Dry-Wall Target Chambers for Direct-Drive Laser Fusion

Gerald L. Kulcinski, Robert R. Peterson and
Donald A. Haynes

presenting for the staff of the
Fusion Technology Institute
University of Wisconsin-Madison

Laser IFE Workshop
February 6-7, 2001
Naval Research Laboratory

Program Plan for the Design of Dry-Wall Target Chambers for Direct Drive Laser Fusion-U. of Wisconsin (WBS 3.1-3)

Overall Objective…………..Integrated direct drive fusion chamber concept

FY 01 Deliverables………

1. **Calculate threat spectra to first wall and assess methods to eliminate wall ablation.**
2. **Identify injection conditions that will allow several direct drive targets to survive to thermal environment inside the chambers.**
3. **Design blanket and shielding to protect critical components.**
4. **Incorporate innovative concepts into previous designs.**

FY01 Funding **$500 k**

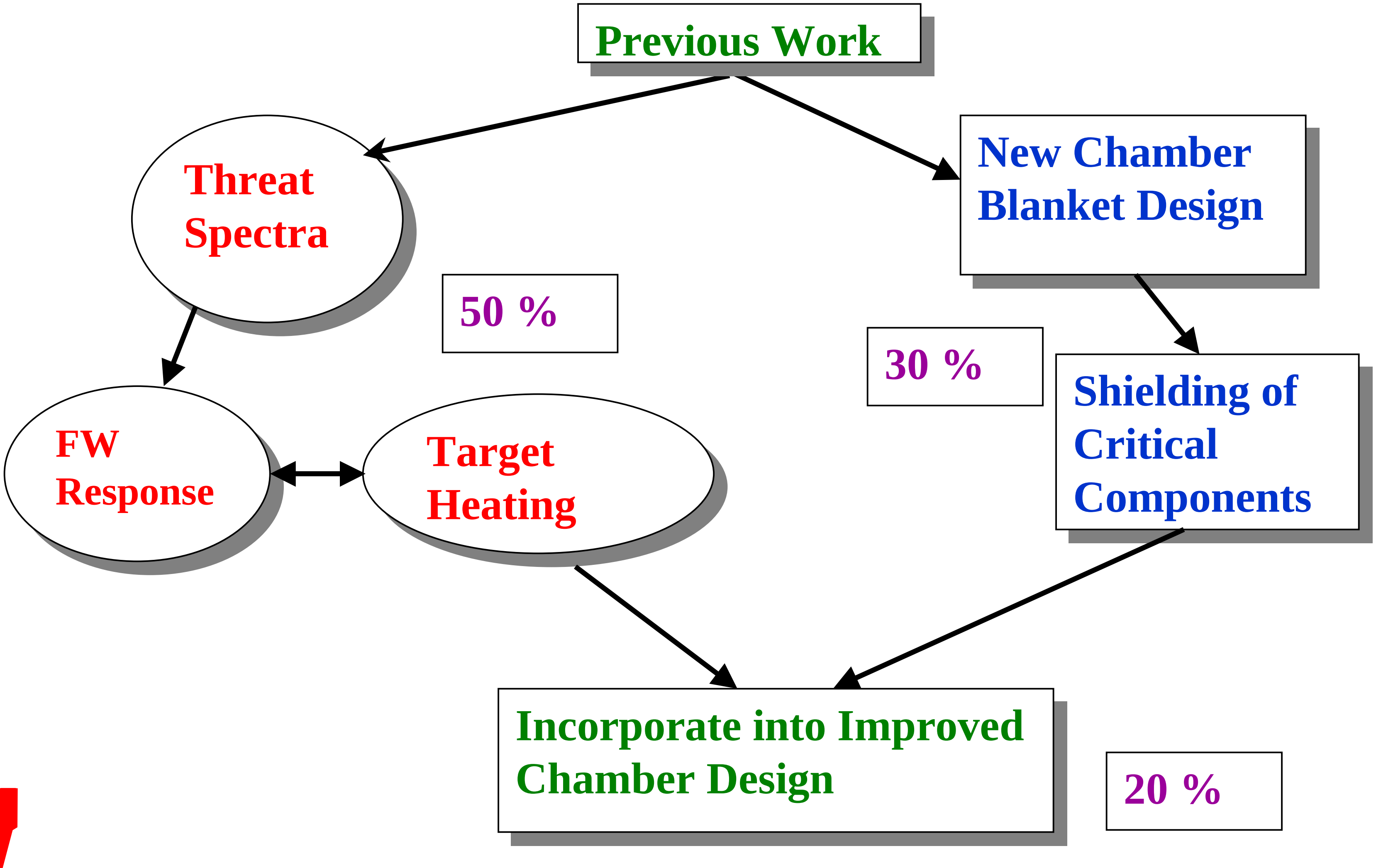
Relevance of Deliverables

NIF-Wall survival (1,3), Safety (3)

DP/NNSA-Reaction products, opacity modeling (1)

Energy-IFE Power Plants (1,2,3,4)

Elements of UW FY 01-02 Research on Dry Wall Target Chambers for Direct Drive Laser Fusion



Previous Work

Threat Spectra

FW Response

Target Heating

50 %

New Chamber Blanket Design

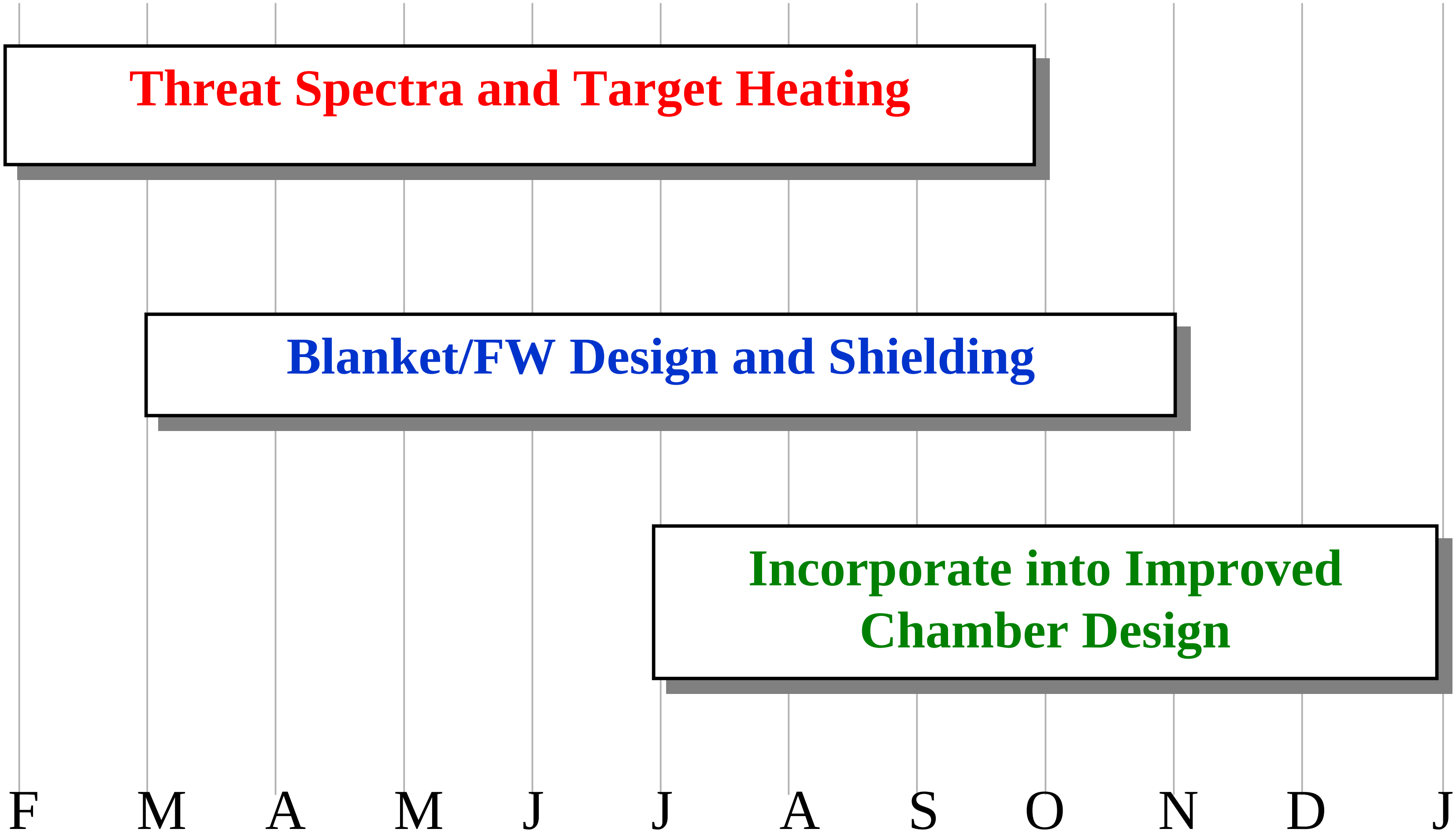
Shielding of Critical Components

30 %

Incorporate into Improved Chamber Design

20 %

Chronology of UW Work on Dry Wall Laser Chambers



Threat Spectra and Target Heating

Blanket/FW Design and Shielding

Incorporate into Improved Chamber Design

Key Personnel for FY01-02 Work on Laser Fusion Chambers-University of Wisconsin

Threat Spectra and Target Heating

Robert Peterson
Donald Haynes
Igor Golovkin
Greg Moses
Elsayed Mogahed
Igor Sviatoslavsky
Paul Wilson
John Santarius
Gerald Kulcinski

Chamber Design and Shielding

Mohamed Sawan
Laila El-Guebaly
Doug Henderson
Hesham Khater
Elsayed Mogahed
Igor Sviatoslavsky
Gerald Kulcinski

Improved Chamber Design

Igor Sviatoslavsky
Mohamed Sawan
Robert Peterson
Gerald Kulcinski

Target Output and First Wall Calculations for Laser Fusion Chambers

Robert R. Peterson, Donald A. Haynes and
Igor E. Golovkin
University of Wisconsin-Madison
Fusion Technology Institute

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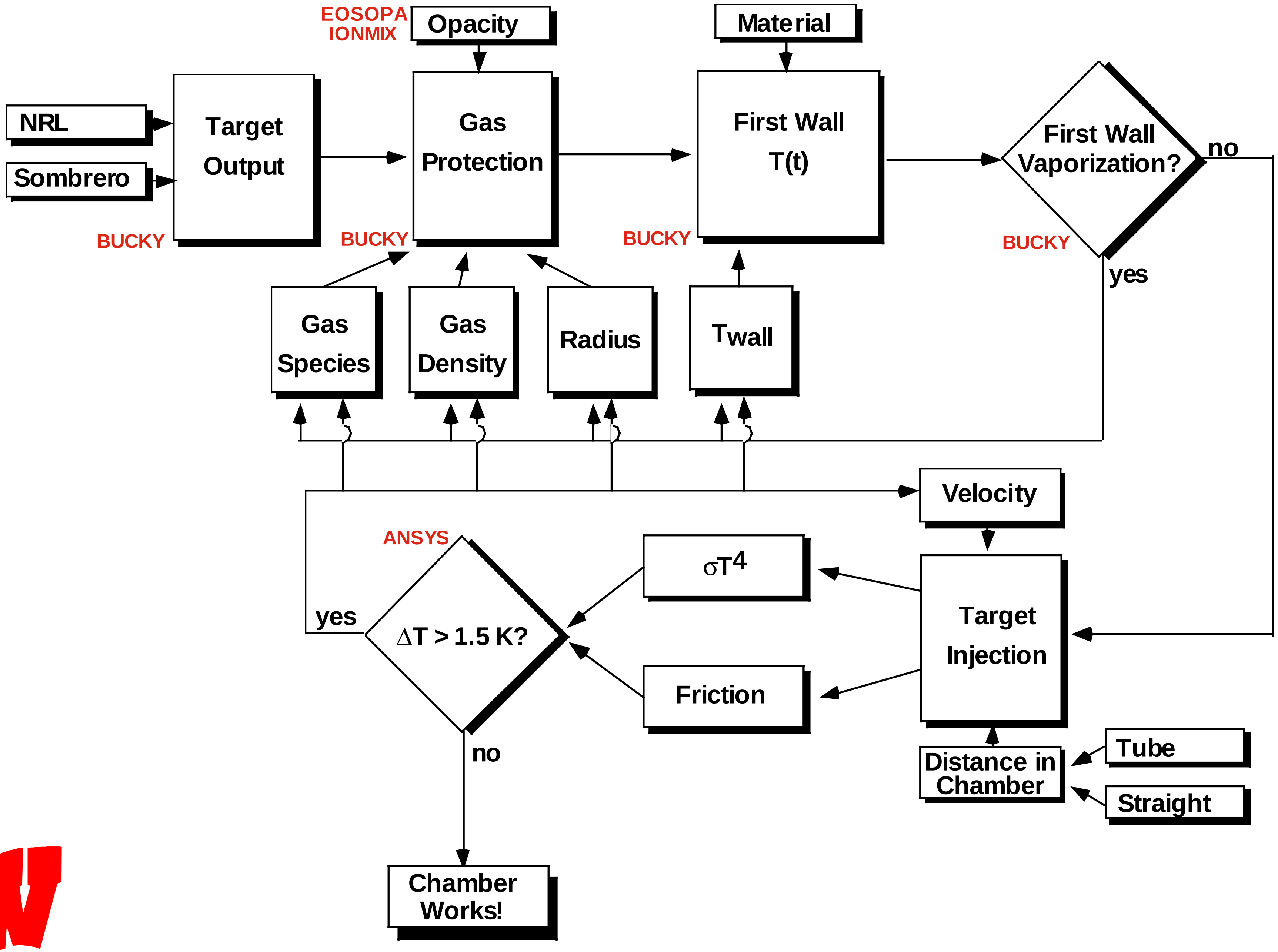
Objective of Present Study

- To understand if the recent NRL direct drive target design can survive in a SOMBRERO-type dry wall chamber (no vaporization of C-C composite)
- To investigate the degree to which the Xe fill gas could be reduced to lower the aerodynamic frictional heating of direct drive targets.
- Apply latest analysis methods and explore the possibility of innovative injection techniques in dry wall chambers

Roadmap to Calculate IFE Wall/Target Survival Conditions



NRL

Sombrero

Target Output

BUCKY

EOSOPA
IONMIX

Opacity

Gas Protection

BUCKY

Material

First Wall T(t)

BUCKY

First Wall Vaporization?

BUCKY

no

yes

Gas Species

Gas Density

Radius

Twall

Velocity

ANSYS

σT^4

Target Injection

yes

$\Delta T > 1.5$ K?

