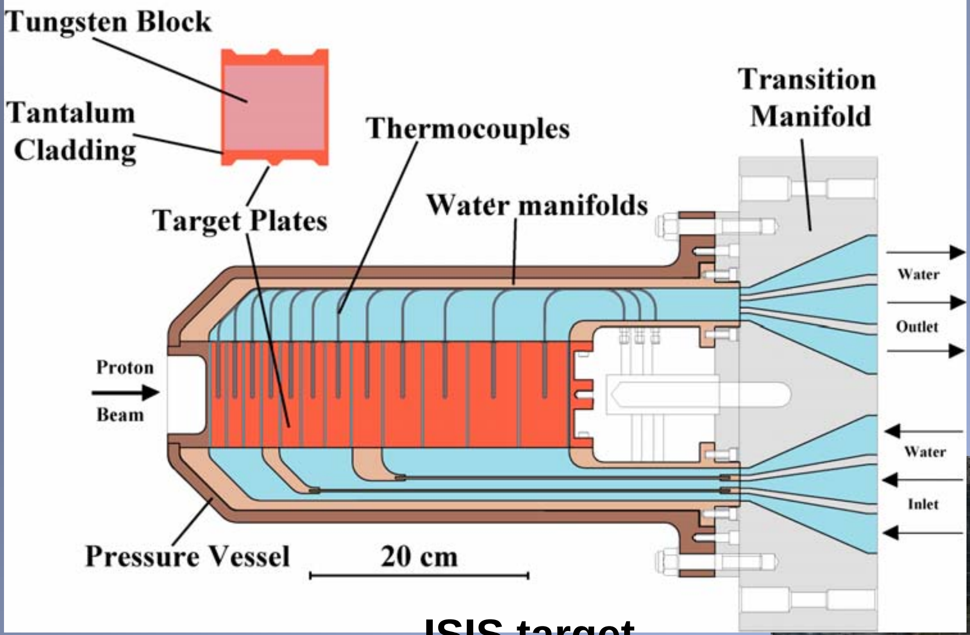
Vertical slew covers 60 mm nominal spot height in 725 µsec macro-pulse

The spallation target uses well established technology

	MTS	ISIS	APT
Target material	Ta-clad W	Ta-clad W	SS-clad W
Coolant	D_2O	D_2O	H_2O
Beam energy (MeV)	800	800	800
Beam current (mA)	1.35	0.2	1
Current density ($\mu A/cm^2$)	75	10	70

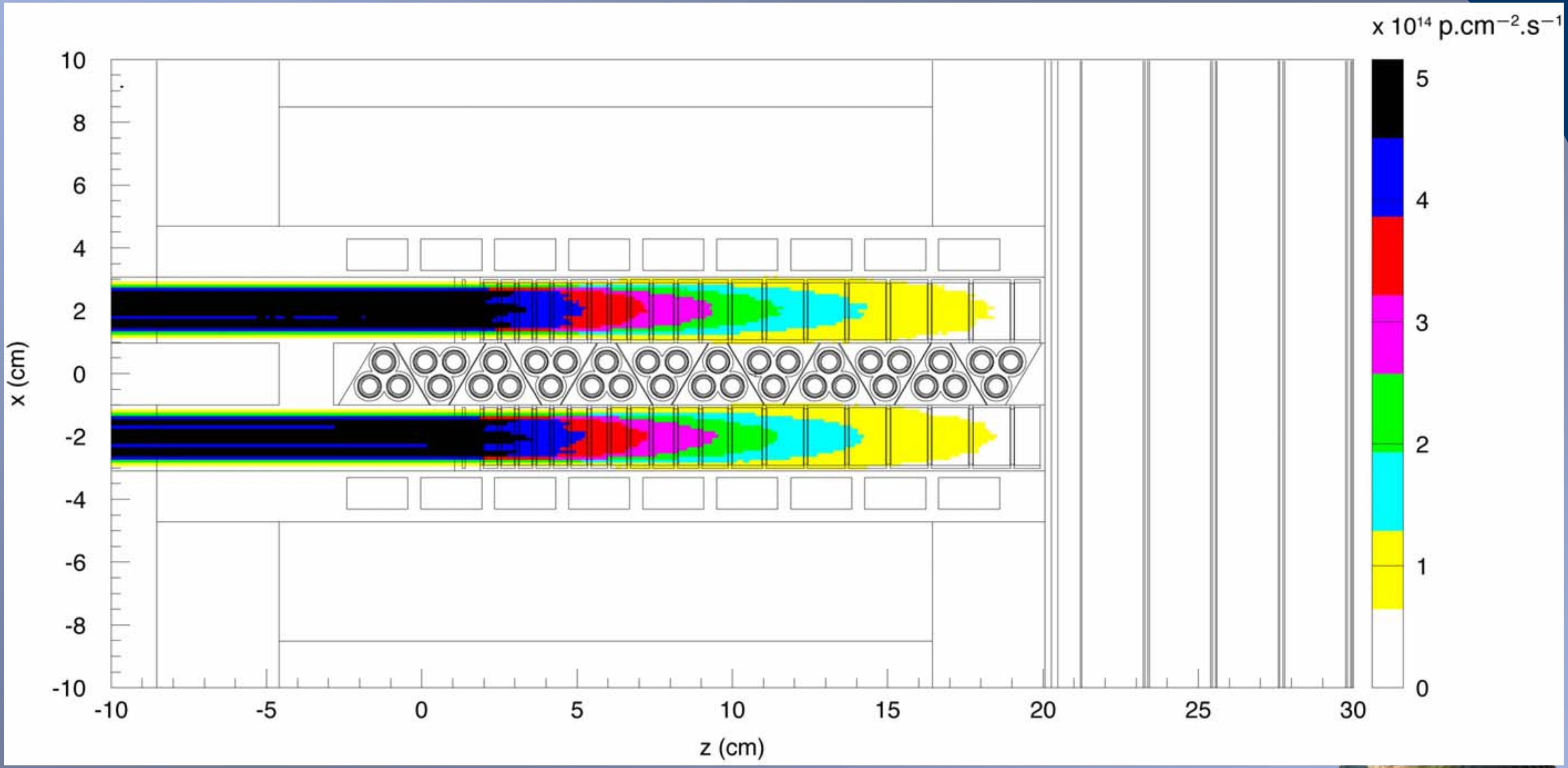


MTS target

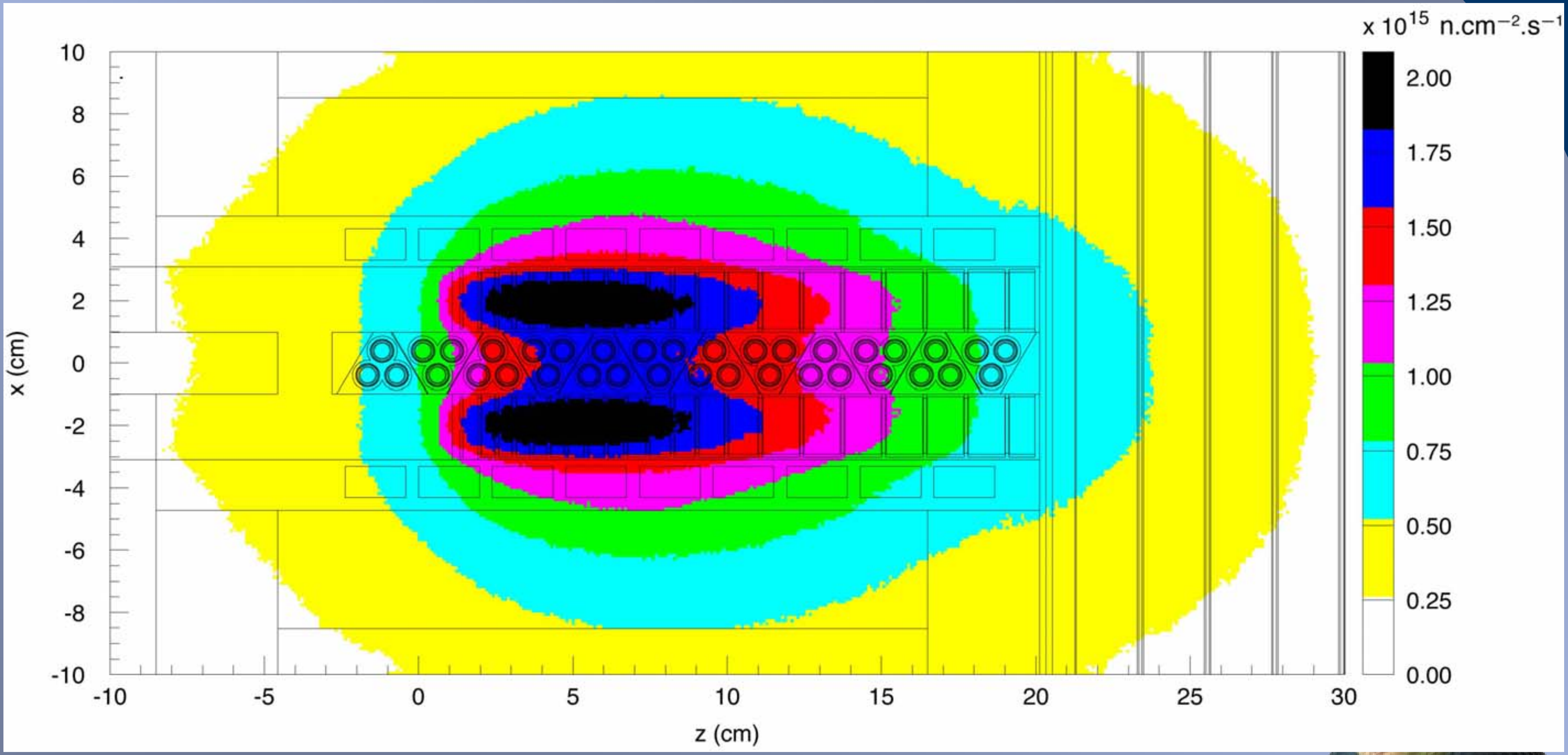