Friction

no

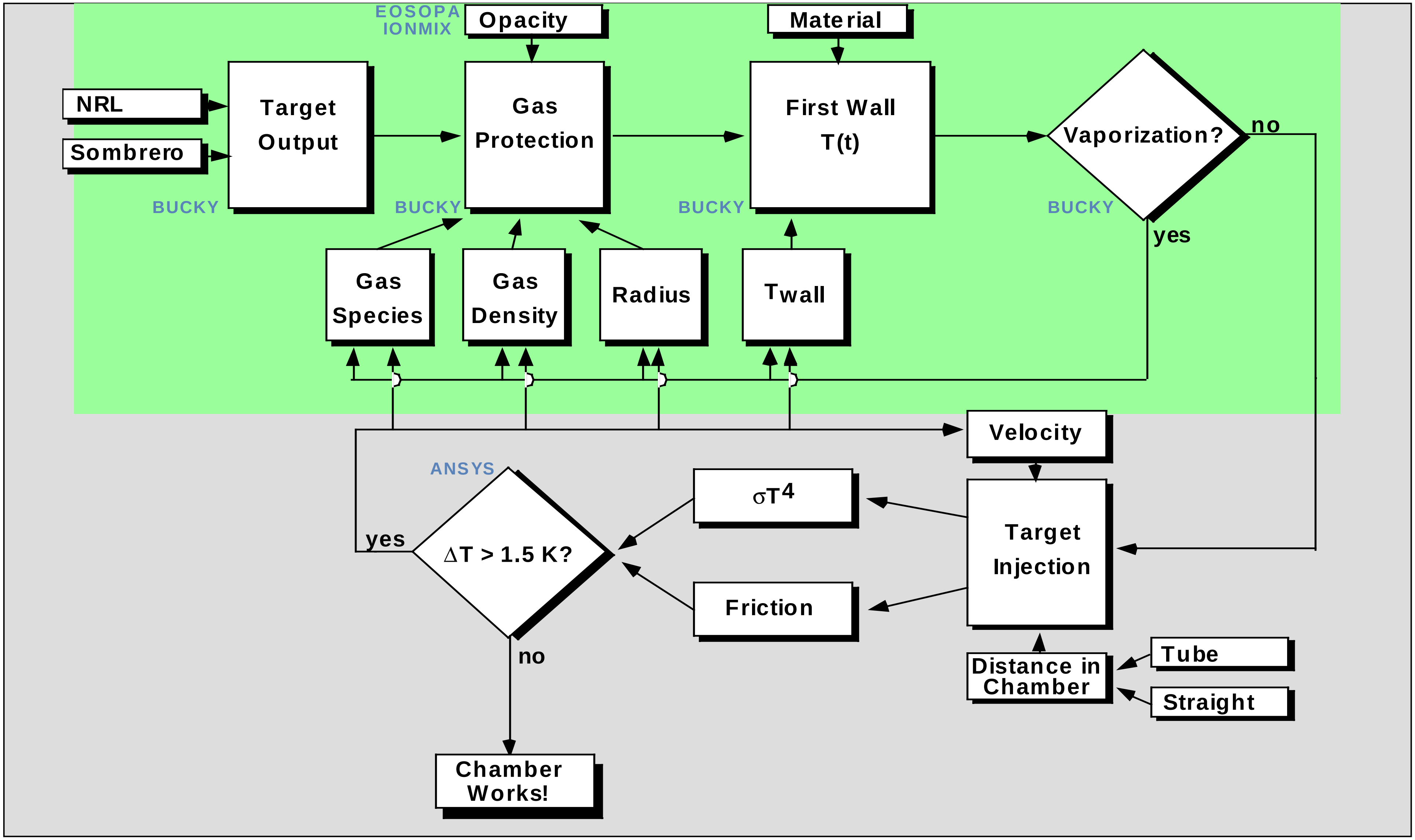
Distance in Chamber

Tube

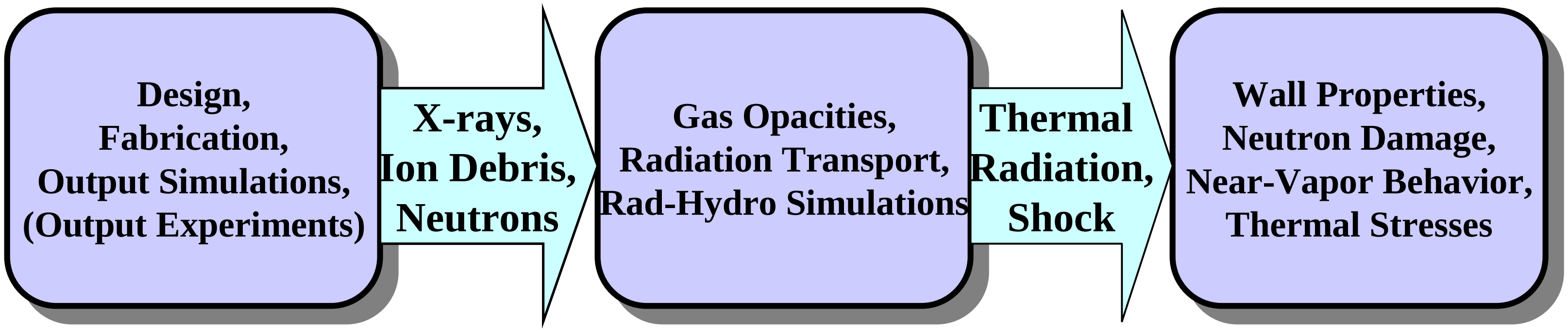
Straight

Chamber Works!

First Wall Erosion and *Target Heating During Injection* are Competing Concerns in Direct-Drive Laser Fusion Dry-Wall Target Chambers



Chamber Physics Critical Issues Involve Target Output, Gas Behavior and First Wall Response



Target Output

Design,
Fabrication,
Output Simulations,
(Output Experiments)

X-rays,
Ion Debris,
Neutrons

Gas Behavior

Gas Opacities,
Radiation Transport,
Rad-Hydro Simulations

Thermal
Radiation,
Shock

Wall Response

Wall Properties,
Neutron Damage,
Near-Vapor Behavior,
Thermal Stresses

UW uses the BUCKY 1-D Radiation-Hydrodynamics Code to Simulate Target, Gas Behavior and Wall Response.

BUCKY, a Flexible 1-D Lagrangian Radiation-Hydrodynamics Code; Useful in Predicting Target Output and Target Chamber Dynamics

- **1-D Lagrangian MHD (spherical, cylindrical or slab).**

- **Thermal conduction with diffusion.**
- **Applied electrical current with magnetic field and pressure calculation.**
- **Equilibrium electrical conductivities**

- **Radiation transport with multi-group flux-limited diffusion, method of short characteristics, and variable Eddington.**
- **Non-LTE CRE line transport.**
- **Opacities and equations of state from EOSOPA or SESAME.**

BUCKY, a Flexible 1-D Lagrangian Radiation-Hydrodynamics Code; Useful in Predicting Target Output and Target Chamber Dynamics

- Thermonuclear burn (DT,DD,DHe^3) with in-flight reactions.
- Fusion product transport; time-dependent charged particle tracking, neutron energy deposition.

- Applied energy sources: time and energy dependent ions, electrons, x-rays and lasers (normal incidence only).
- Moderate energy density physics: melting, vaporization, and thermal conduction in solids and liquids.

- Benchmarking: x-ray burn-through and shock experiments on Nova and Omega, x-ray vaporization, RHEPP melting and vaporization, PBFA-II K_α emission, …
- Platforms: UNIX, PC, MAC

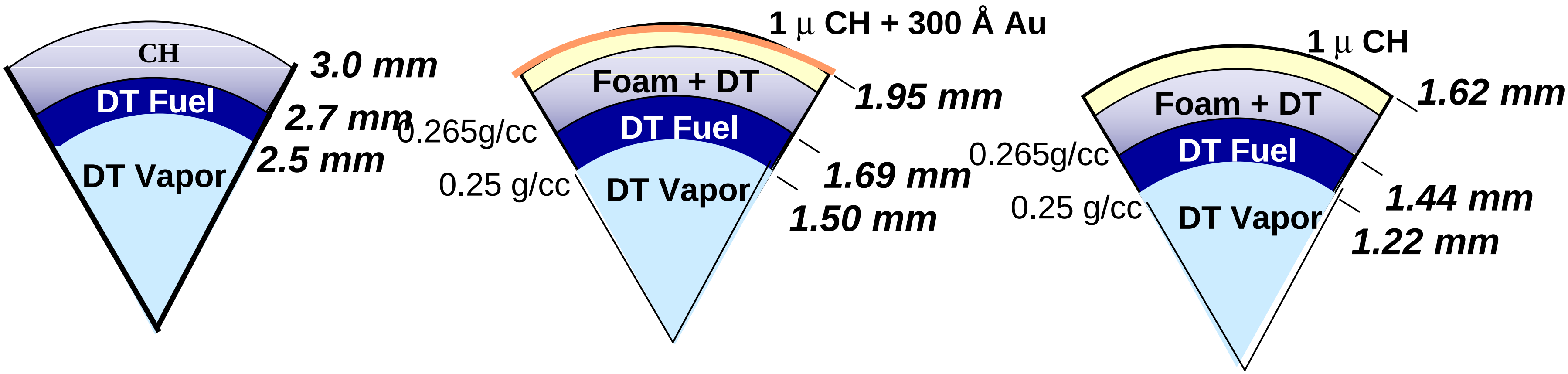
Direct-Drive Targets Under Consideration Have Different Output

Direct-drive Laser Targets

SOMBRERO (1990)
Standard Direct-Drive

NRL (1999)
Radiation Tailored-Wetted Foam

NRL (1999)
Wetted Foam



Laser Energy: 4 MJ
Laser Type: KrF
Gain: 100
Yield: 400 MJ

Laser Energy: 1.3 MJ
Laser Type: KrF
Gain: 127
Yield: 165 MJ

Laser Energy: 1.6 MJ
Laser Type: KrF
Gain: 108
Yield: 173 MJ

Debris Ions

94 keV D -	5.81 MJ
141 keV T -	8.72 MJ
138 keV H -	9.24 MJ
188 keV He -	4.49 MJ
1600 keV C -	55.24 MJ
Total -	83.24 MJ per shot

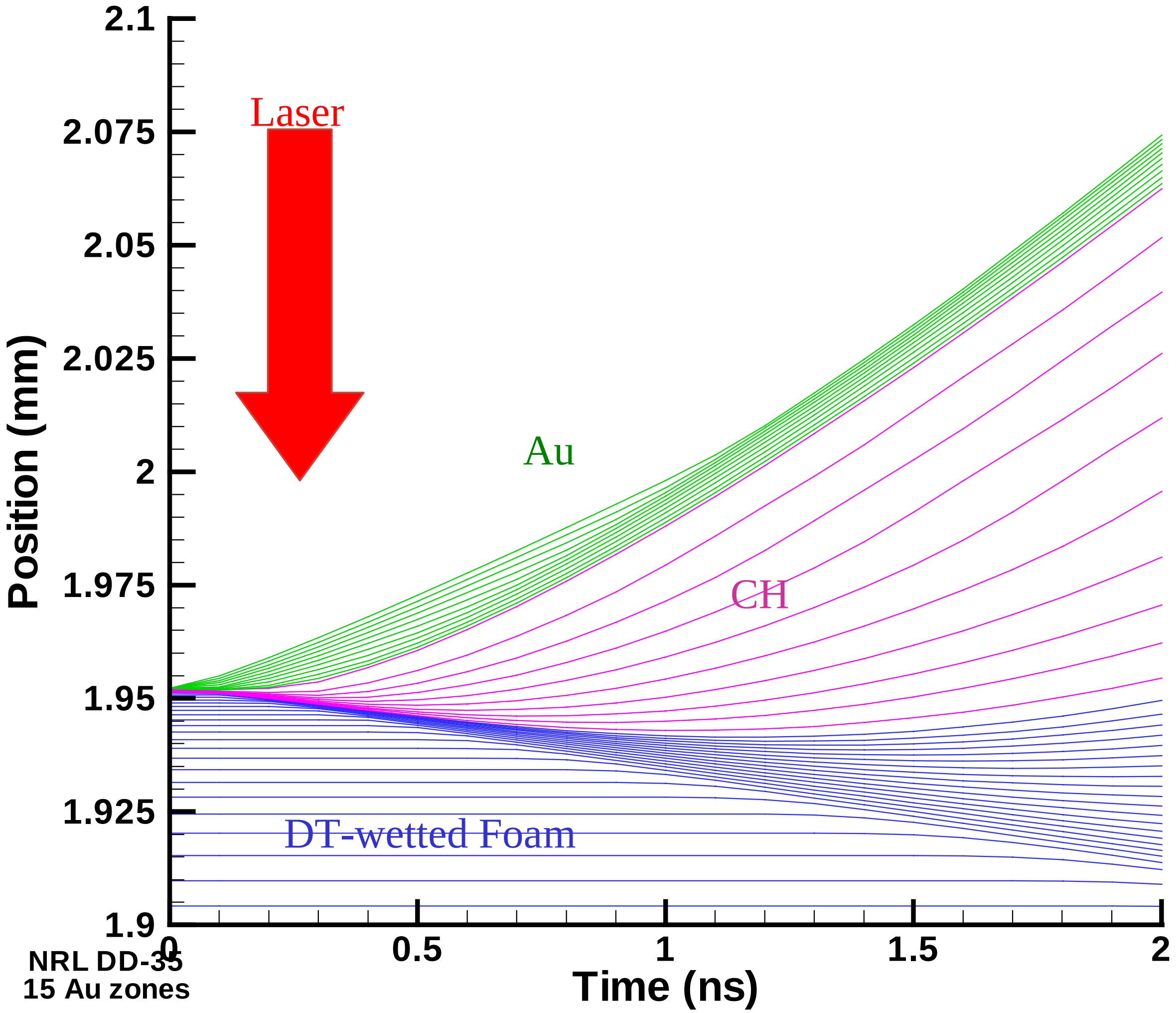
Spectra:
- Calculated with BUCKY
- Calculated by NRL
- Calculated with Lasnex

Spectra:
- Not Yet Calculated

The energy partition and spectra for SOMBRERO were supplied by DOE and need to be calculated.

Laser Quickly Burns though 300 Å Au and Radiatively Pre-Heats the Ablator

- Close-up of laser burning through thin gold and plastic shells of NRL target
- Gold and plastic are hot and rapidly rarifying, probably not in local thermodynamic equilibrium.
- Gold is expanding at 75 km/s from laser blow-off.



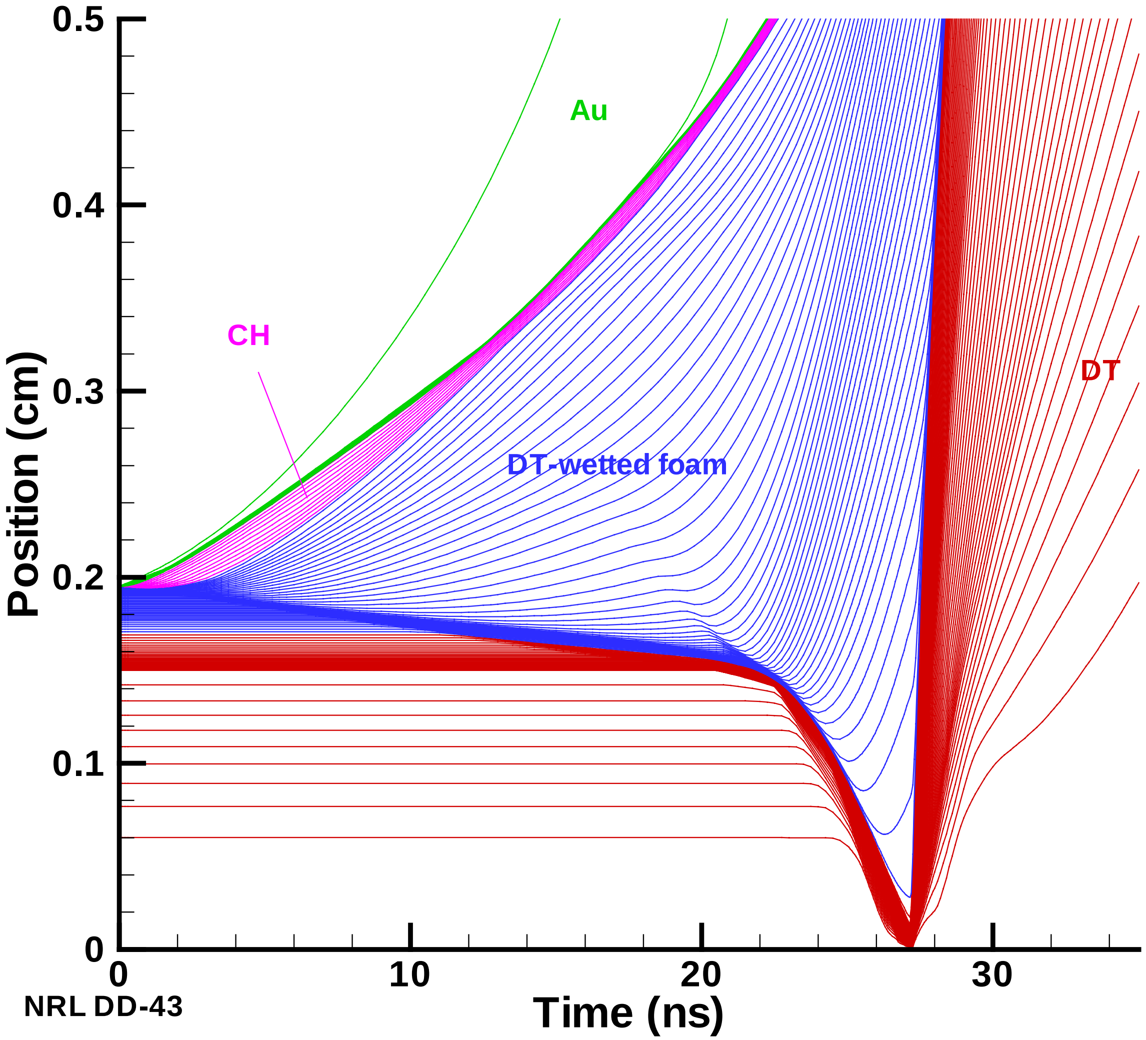
Implosion, Burn and Explosion of NRL Radiation Smoothed Direct-Drive Laser Fusion Target

- 22% of DT ice is burned; NRL and LLNL get about 32 %, though peak ρR (LLNL) and bang time (NRL) do agree.