ISIS target

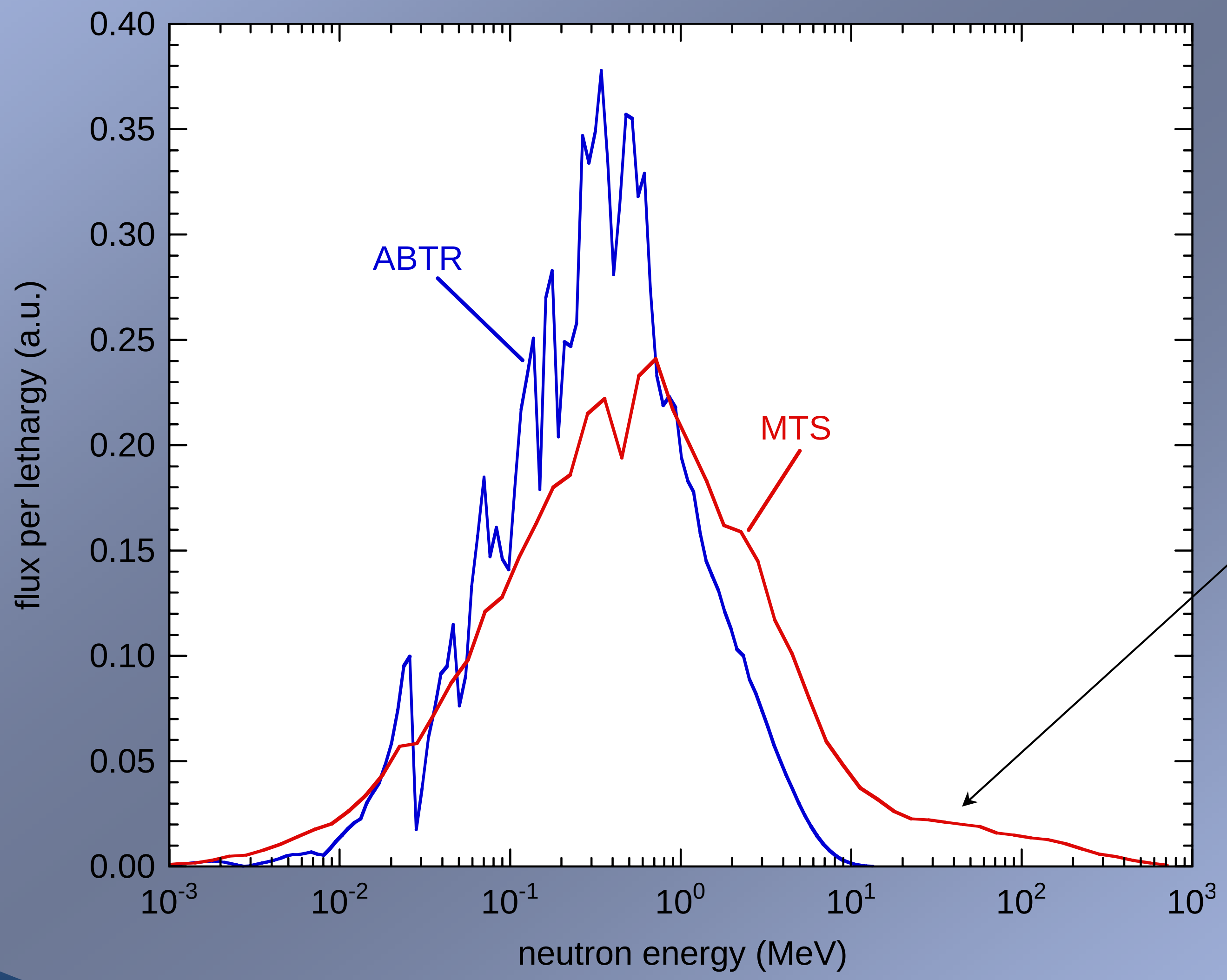
Proton flux distribution at target mid-plane



Neutron flux distribution at target mid-plane



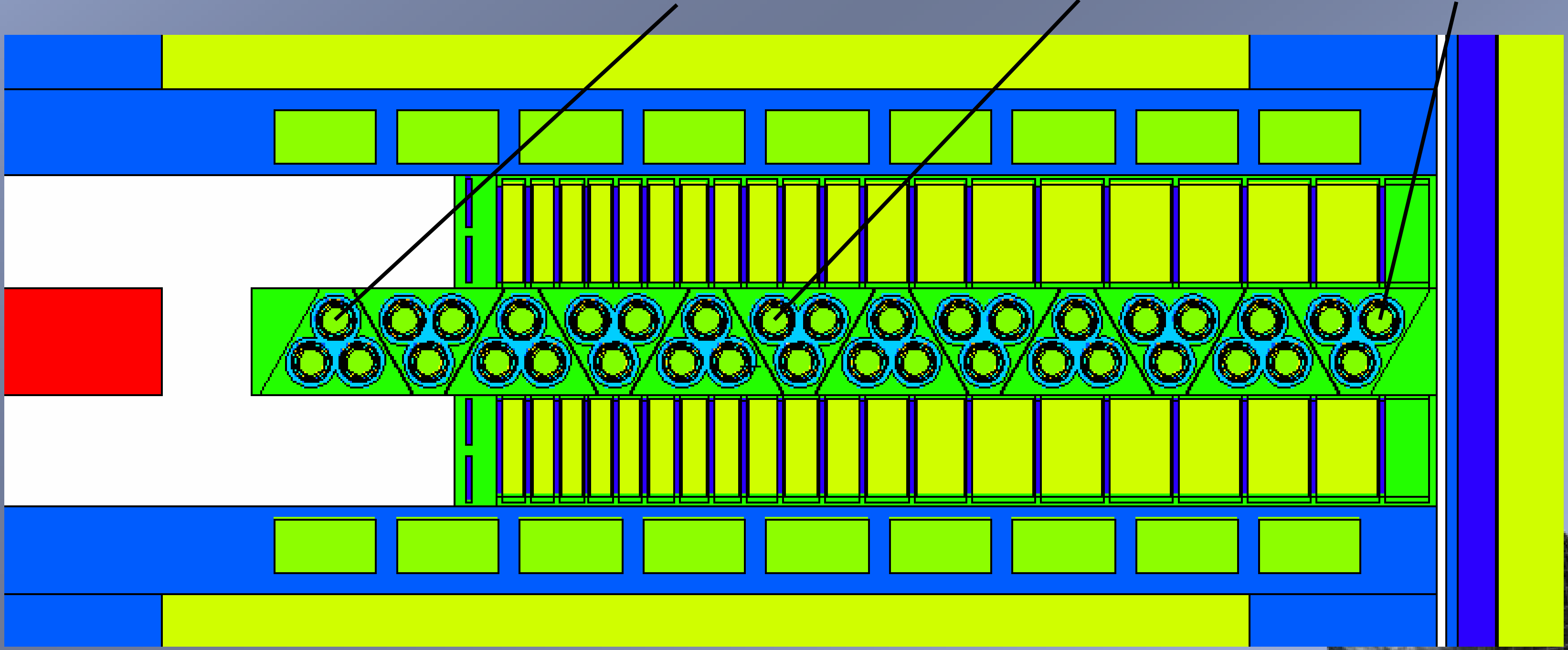
MTS neutron spectrum is similar to that of a fast reactor with the addition of a high-energy tail