- Very little DT in wetted foam is burned.
- This calculation yielded 115 MJ; another, 200 MJ

- Other yields would be achieved with further tuning.

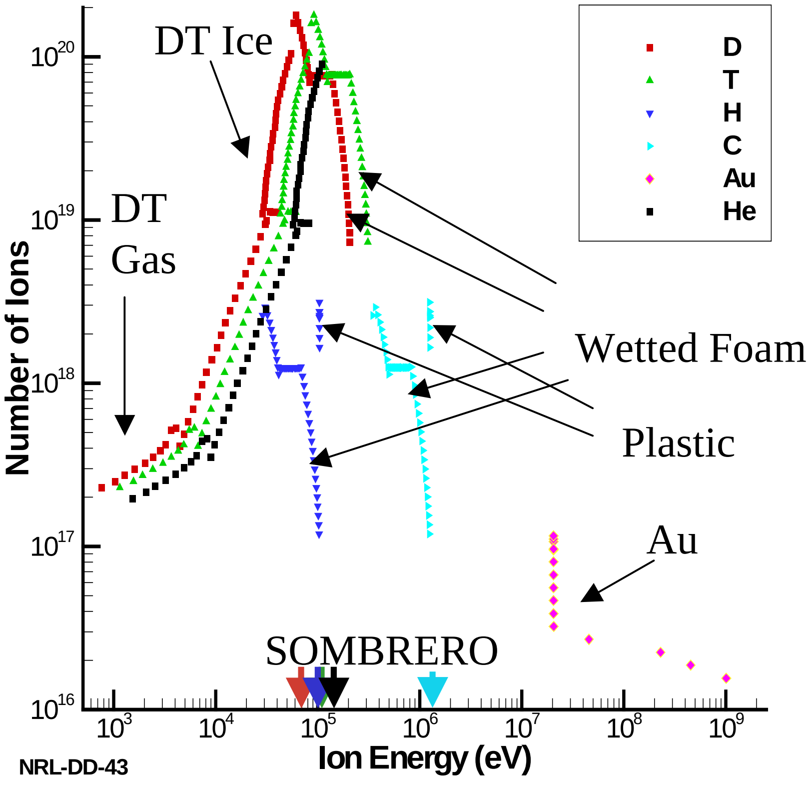
- Target expands at a few time 10^8 cm/s and radiates.



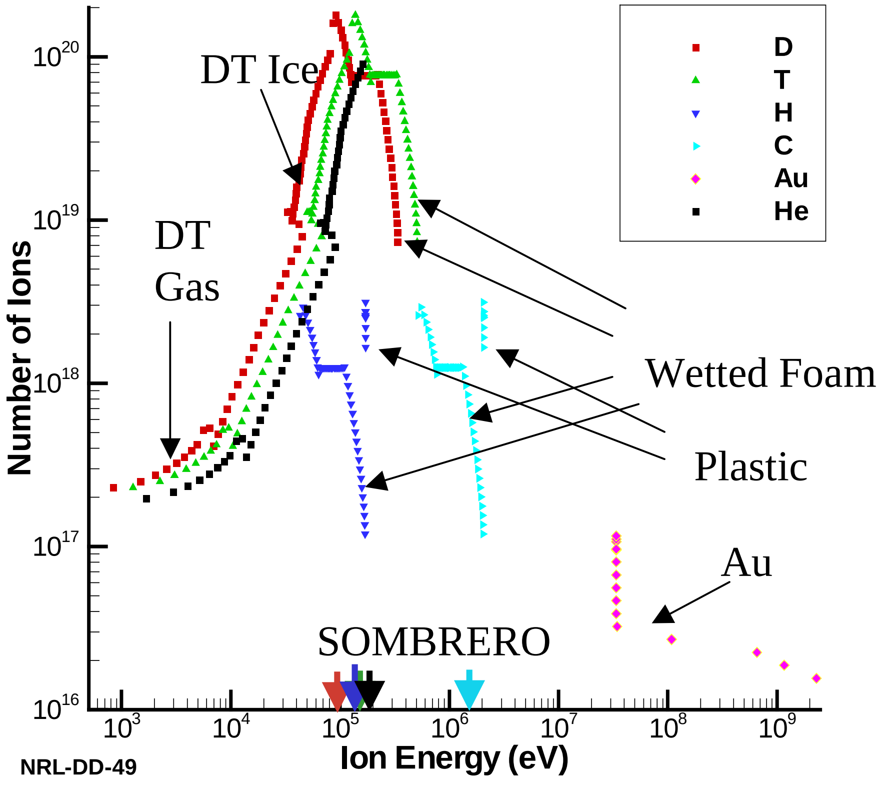
Ion Spectrum for NRL Radiation Pre-Heated Target Depends on Yield

- The particle energy of each species in each zone is then calculated as $mv^2/2$ on the final time step of the BUCKY run. This time is late enough that the ion energies are unchanging. The numbers of ions of each species in each zone are plotted against ion energy.
- The spectra from direct fusion product D, T, H, He^3, and He^4 are calculated by BUCKY but they don't make it out of the target.
- The ion spectra is more energetic for 200 MJ yield

Ion Spectrum for 115 MJ Yield NRL Target



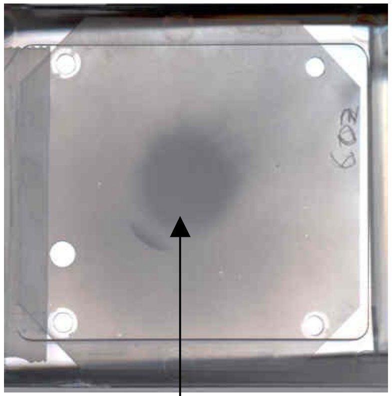
Ion Spectrum for 200 MJ Yield NRL Target



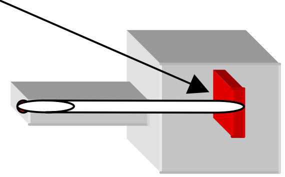
Ion Spectrum Experiments on Z are in Progress to Validate Target Output Calculations

SHOT # 603 **06/26/00 16:13**

CR39 film measures ion energy through damage track lengths.



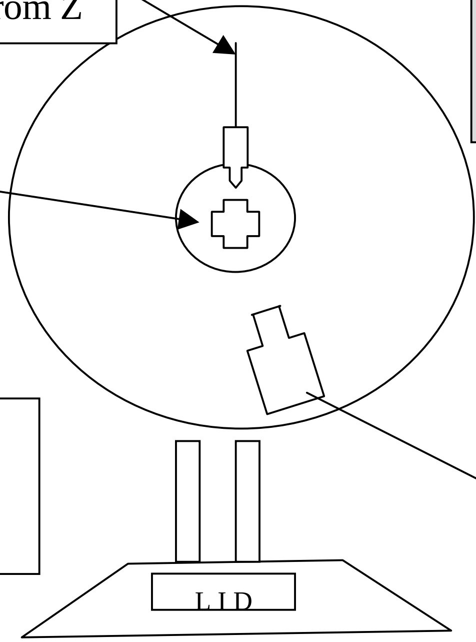
Damage by ions



Open collimator LOS 1/2 8” from Z

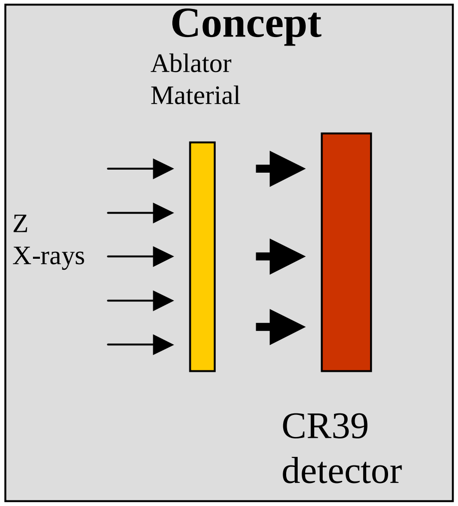
Z-pinch x-ray source

Ion track analysis and supporting BUCKY simulations are in progress.



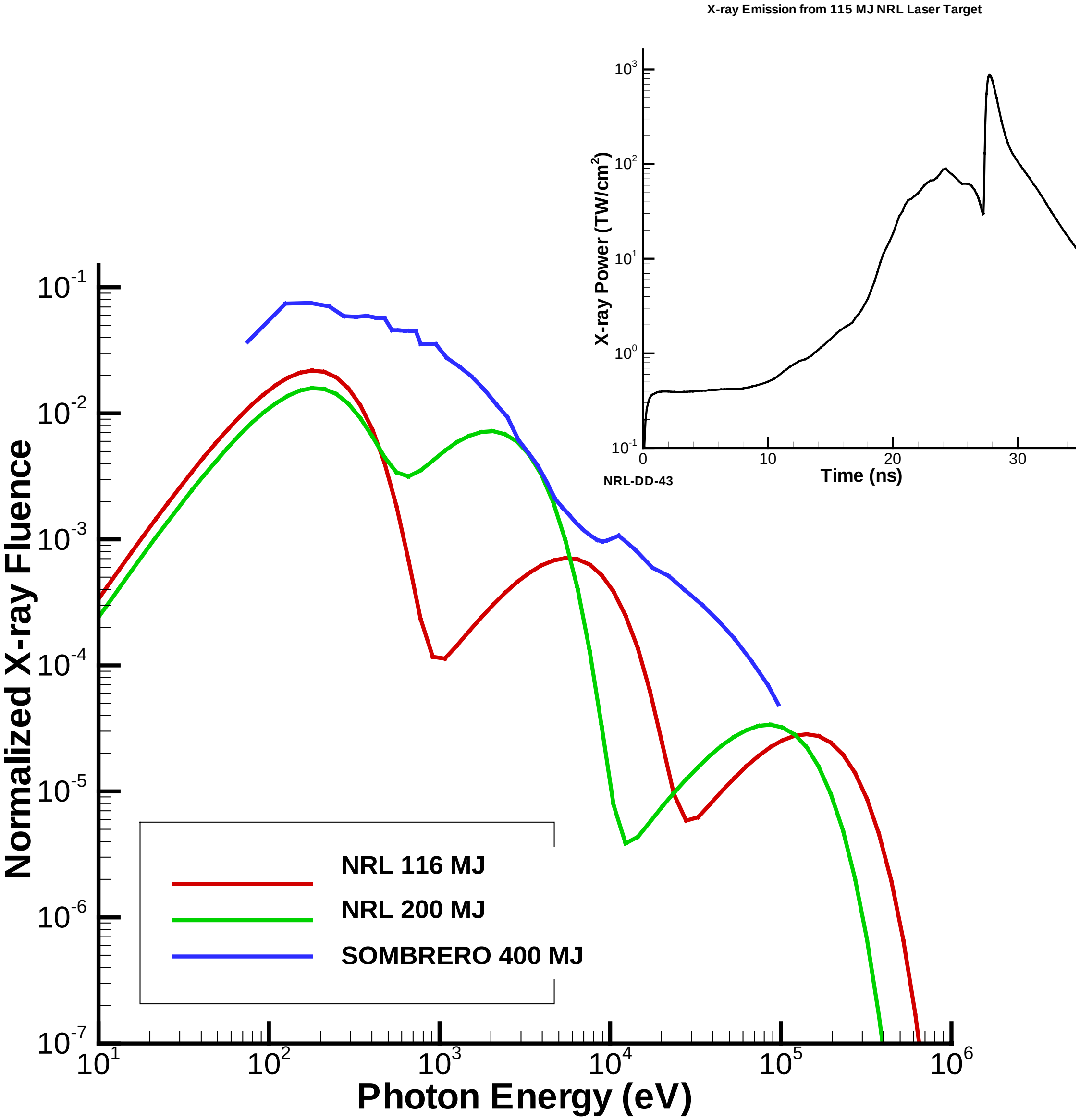
Pin Hole Camera 10 degrees tilt to center.
9” from center of camera hole plate to blast shield.

Concept

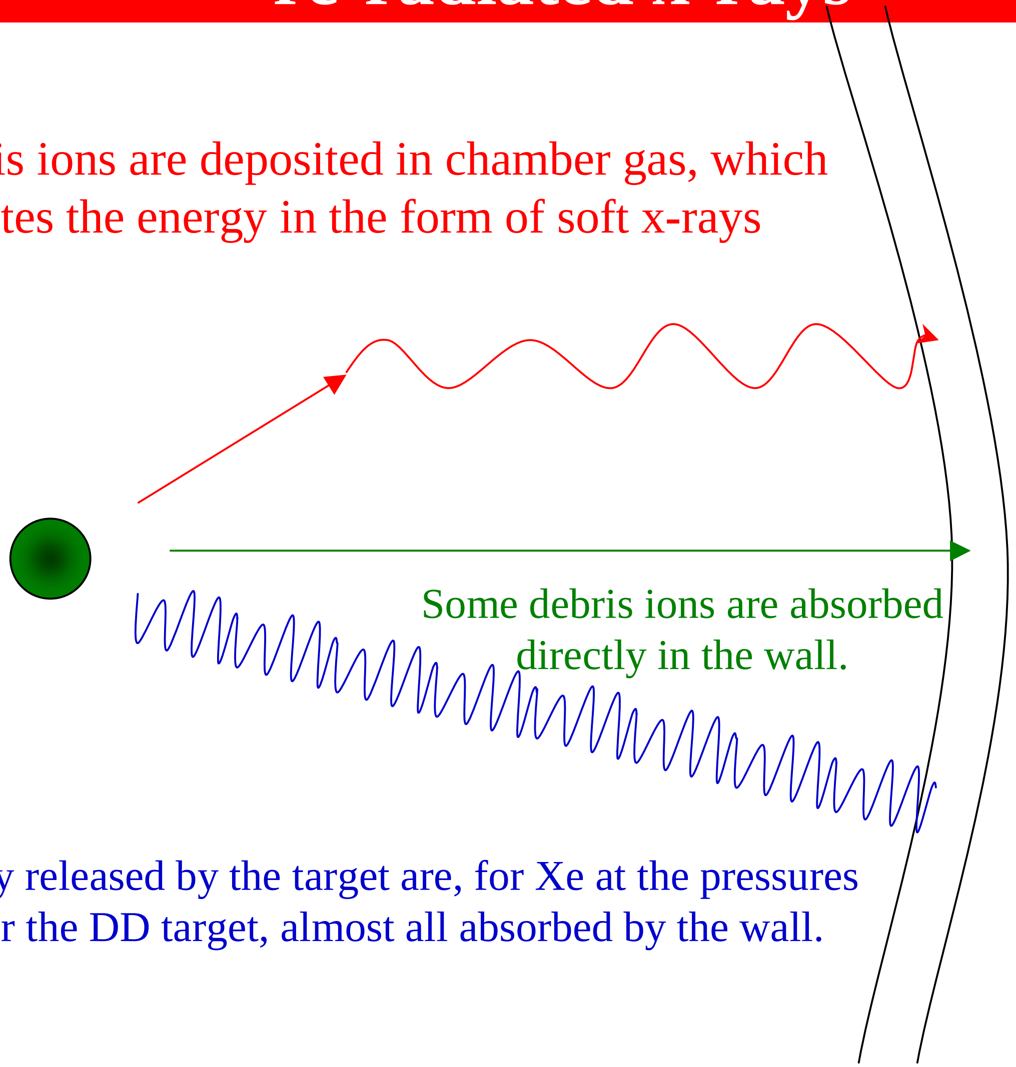


X-ray Spectra from Targets is Changed by High Z Components and Yield

- •X-ray spectra are converted to sums of 3 black-body spectra.
- •Time-dependant spectra are in Gaussian pulses with 1 ns half-widths and are used in chamber simulations.
- • Time-integrated fluences are shown for 115 MJ and 200 MJ NRL and 400 MJ SOMBRERO.
- •The presence of Au in the NRL targets adds emission in spectral region above a few keV.
- •At higher yield the Au is more important.



The threat spectrum can be thought of as arising from three contributions: fast x-rays, unstopped ions, and re-radiated x-rays



Some debris ions are deposited in chamber gas, which re-radiates the energy in the form of soft x-rays

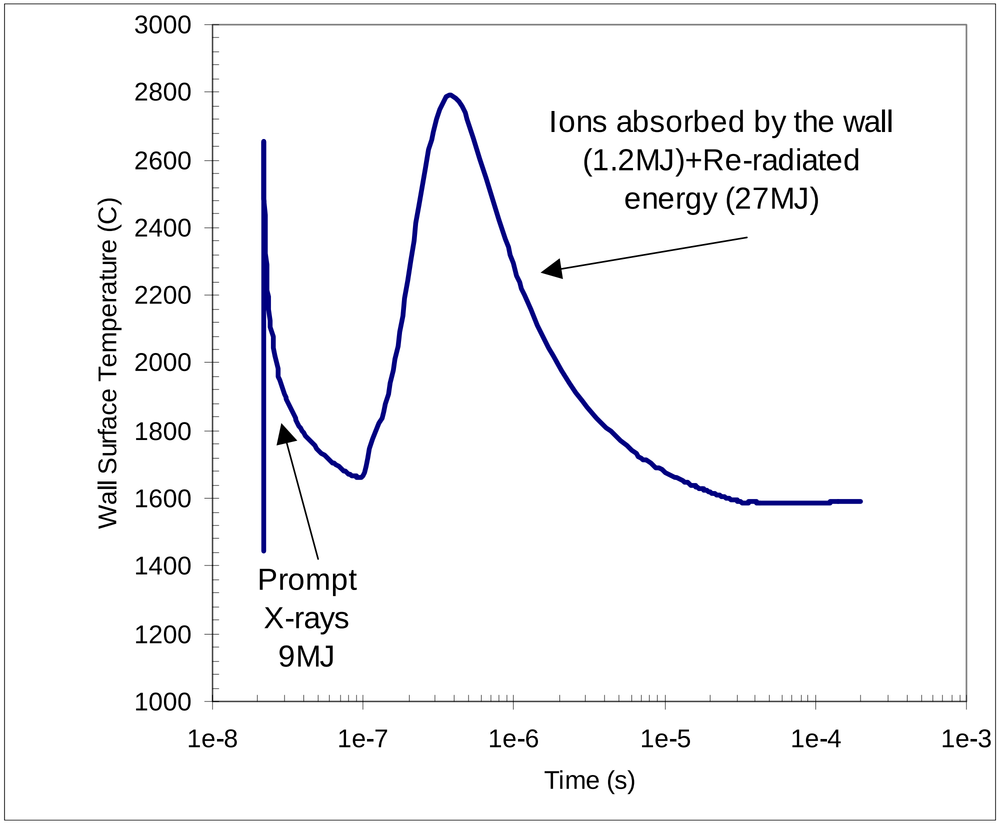
Some debris ions are absorbed directly in the wall.

The x-rays directly released by the target are, for Xe at the pressures contemplated for the DD target, almost all absorbed by the wall.

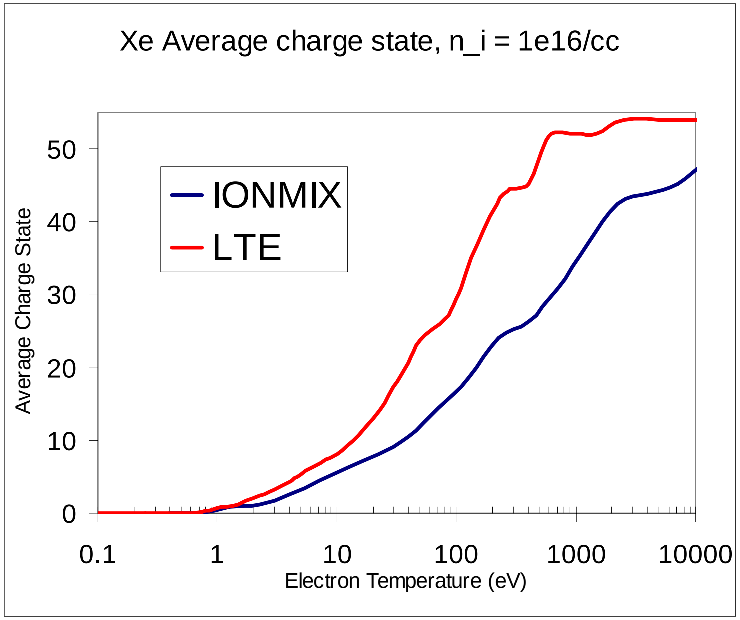
The wall (or armor) reacts to these insults in a manner largely determined by it’s thermal conductivity and stopping power.

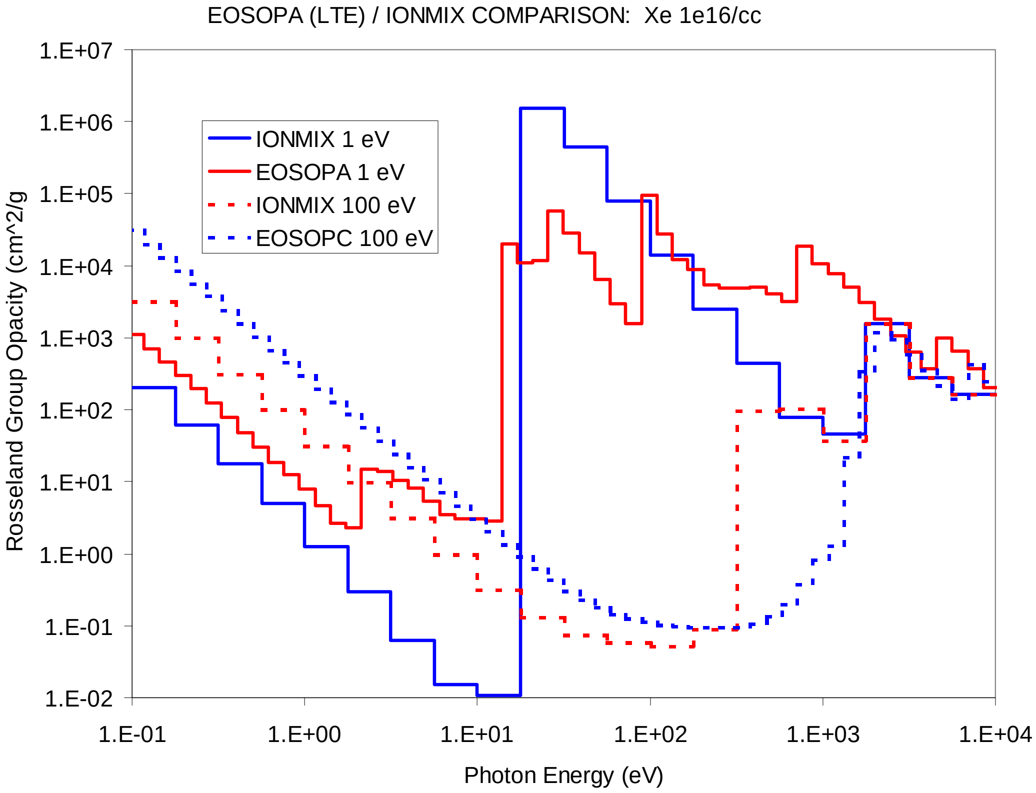
For example, the first wall does not vaporize for the SOMBRERO target in a 6.5m radius chamber filled with 0.1 torr Xe and a wall equilibrium temperature of 1450C.

- The separation in time of the insults from the prompt x-ray, the ions, and the re-radiated x-rays is crucial to the survival of the wall.
- The Xe serves to absorb the vast majority of the ion energy and almost half of the prompt x-rays and slowly re-radiates the absorbed energy at a rate determined by the Plank emission opacity of the Xe.



For the current calculations, IONMIX has been used to generate Non-LTE Xe opacity tables

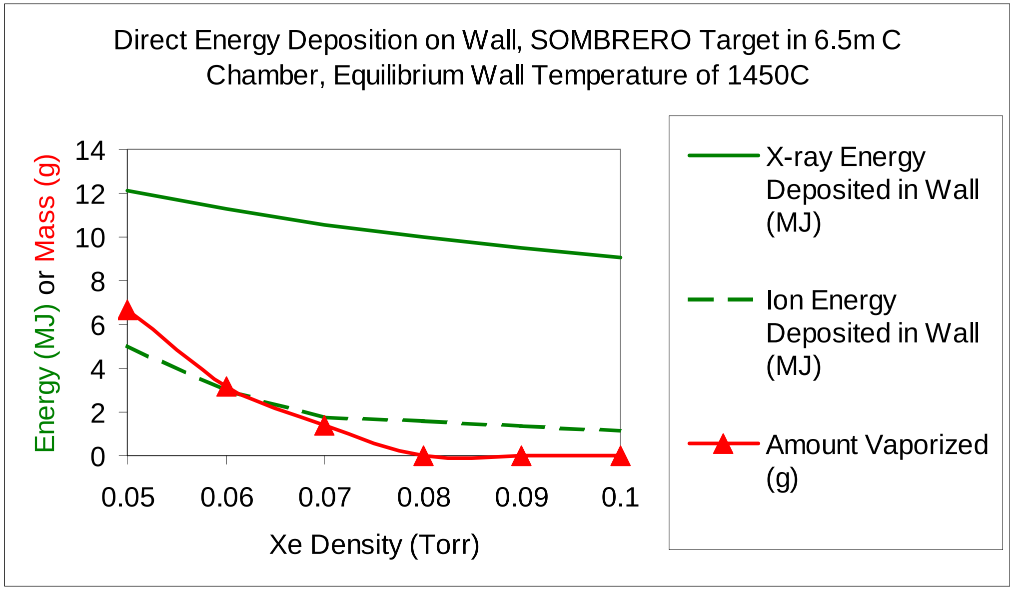


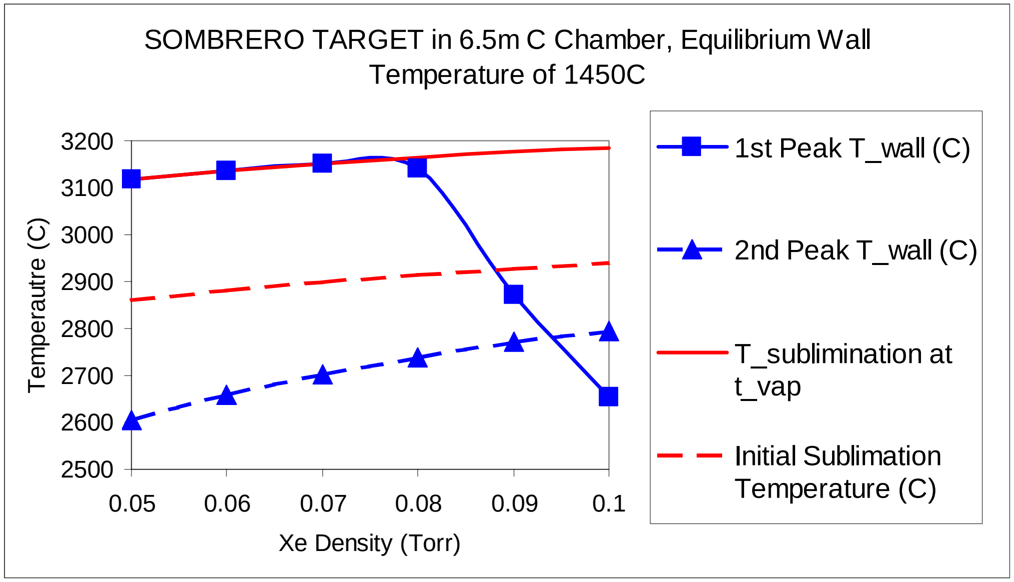


- Xe gas at or below 0.5 Torr in Density is not in LTE.
- Non LTE (IONMIX) ionization is substantially below the LTE (Saha) ionization.
- The Xe opacity can differ substantially between LTE (EOSOPC) and Non-LTE (IONMIX).
- IONMIX opacities are used in this study.

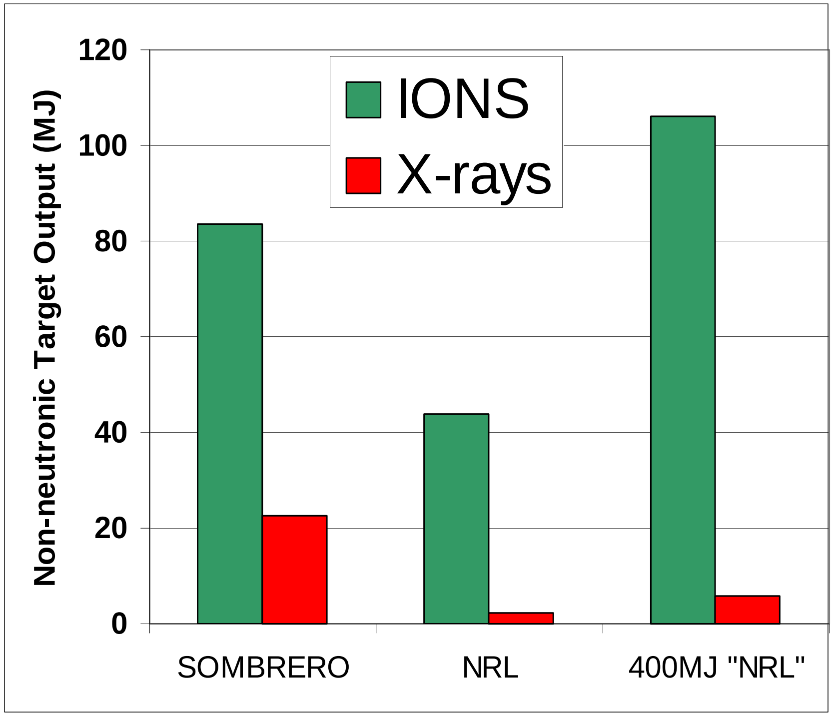
A scan of Xe density holding the first wall equilibrium temperature fixed at 1450C was performed to examine the onset of vaporization.

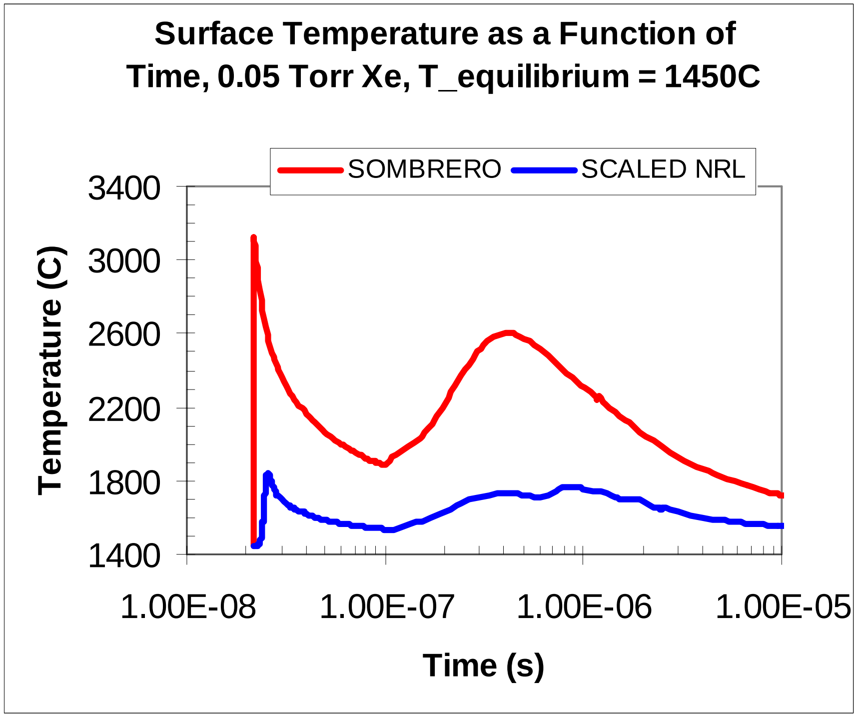
- For the SOMBRERO target in a 6.5m graphite chamber, the prompt x-rays are the major threat.
- Even at 0.05 Torr Xe, 78MJ of the 83MJ of ion energy is absorbed by the gas, slowly re-radiated to contribute to the second peak in temperature.
- The sublimation threshold occurs when the prompt x-rays loading is above 1.88 J/cm^2 for x-rays with the SOMBRERO spectrum, for this equilibrium wall temperature.





The SOMBRERO and NRL targets differ significantly in yield, partitioning, and spectra. These differences lead to very different target chamber dynamics.