Only 6% of neutron flux is >10 MeV

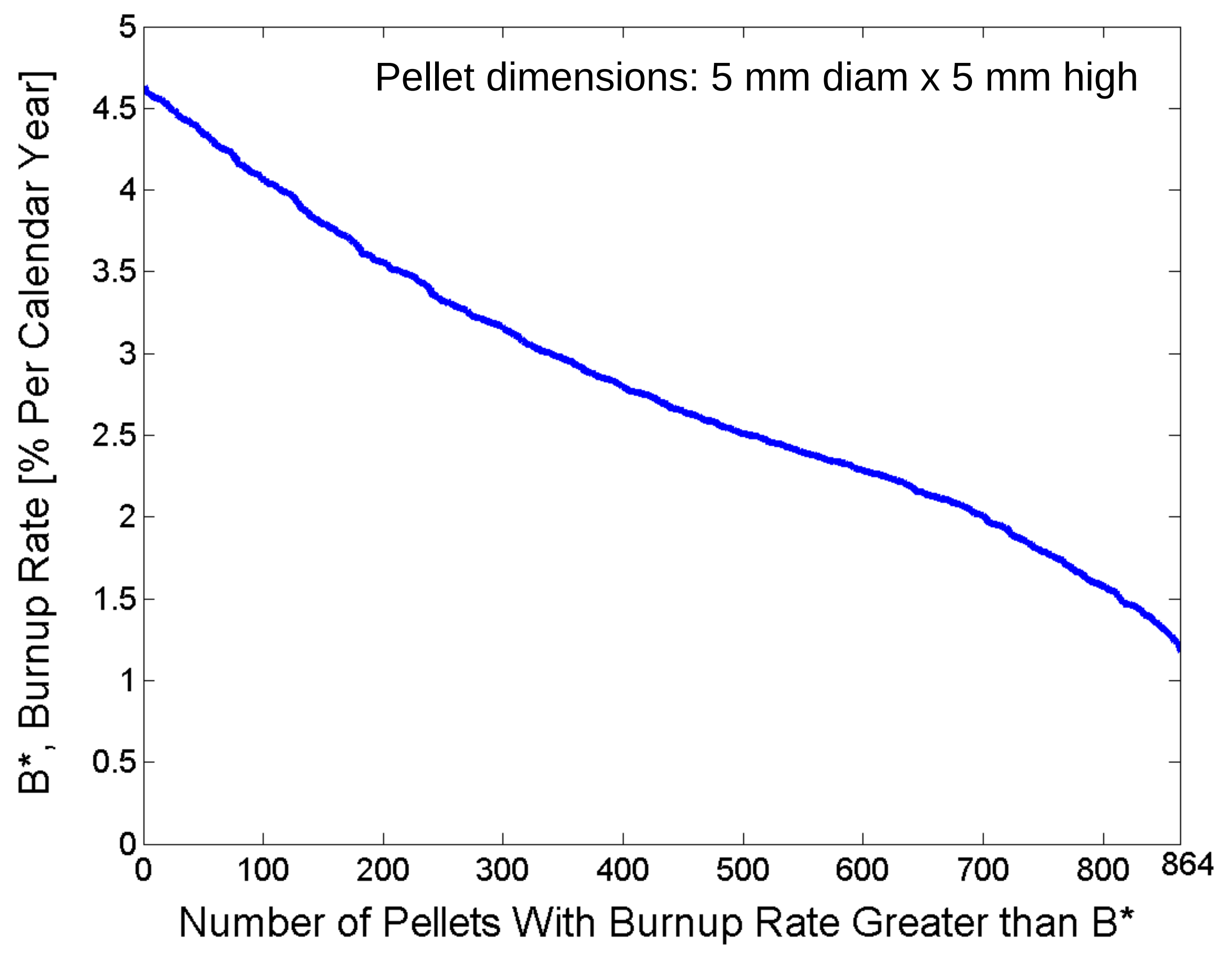
Compared to a fast reactor, the high-E tail of the MTS spectrum causes greater He production in Fe