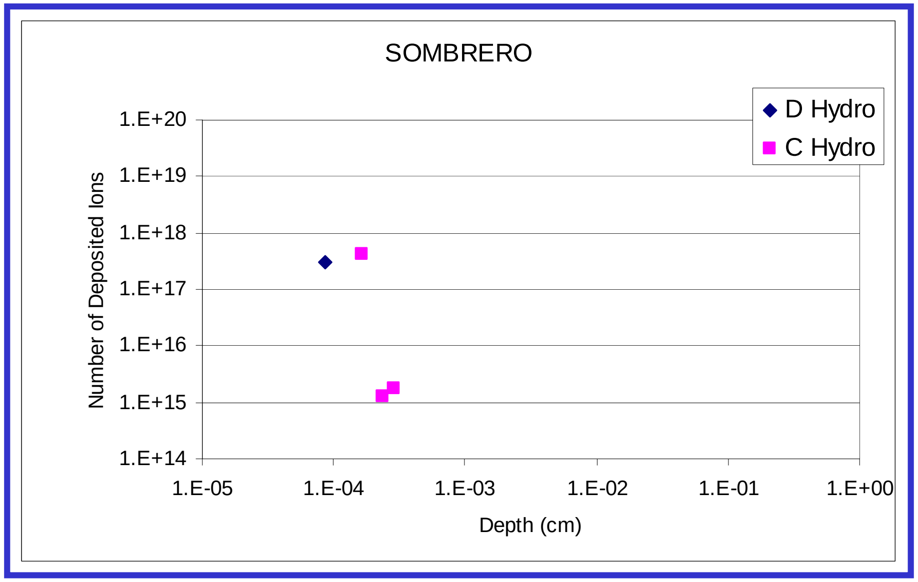
•Even if the NRL spectra are scaled up by the ratio of the total yields (400/165), it poses considerably less threat to the target chamber.

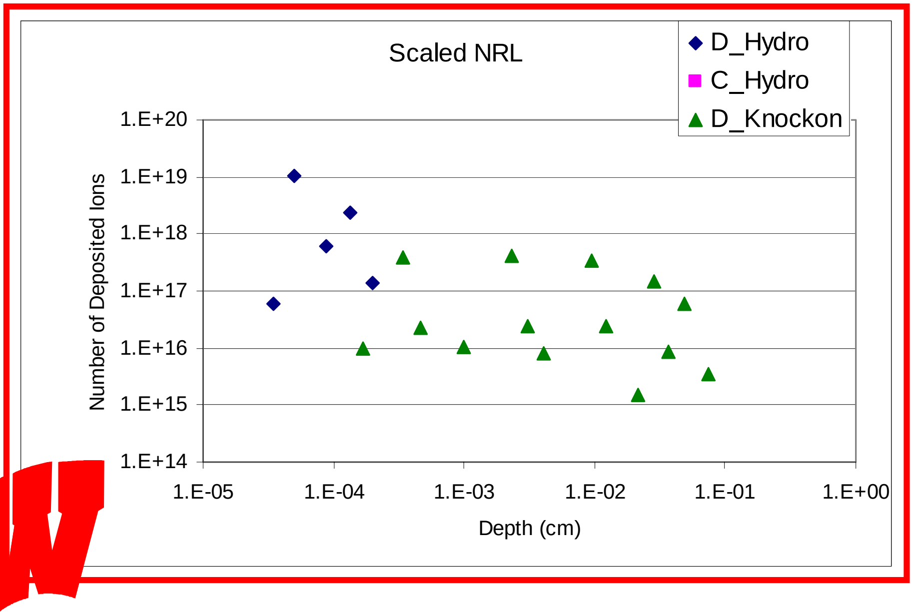
• It has fewer of the dangerous, prompt x-rays and a different ion spectrum.

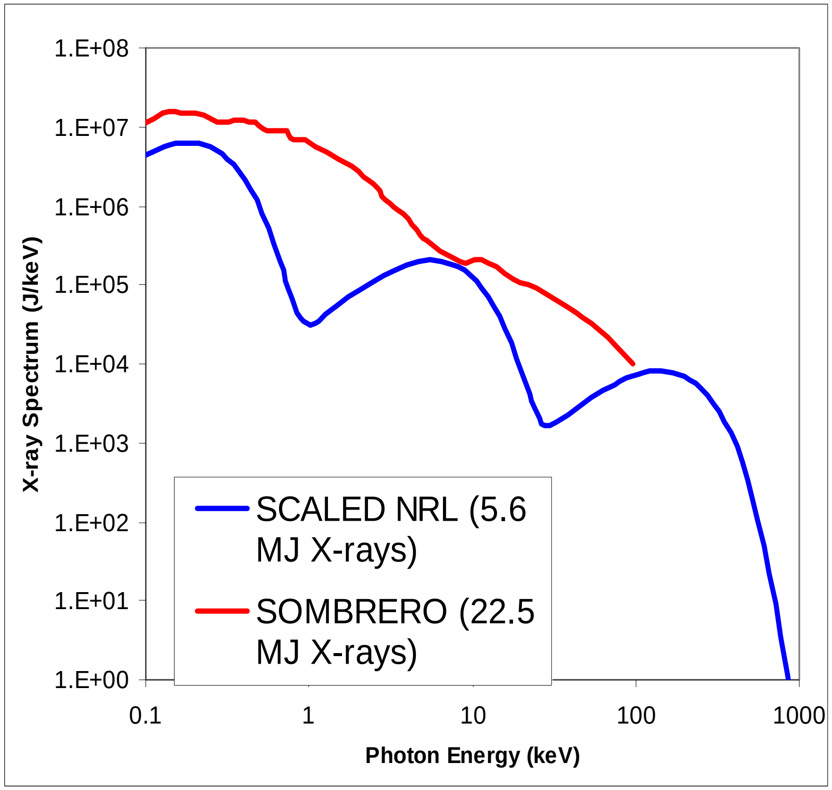
• For instance, the first wall survives at conditions where the SOMBRERO target vaporizes 6.7g of wall material per shot. (This assumes that the energy is increased by increasing the flux, and not the shape, of the spectra..)

Detail: Carbon and deuterium deposition and X-ray spectra for SOMBRERO and Scaled NRL Targets in 6.5m Radius C Chamber

Xe density is 50 mtorr and wall temperature is 1450 ° C.







The spectra differ primarily due to the Au and knock-ons in the NRL spectrum and the 55MJ of 1.6MeV C ions in the SOMBRERO spectrum. The NRL knock-ons heat the 1st mm of the wall volumetrically.

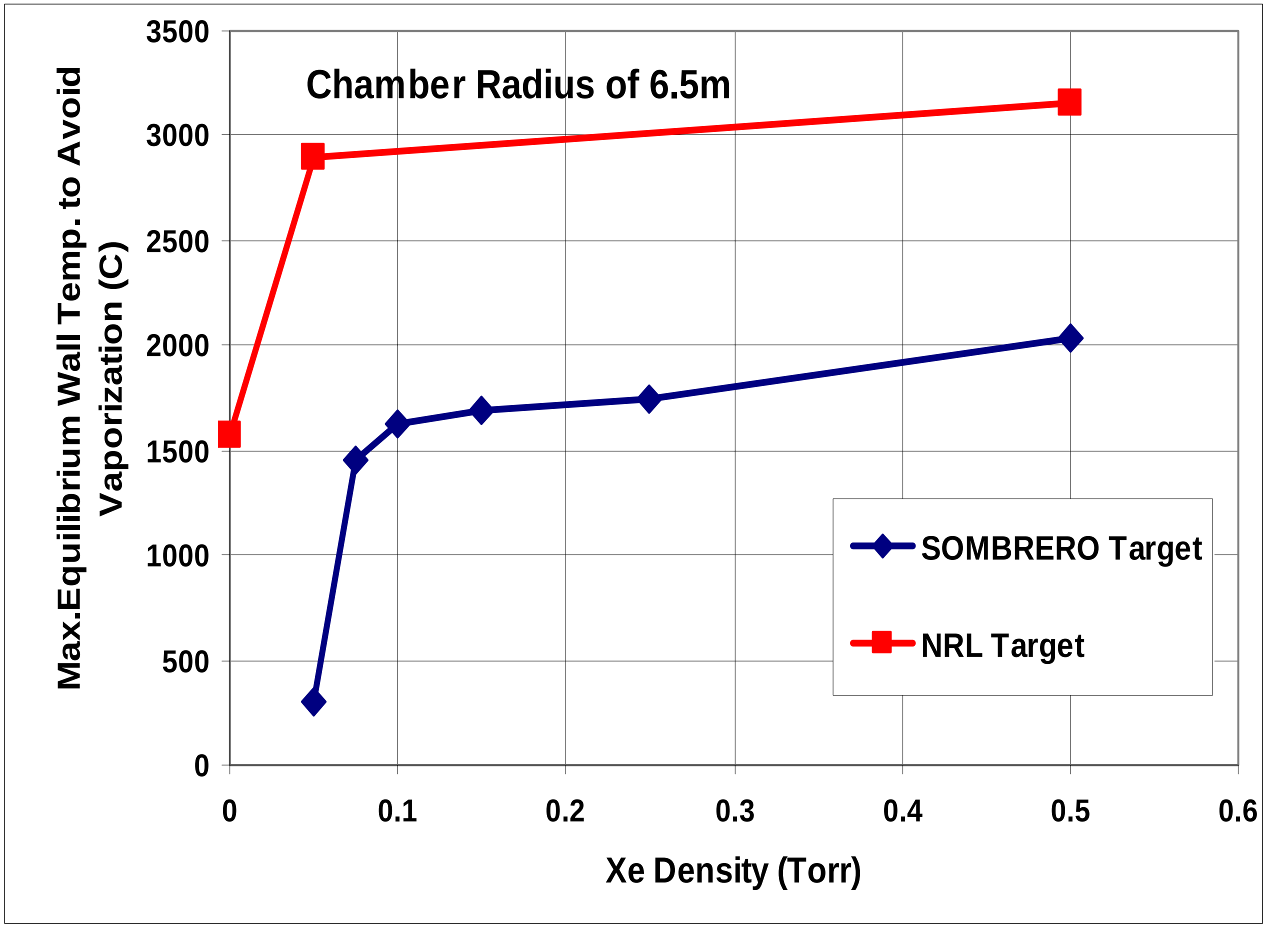
A C-C Target Chamber Can Survive, with Proper Gas Protection and Wall Temperature

•A series of BUCKY calculations have been performed of the response of a 6.5 m radius graphite wall to the explosions of SOMBRERO and NRL targets. Time-of-flight dispersion of debris ions is important, especially for low gas density.

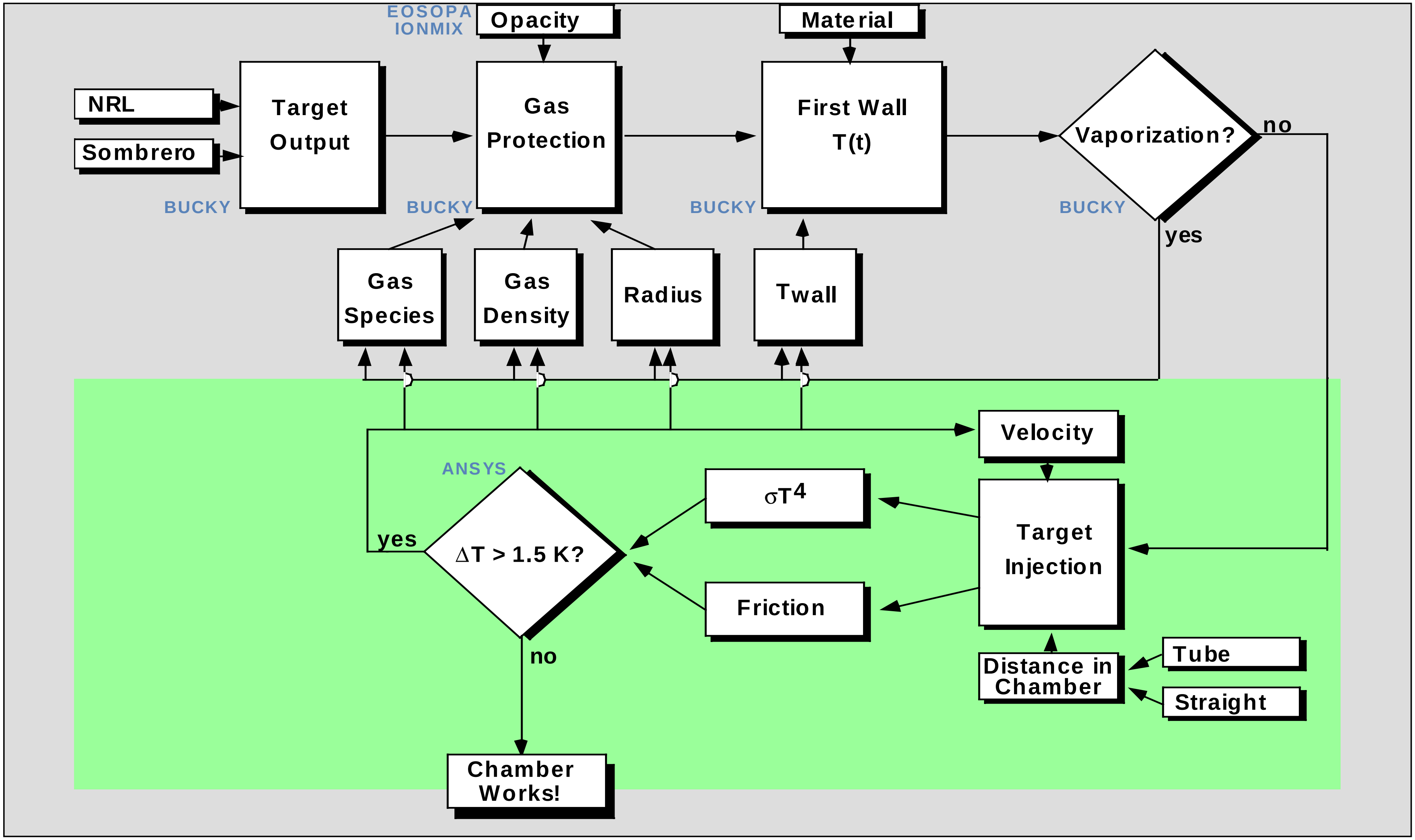
•The gas density and equilibrium wall temperature have been varied to find the highest wall temperature that avoids vaporization at a given gas density.

•Vaporization is defined as more than one mono-layer of mass loss from the surface per shot.

•The use of Xe gas to absorb and re-emit target energy increases the allowable wall temperature substantially.



First Wall Erosion and *Target Heating During Injection* are Competing Concerns in Direct-Drive Laser Fusion Dry-Wall Target Chambers



Target Injection for Laser Fusion Chambers

G.L. Kulcinski, E. A. Mogahed, and
I. N. Sviatoslavsky
University of Wisconsin-Madison
Fusion Technology Institute

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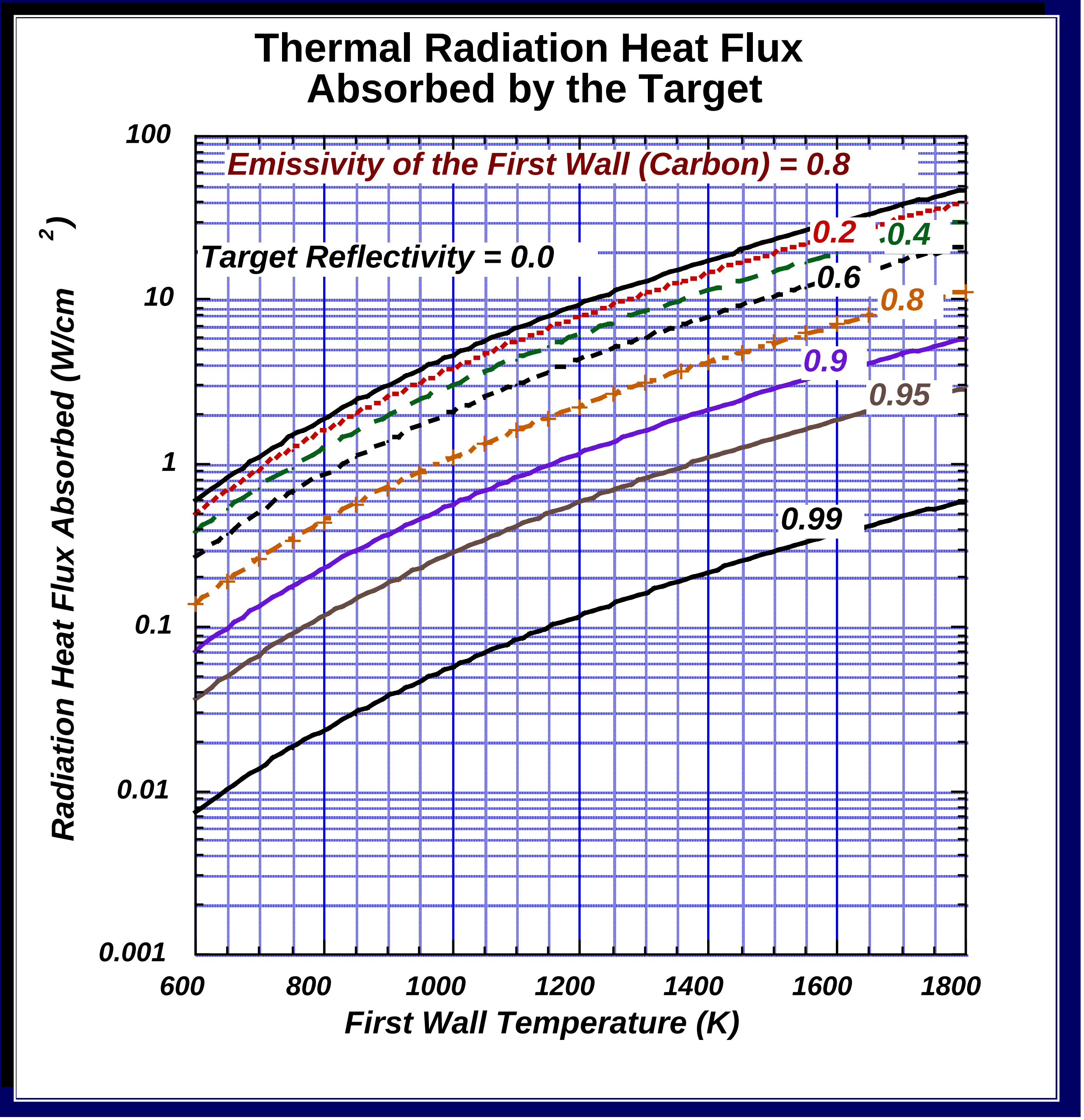
Assumptions For NRL Target Heating Calculations

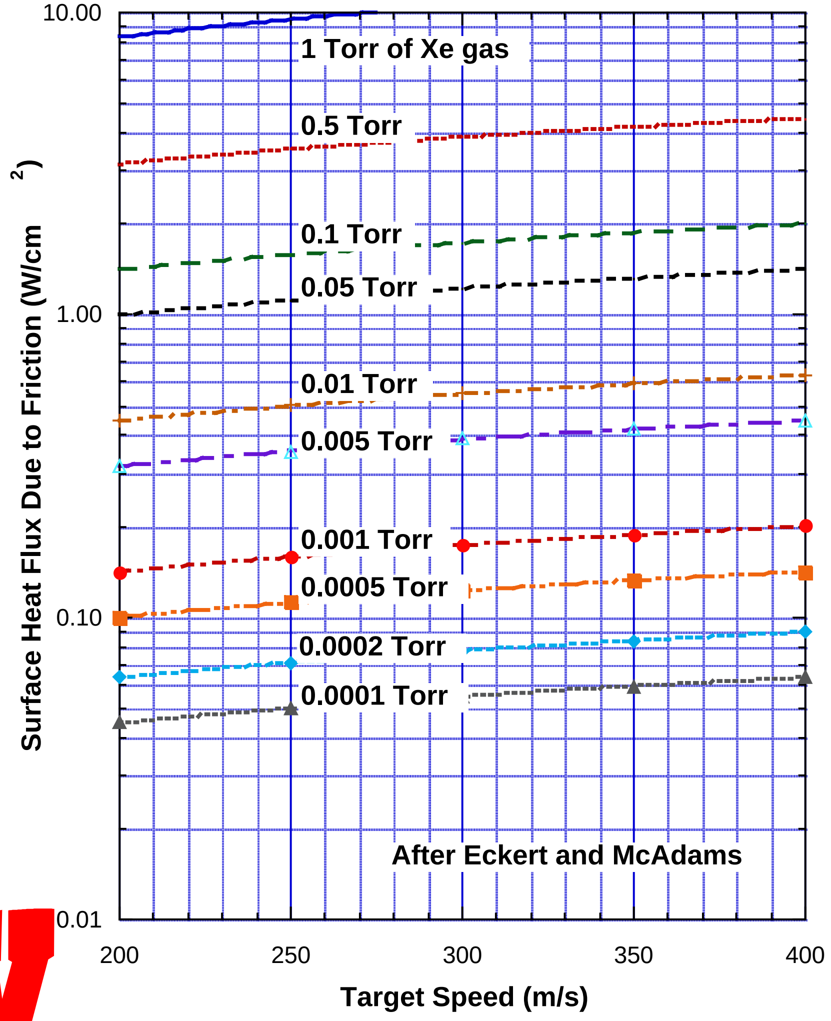
- Injection velocity = 400 m/s
- Target spectral reflectivity = 99%
- Transport distance in chamber = 2 m (tube)
- Thermal diffusivity of CH @ 18 K = 0.009 cm^2/s
- ΔT at DT/CH interface < 1.5 K
- Tumbling target (symmetric heat transfer)

The Heat Flux Absorbed in the Outer Surface of the Target Depends on the FW Temperature and the Target Emissivity

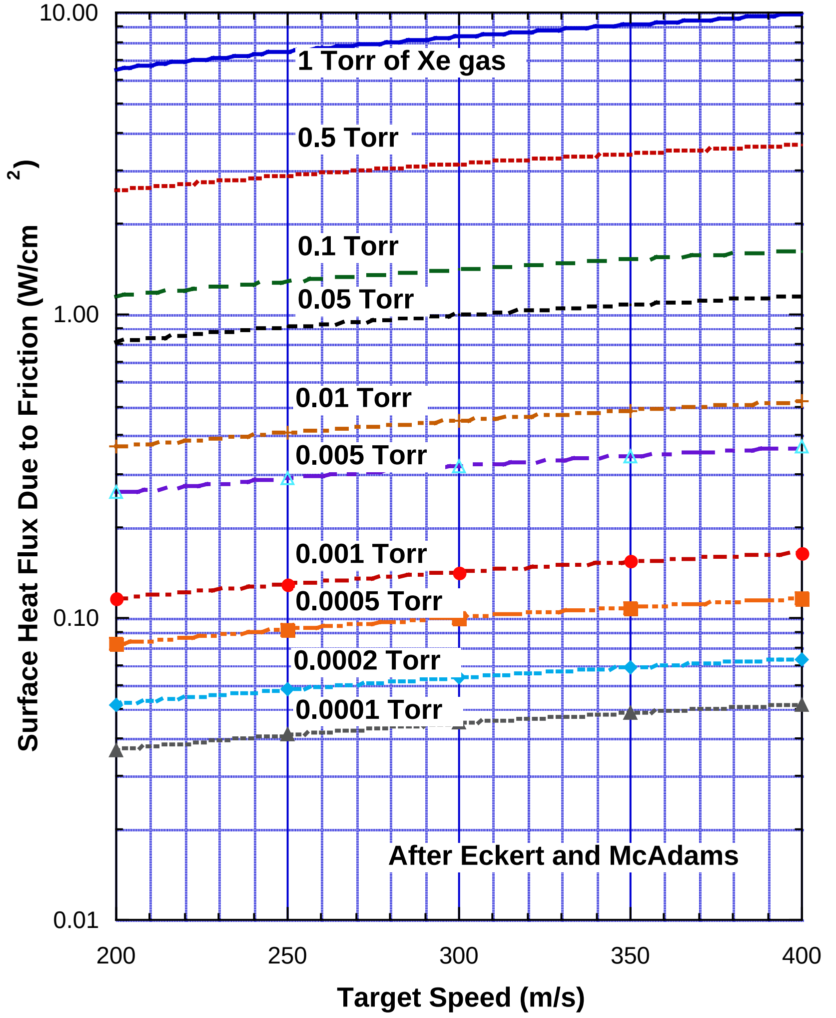


Thermal Radiation Heat Flux Absorbed by the Target

The Heat Flux Due to Aerodynamic Friction on the Target Outer Shell is Strongly Dependent on the Chamber Gas Density and the Velocity of the Target.



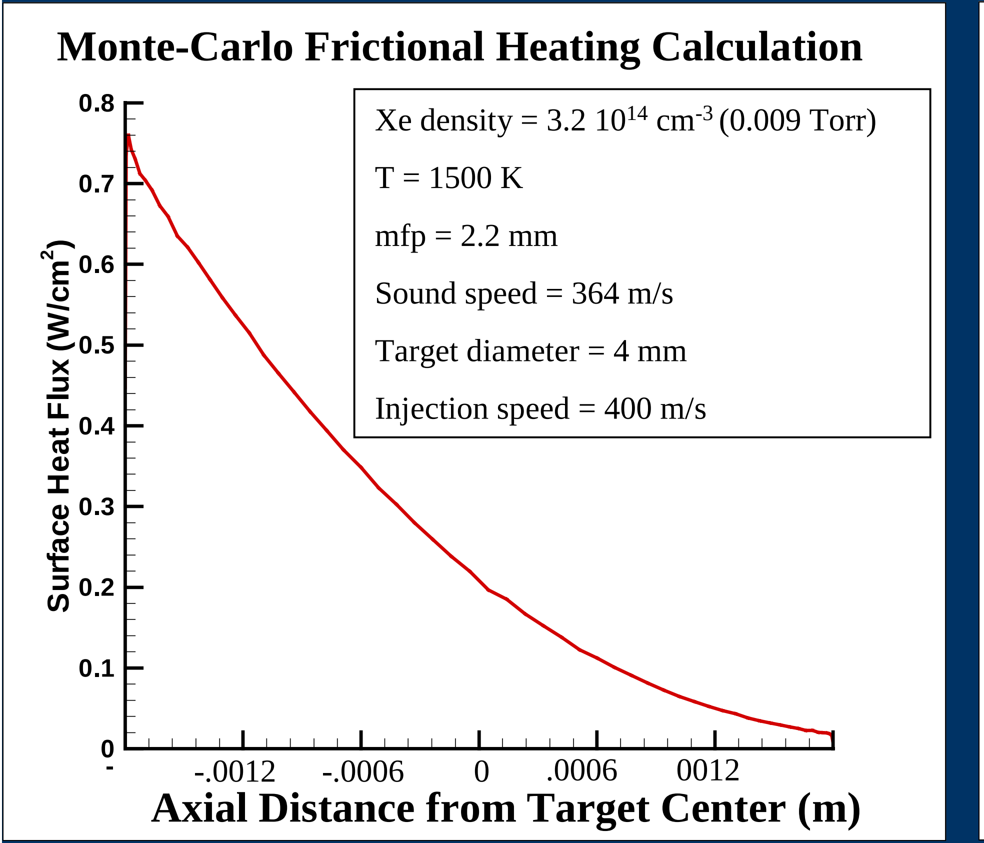
Frictional Heat Flux for a 6 mm Diameter Target



Frictional Heat Flux for a 4 mm Diameter Target

UW has started the use of a 2-D Monte-Carlo Hydrodynamics Code from Sandia to Model Frictional Target Heating

Since the collisional mean-free-path is the same order as the target size, a detailed calculation is needed.


Monte-Carlo Frictional Heating Calculation

Xe density = 3.2 10^{14} cm^{-3} (0.009 Torr)

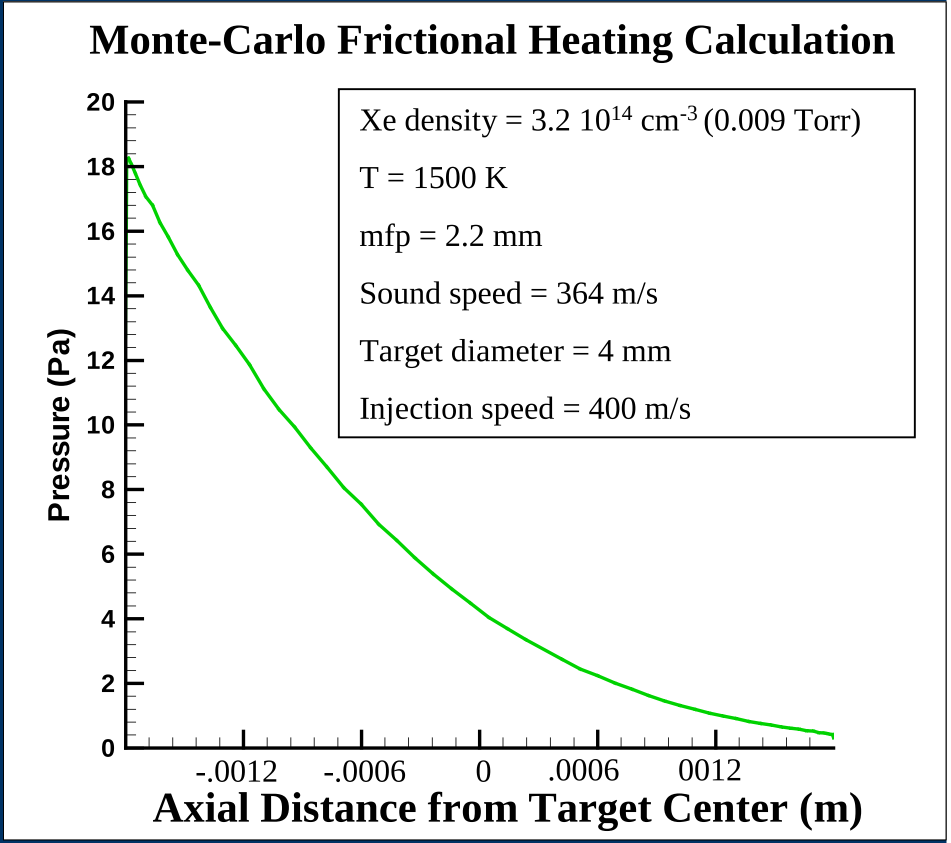
T = 1500 K

mfp = 2.2 mm

Sound speed = 364 m/s

Target diameter = 4 mm

Injection speed = 400 m/s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T = 1500 K

mfp = 2.2 mm

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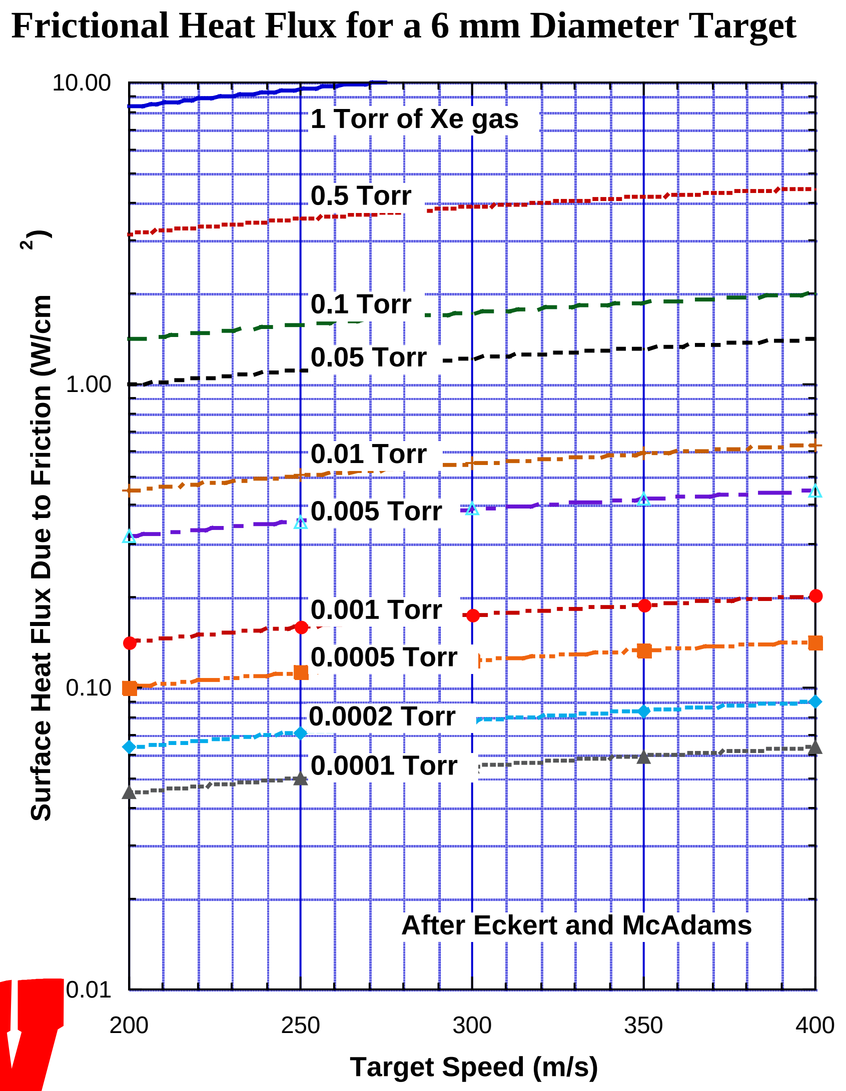
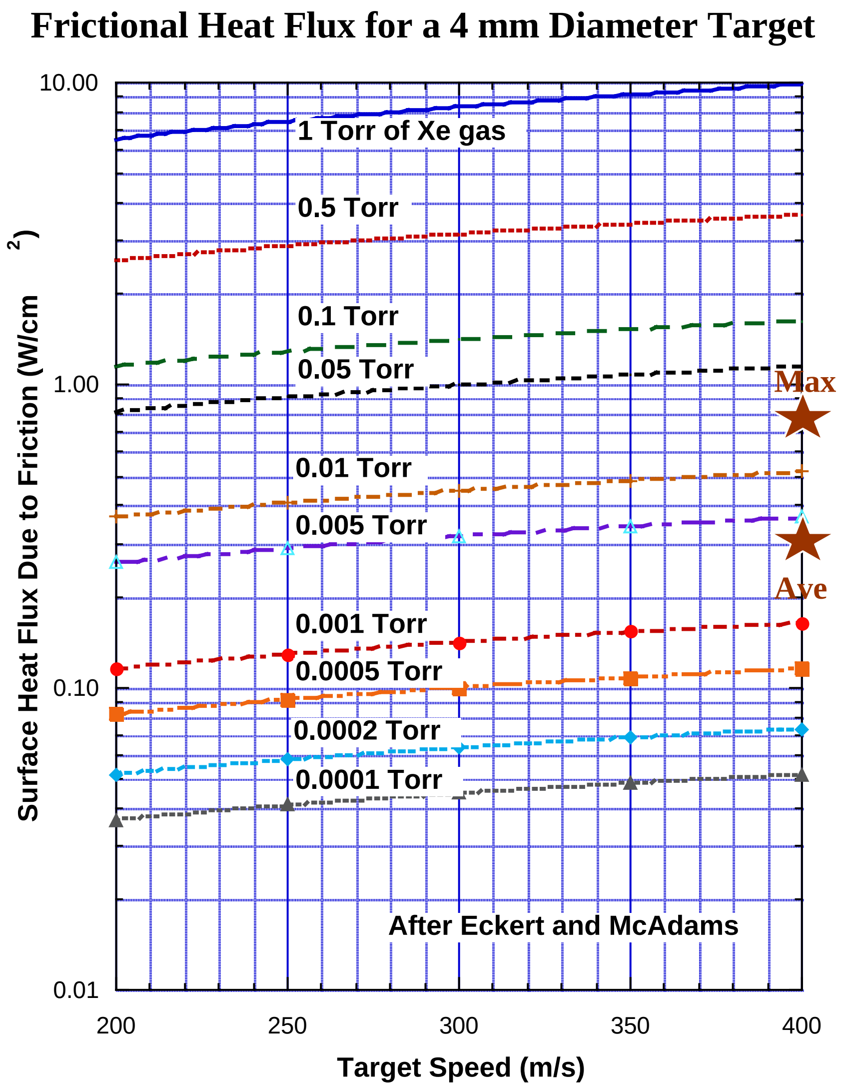
Target diameter = 4 mm