He production (appm/y)*	**8.6**	**226**	**177**
Atomic displacements (dpa/y)*	**3.9**	**17.9**	**8.1**
He/dpa	**2.2**	**12.6**	**21.7**
Burnup (%/y)*	**1.4**	**4.6**	**2.2**
Neutron flux (10^{14} n/cm^2/s)	**5.1**	**16.7**	**8.1**



***Per calendar year (4,400 hours of full-power operation).**

Burnup rate histogram, 864 fuel pellets (HEU-WGPu oxide fuel / Ta housing, H_2O coolant)



The peak flux in MTS shows little dependence on test fuel composition

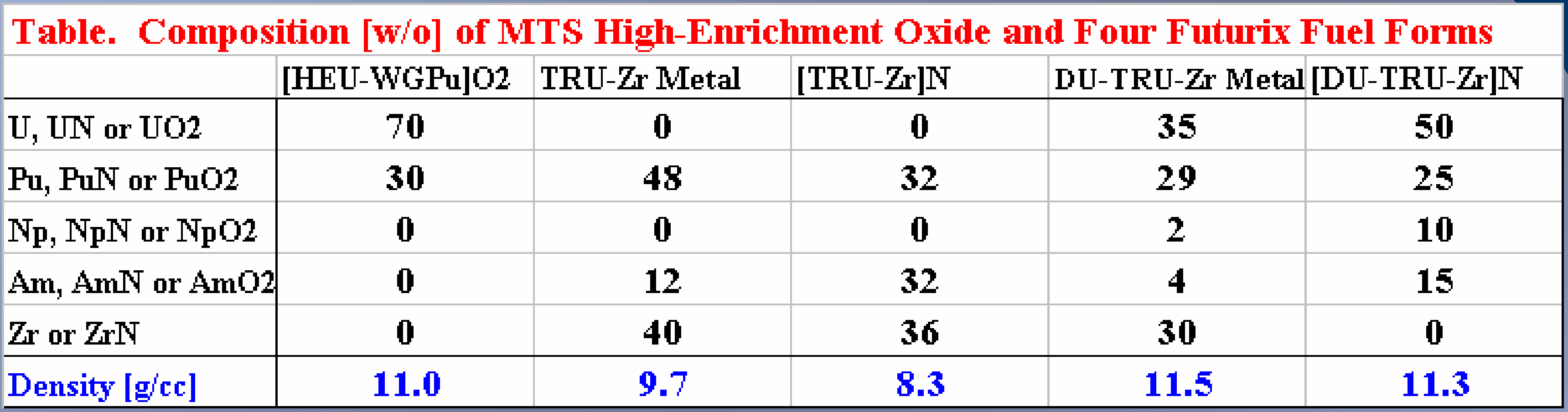
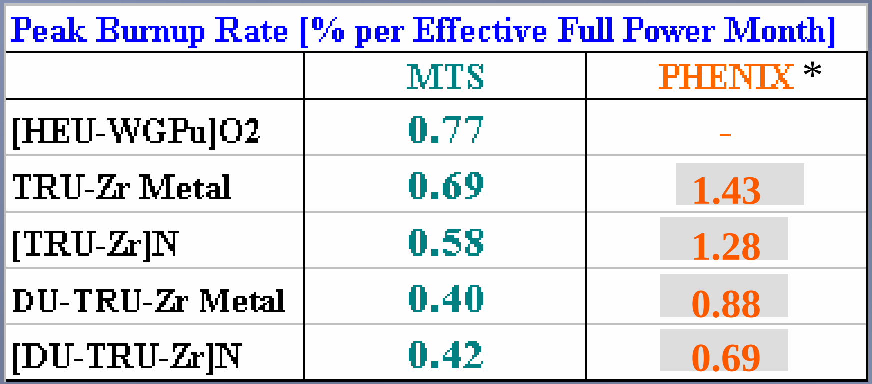