Injection speed = 400 m/s

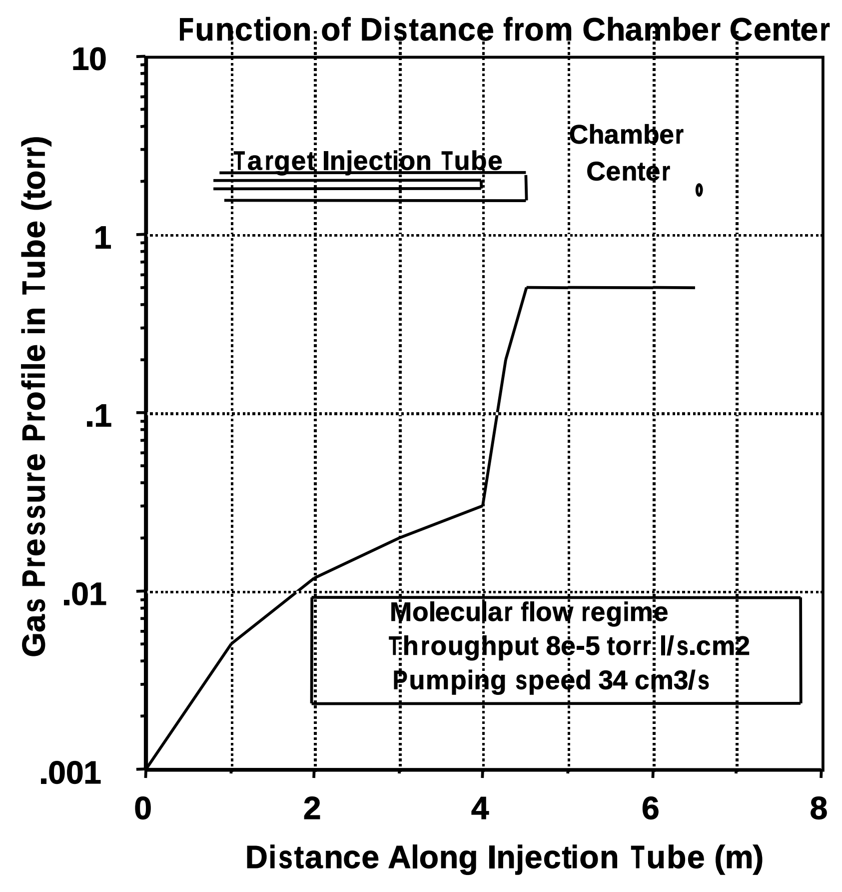
This calculation was performed with the Icarus code by Tim Bartel of SNL.

The Heat Flux Due to Aerodynamic Friction on the Target Outer Shell is Strongly Dependent on the Chamber Gas Density and the Velocity of the Target.


Frictional Heat Flux for a 6 mm Diameter Target


Frictional Heat Flux for a 4 mm Diameter Target

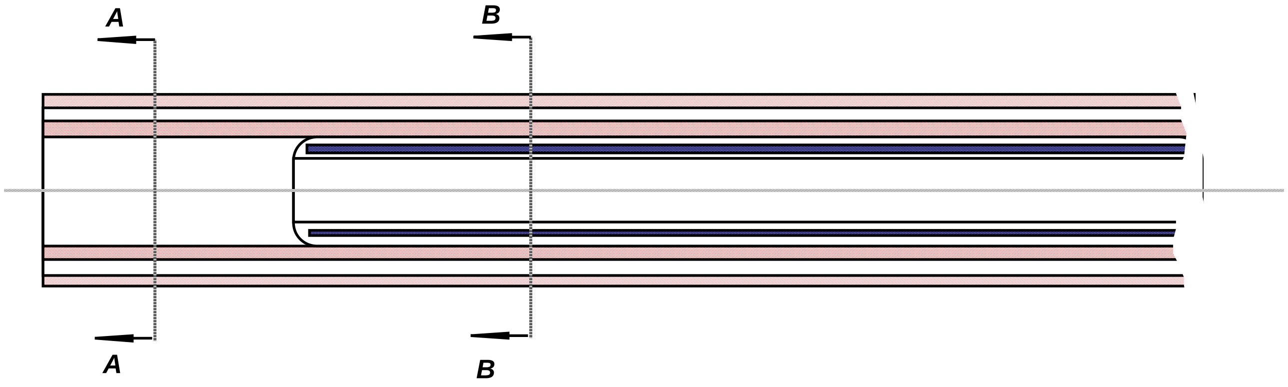
The Target Injection Tube Protects the Target from Thermal Damage During Injection

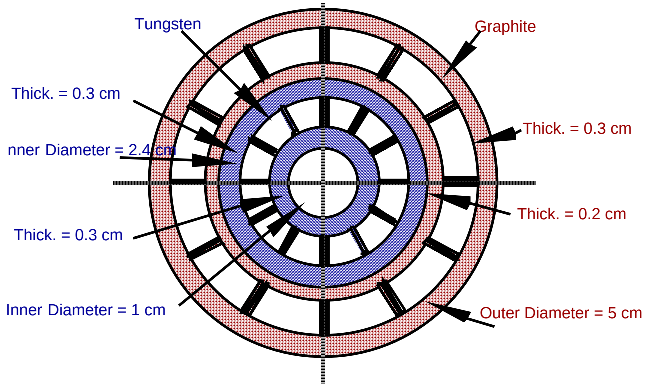


Pressure Profile in Target Injection Tube as a Function of Distance from Chamber Center

- A target injection tube extends from the top of the chamber to within 2 meters of the chamber center.
- It consists of a tungsten core which is He gas cooled in a closed cycle cooling system.
- The tungsten core is surrounded by a carbon double tube assembly cooled by Xe gas, extending 0.5m beyond the tungsten core.
- The Xe gas after cooling the carbon tube enters the chamber replenishing the chamber buffer gas.
- The tungsten core is stationary, but, the carbon tube is slowly moved forward at the rate at which the carbon evaporates.
- The target is shielded from high temperature radiation from the first wall, and by tube differential pumping avoids frictional heating with the buffer gas along most of its trajectory.

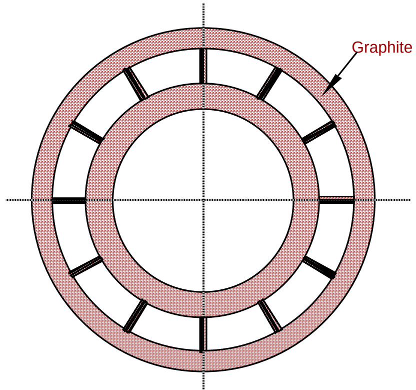
TARGET INJECTION TUBE DETAILS





Section B-B

Cross-Section of the Target Injection Tube



Section A-A

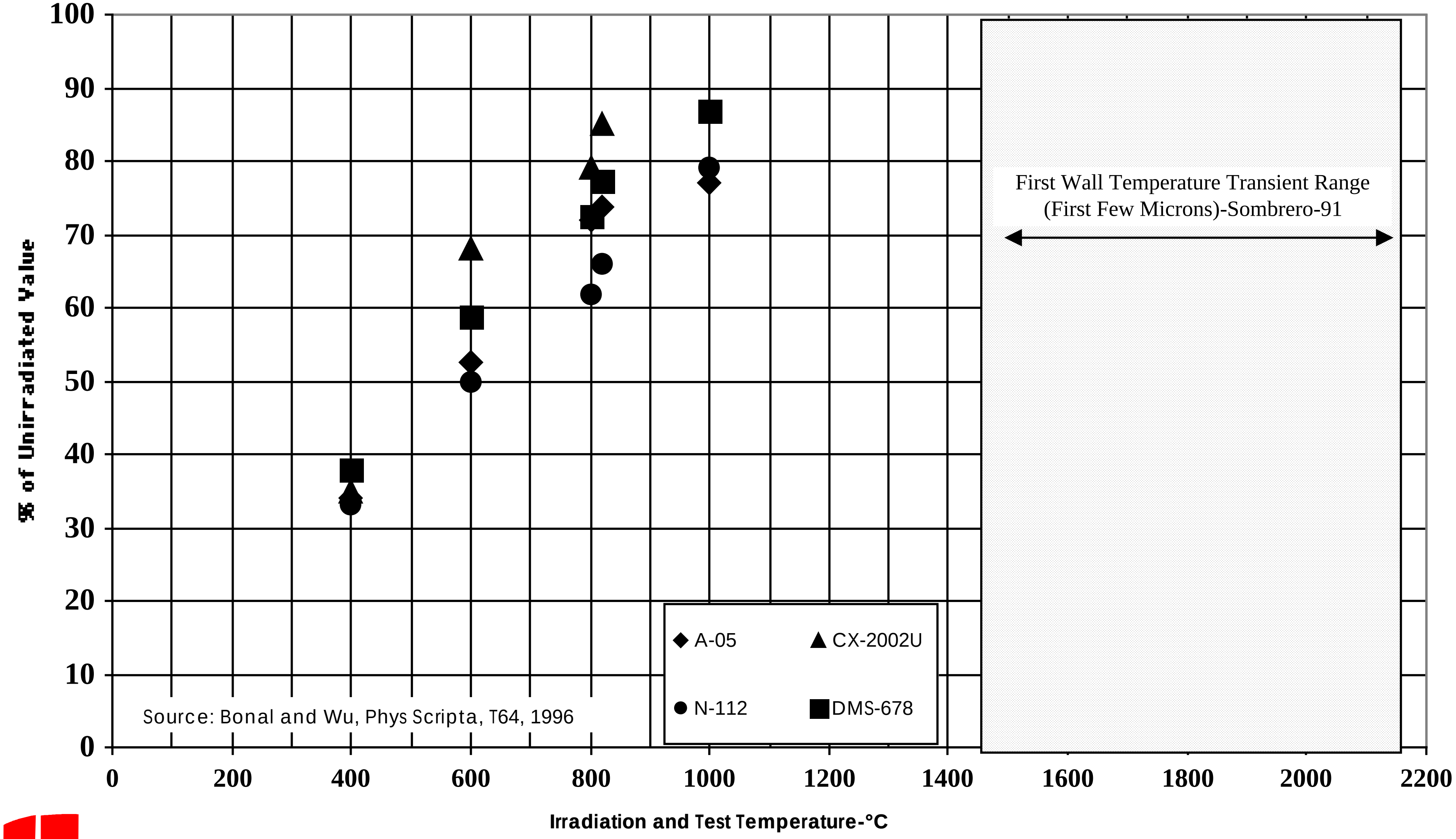
PARAMETERS OF TARGET INJECTION TUBE

	Material	ID (cm)	OD (cm)	t (cm)
Inner W tube	W	1.0	1.6	0.3
Outer W tube	W	2.4	3.0	0.3
Coolant Flow area	He	1.6	2.4	0.4
Inner Graphite tube	C	3.0	3.4	0.2
Outer Graphite tube	C	4.4	5.0	0.3
Coolant Flow area	Xe	3.4	4.4	0.5

THERMAL HYDRAULIC PARAMETERS OF TARGET INJECTION TUBE

W tube coolant	He gas
Length of W tube(m)	4.0
Nuclear heating in W tube (Kw)	86.0
He gas pressure (atm)	80.0
Inlet temperature (K)	77
Outlet temperature (K)	300
He gas velocity (m/s)	21
Average temperature of inner W wall (K)	250
Graphite tube coolant	Xe
Length of tube (m)	4.5
Nuclear heating in graphite tube (Kw)	48.0
Radiant heating in graphite tube (Kw)	30.0
Xe gas pressure (atm)	10
Inlet temperature (K)	300
Outlet temperature (K)	1174
Xe gas velocity (m/s)	81
Average temperature of inner graphite tube (K)	1000

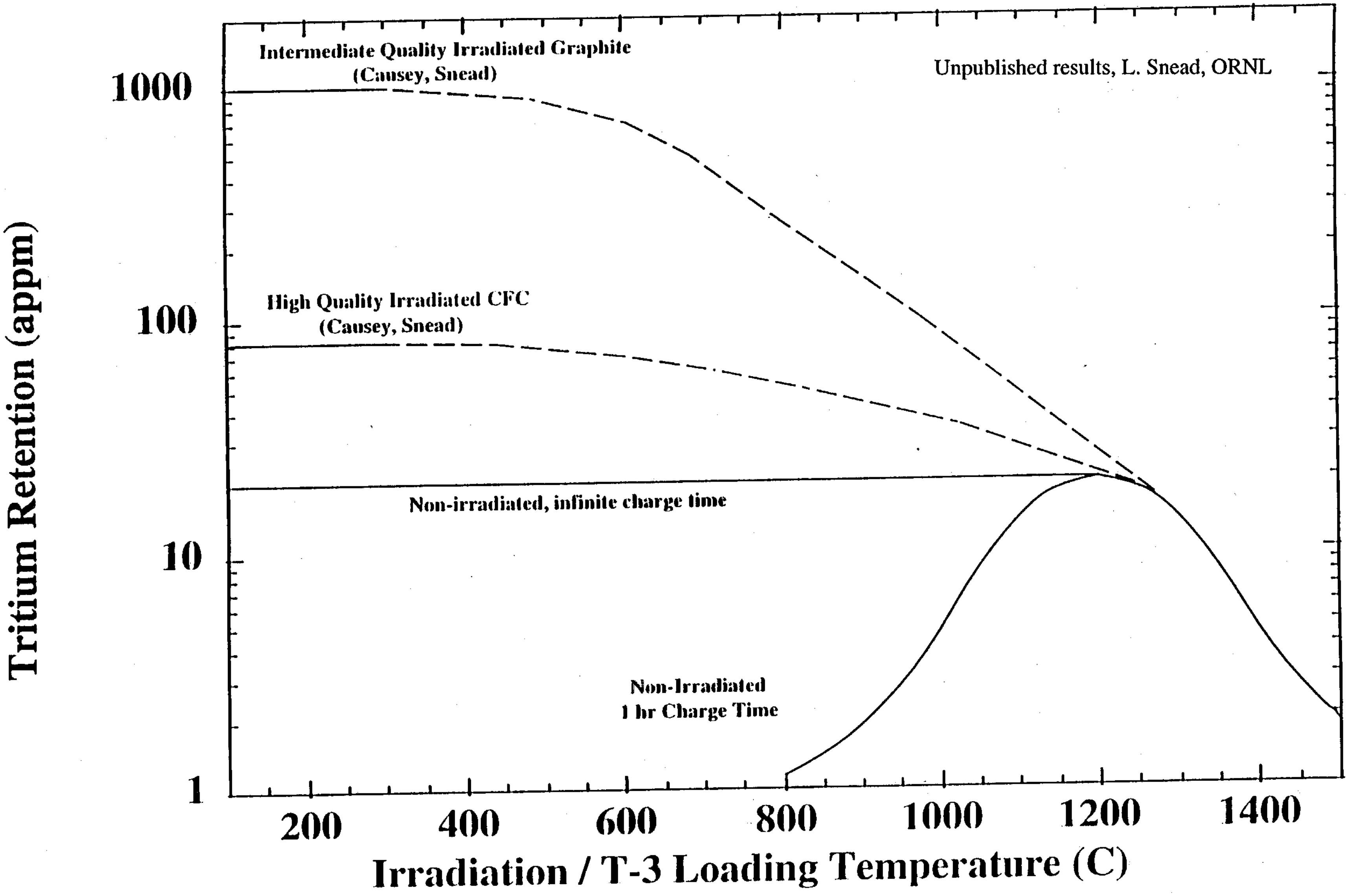
The Neutron Irradiated Thermal Conductivity of Graphite at -1-2 dpa Approaches the Unirradiated Value at High Temperatures