Table. Composition [w/o] of MTS High-Enrichment Oxide and Four Futurix Fuel Forms

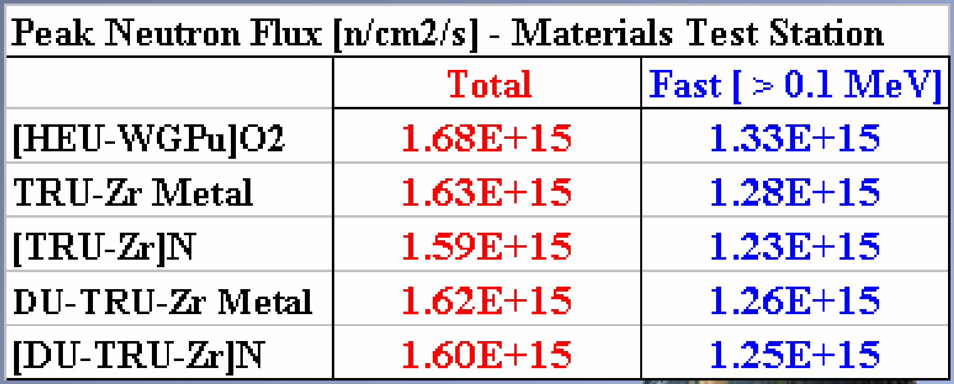
	[HEU-WGPu]O2	TRU-Zr Metal	[TRU-Zr]N	DU-TRU-Zr Metal	[DU-TRU-Zr]N
U, UN or UO2	70	0	0	35	50
Pu, PuN or PuO2	30	48	32	29	25
Np, NpN or NpO2	0	0	0	2	10
Am, AmN or AmO2	0	12	32	4	15
Zr or ZrN	0	40	36	30	0
Density [g/cc]	11.0	9.7	8.3	11.5	11.3



Peak Burnup Rate [% per Effective Full Power Month]

	MTS	PHENIX *
[HEU-WGPu]O2	0.77	-
TRU-Zr Metal	0.69	1.43
[TRU-Zr]N	0.58	1.28
DU-TRU-Zr Metal	0.40	0.88
[DU-TRU-Zr]N	0.42	0.69

*From Jaecki, et al., Global 2005.



Peak Neutron Flux [n/cm2/s] - Materials Test Station

	Total	Fast [> 0.1 MeV]
[HEU-WGPu]O2	1.68E+15	1.33E+15
TRU-Zr Metal	1.63E+15	1.28E+15
[TRU-Zr]N	1.59E+15	1.23E+15
DU-TRU-Zr Metal	1.62E+15	1.26E+15
[DU-TRU-Zr]N	1.60E+15	1.25E+15

PHENIX 4th ring 1.92E+15

The schedule shows project completion near the end of FY10

- Cleanout of Area A is estimated to take one year
- The total construction/installation process is estimated to take three years
- The actual completion date will depend on timely DOE Critical Decision approvals and adequate funding
- MTS Total Project Cost estimate is $73M, including 25% contingency
- Operating cost is $6M - $10M per year