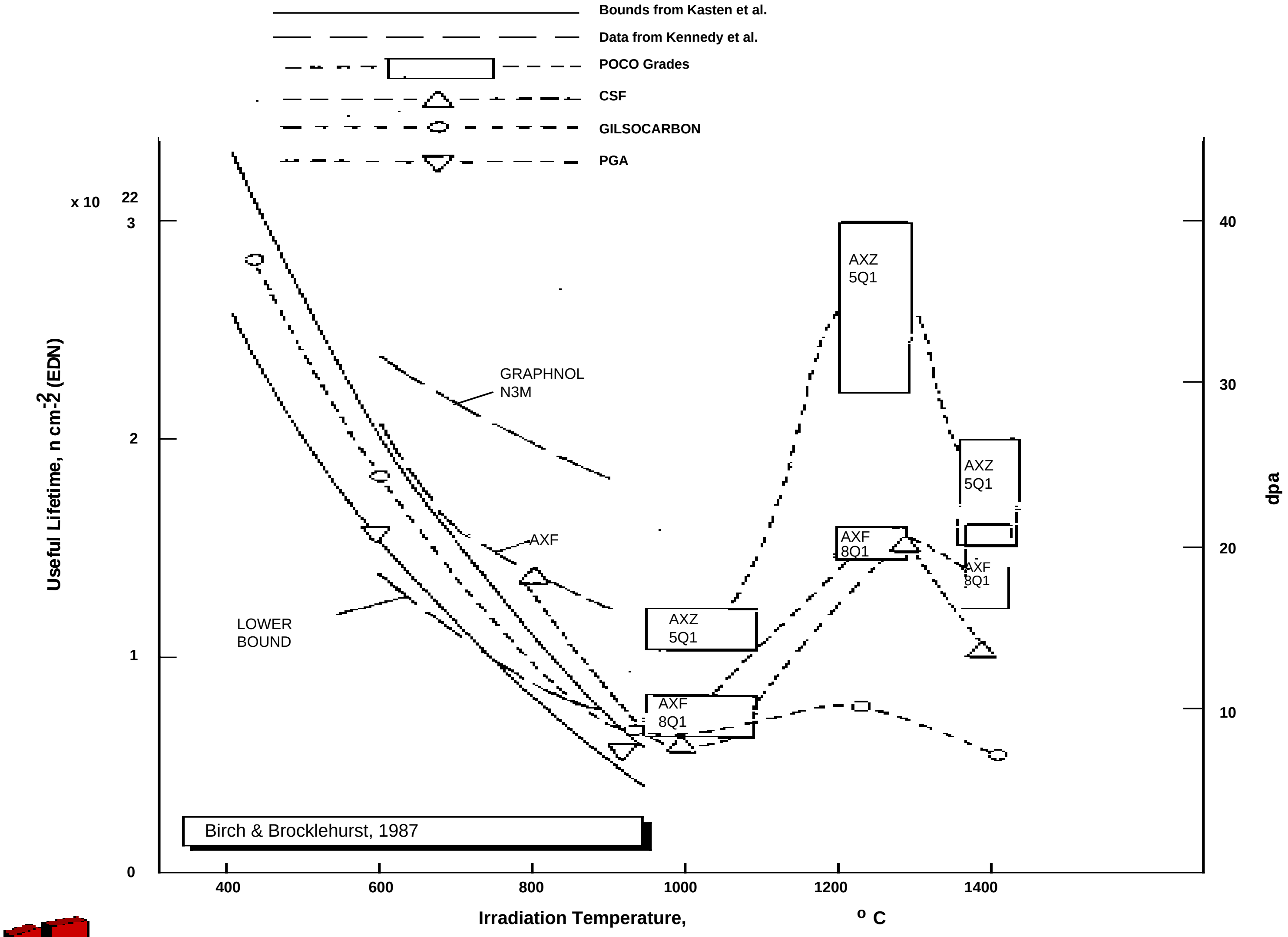
First Wall Temperature Transient Range
(First Few Microns)-Sombrero-91

Source: Bonal and Wu, Phys Scripta, T64, 1996

Tritium Retention is Reduced by Increasing Irradiation Temperatures

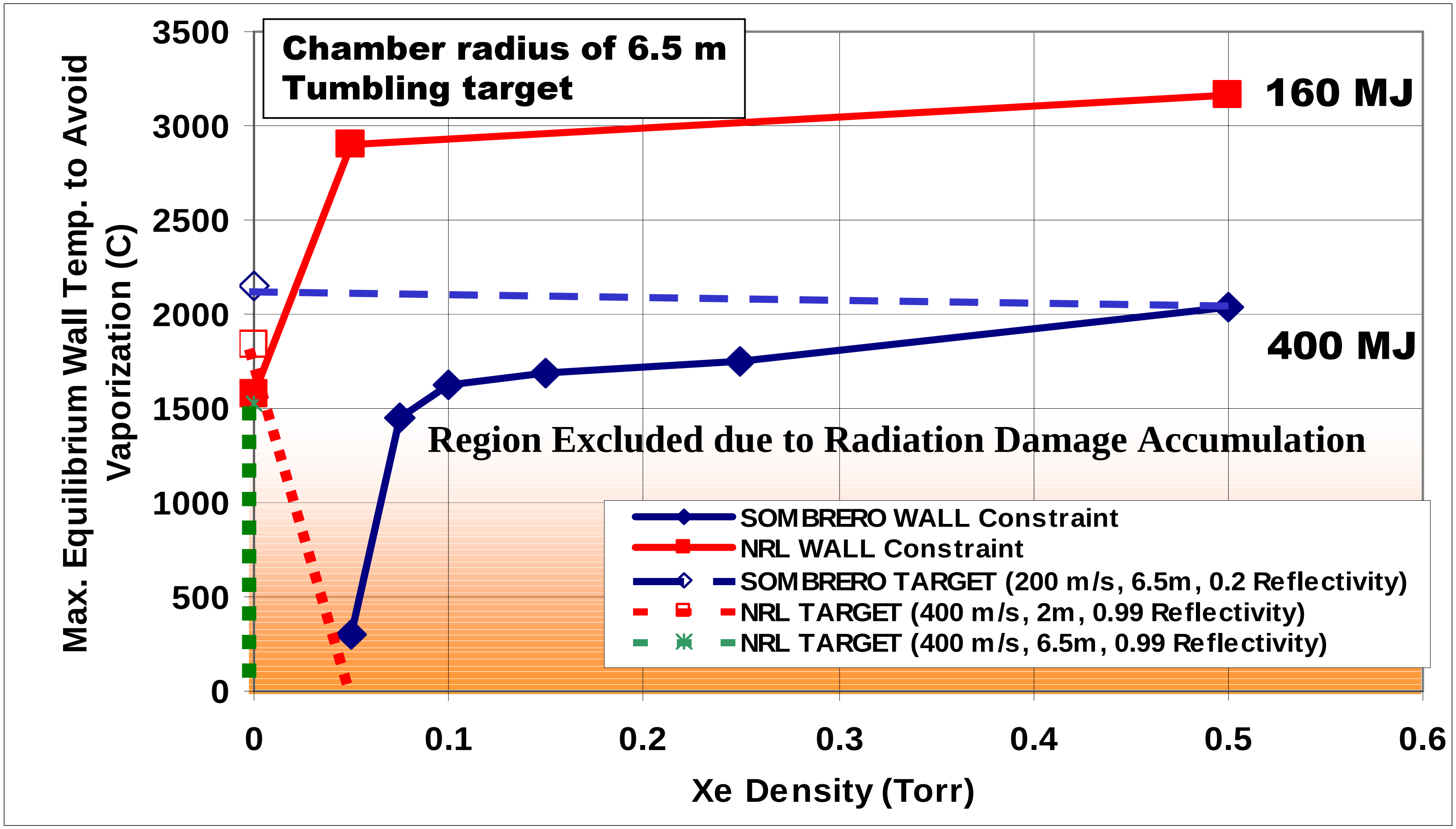

Unpublished results, L. Snead, ORNL

The Useful Lifetime of Graphite is a Function of the Neutron Irradiation Temperature



Birch & Brocklehurst, 1987

It is Difficult to Find an Operational Regime for the NRL Target in a Dry-Wall Chamber (Assuming 1.5 K Fuel Temperature Rise)



Survivability of Targets and C-C First Walls in SOMBRERO Dry Wall Chamber with No Fill Gas

	Target	First Wall
SOMBRERO	**Yes** **(T_{FW}<2,100 °C)**	**No** **(evaporation, unless T_{FW} < RT)**
NRL	**Yes** **(if T_{FW}<1,600 °C)**	**Yes** **(if T_{FW}<1,500 °C)**

Survivability of Targets and C-C First Walls in SOMBRERO Dry Wall Chamber with 0.1 Torr Xe Fill Gas

	Target	First Wall
SOMBRERO	**Yes** **(if T_{FW}<2,100 °C)**	**Yes** **(T_{FW}<1,600°C)**
NRL	**No** **(frictional heating, T_{FW} << RT)**	**No Solution** **(T_{FW}<< RT))**

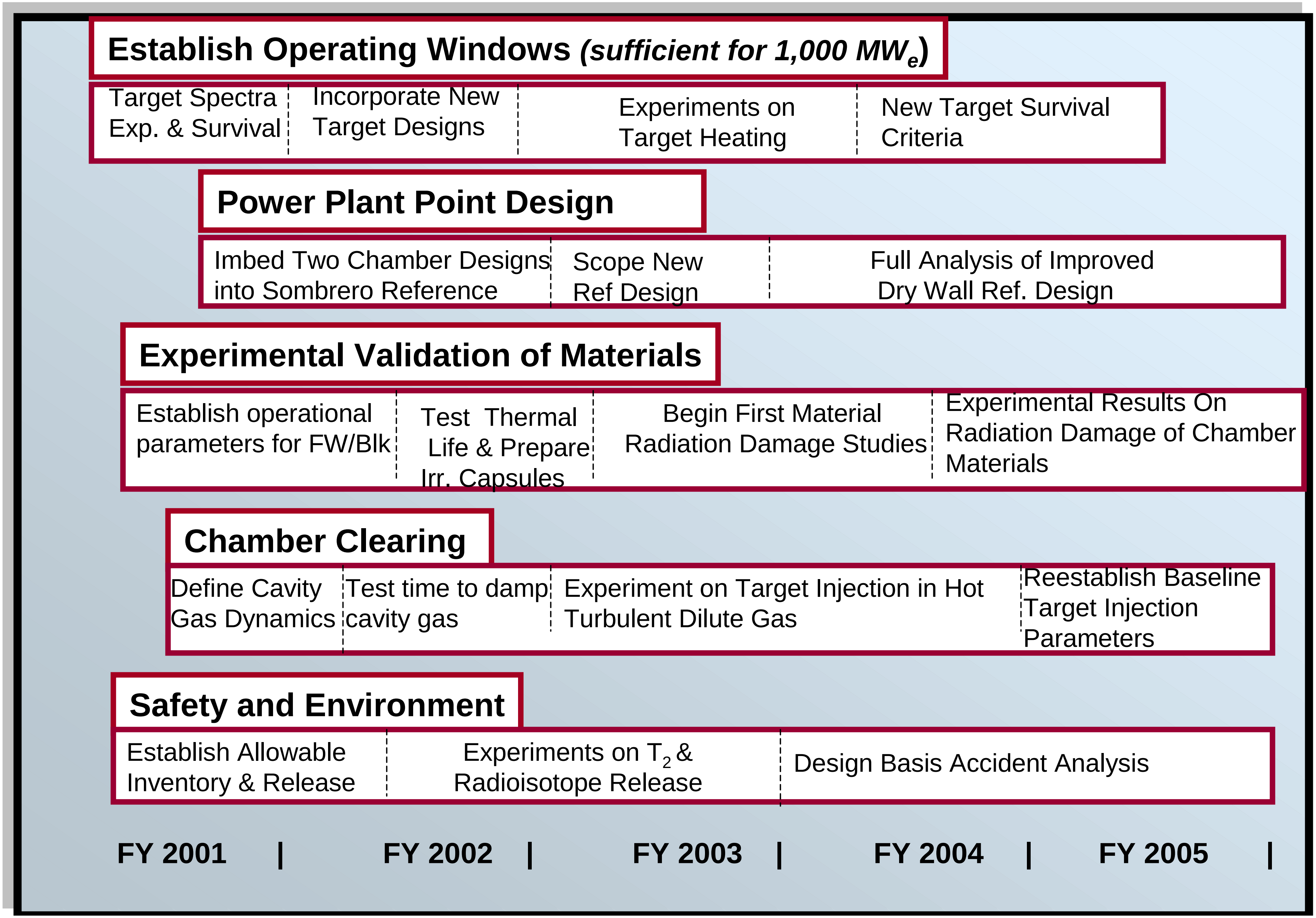
Survivability of Targets and C-C First Walls in SOMBRERO Dry Wall Chamber with 0.01 Torr Xe Fill Gas

	Target	First Wall
SOMBRERO	**Yes** **(T_{FW}<2,100 °C)**	**No** **(evaporation, unless T_{FW} < RT)**
NRL	**Yes** **(if T_{FW}<1,600 °C)**	**Yes** **(if T_{FW}<1,600 °C)**

Parametric Studies for Laser Chamber Analysis, Feb. to Oct. 2001

Targets	NRL-ref, SOMBRERO, NRL-400
Temp Rise in DT, K	1.5, 5, 10
Target Reflectivity	0.2, 0.9, 0.99
Injection Velocity, m/s	200, 400
Distance Target Exposed, m	2, 6.5, 8
FW Material	C-C, SiC, W
Cavity Gas	Xe, Kr
Gas Pressure, Torr	0, 0.01, 0.1

Laser Dry-Wall Chamber Program Plan



Establish Operating Windows ***(sufficient for 1,000*** MW_e**)**

Target Spectra Exp. & Survival

Incorporate New Target Designs

Experiments on Target Heating

New Target Survival Criteria

Power Plant Point Design

Imbed Two Chamber Designs into Sombrero Reference

Scope New Ref Design

Full Analysis of Improved Dry Wall Ref. Design

Experimental Validation of Materials

Establish operational parameters for FW/Blk

Test Thermal Life & Prepare Irr. Capsules

Begin First Material Radiation Damage Studies

Experimental Results On Radiation Damage of Chamber Materials

Chamber Clearing

Define Cavity Gas Dynamics

Test time to damp cavity gas

Experiment on Target Injection in Hot Turbulent Dilute Gas

Reestablish Baseline Target Injection Parameters

Safety and Environment

Establish Allowable Inventory & Release

Experiments on T_2 & Radioisotope Release

Design Basis Accident Analysis

FY 2001 | FY 2002 | FY 2003 | FY 2004 | FY 2005 |