

Final Report for NIF Chamber Dynamics Studies

Final Report (May 1997), Subcontract No. B291847

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July 1997



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Final Report for NIF Chamber Dynamics Studies

Per F. Peterson, Andy Anderson, Hui Jin and John M. Scott

Work Accomplished Under Contract LLNL B291847

April 1, 1996 - March 31, 1997

May 1997

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Introduction

The National Ignition Facility (NIF), a 1.8 MJ, 192 laser beam facility, will have anticipated fusion yields of up to 20 MJ from D-T pellets encased in a gold hohlraum target. The energy emitted from the target in the form of x rays, neutrons, target debris kinetic energy, and target shrapnel will be contained in a 5 m. radius spherical target chamber. Various diagnostics will be stationed around the target at varying distances from the target. During each shot, the target will emit x rays that will vaporize nearby target facing surfaces including those of the diagnostics, the target positioner, and other chamber structures. This ablated vapor will be transported throughout the chamber, and will eventually condense and deposit on surfaces in the chamber, including the final optics debris shields.

The research at the University of California at Berkeley relates primarily to the NIF chamber dynamics. The key design issues are the ablation of the chamber structures, transport of the vapor through the chamber and the condensation or deposition processes of those vaporized materials. An understanding of these processes is essential in developing a concept for protecting the final optics debris shields from an excessive coating ($> 10 \text{ \AA}$) of target debris and ablated material, thereby prolonging their lifetime between change-outs. At Berkeley, we have studied the physical issues of the ablation process and the effects of varying materials, the condensation process of the vaporized material, and design schemes that can lower the threat posed to the debris shields by these processes.

In addition to the work described briefly above, we performed extensive analysis of the target-chamber thermal response to in-chamber CO_2 cleaning and of work performed to model the behavior of silica vapor. The work completed this year has been published in several papers and a dissertation [1-6]. This report provides a summary of the work completed this year, as well as copies of presentation materials that have not been published elsewhere. In particular, the Appendix contains copies of presentations made on CO_2 cleaning that are not available elsewhere.

Summary of Contract Tasks

The following section provides brief summaries of the status of tasks performed

1.) Perform thermal and performance analysis for frost- or ice-coated protection systems for target-facing surfaces.

Prof. Peterson participated in eight meetings at LLNL discussing frost and ice-coated protection systems. TSUNAMI calculations were performed showing that the impulse loading generated by high-velocity target debris can be of the same magnitude as impulse loading from x-ray ablation. Mounting schemes and cooling system designs were proposed for protection of cryogenic target positioners. Small-frontal-area refractory target positioners were studied as an alternative to frost and ice-protected systems.

2.) Perform 2-D TSUNAMI calculations to determine debris emission parameters at key chamber locations for: the baseline NIF hohlraum for 0 to 45 MJ yield; the baseline direct drive target for 0 to 100 MJ yield; and radiation sciences targets as required (e.g. gas bags, disks, etc.), considering the effects of frost ablation from the target positioner and diagnostics on the deposition distribution. (Task continued from previous contract).

As an ongoing part of the previous contract, additional TSUNAMI calculations were performed for debris distributions in the chamber. These calculations focused on the development of species conservation modeling capabilities, to study the effect of the interaction of target debris with ablated frost from the target positioner. Additional work was performed investigating the target source term [1] and the stopping of target debris in ablated materials [2].

3.) Comment on impacts to the NIF system envisioned by implementing direct drive.

Have participated in discussions and planning for NIF direct drive as required.

4.) Recommend and assist in the design of additional experiments to validate x-ray debris source term predictions, and subsequent material response.

Have actively participated in the design of and experiment to study the x-ray response of materials and the subsequent condensation of vaporized materials that was performed in NOVA. Results of this work were summarized in the dissertation completed by Andy Anderson [3]. The results were presented at the ANS Fusion Topical Meeting [4].

5.) Perform analysis of witness samples placed in the Nova chamber. Use witness-sample debris deposition patterns in the Nova chamber to validate TSUNAMI debris deposition calculations.

We have modeled an ablation/condensation experiment that was performed on NOVA with TSUNAMI. The numerical predictions compare well to the experimental results that were found. The results were presented at the ANS Fusion Topical Meeting [5].

6.) Make the following code improvements to TSUNAMI:

The following code upgrades were completed for the TSUNAMI code:

- Improved real gas Riemann solver;
- Improved ablation;
- Condensation;
- Complete implementation of SESAME EOS

Our studies have utilized the numerical code TSUNAMI (Transient Shock Upwind Analysis Method for ICF), an Eulerian finite-difference compressible gas dynamics code. TSUNAMI utilizes a second order extension of Godunov's scheme for the gas dynamics and includes a model for x-ray ablation. Since the Godunov scheme utilizes a Riemann solver, formulation of boundary conditions and the ability to handle curved boundary surfaces is fairly simple. Recently, TSUNAMI has been updated with multi-fluid capability allowing for the ability to track target debris species separately from material ablated off surfaces. The addition of a real gas Riemann solver and the SESAME equation of state library allows TSUNAMI to handle the real gas effects encountered at the high energy density situations encountered in environments such as the NIF mini-chamber.

7.) *Continue study of advanced protection concepts, concentrating on the frost-coated mini-chamber system.*

The continuing study of advanced chamber protection concepts has focused heavily on the cylindrical frost-coated mini-chamber design. The addition of species conservation into TSUNAMI has provided the ability to calculate the effectiveness of the mini-chamber design to capture target debris and prevent this debris from entering the NIF chamber. Our results show that up to 80% of the target debris can be captured and prevented from venting into the primary chamber by the cylindrical mini-chamber. The results were presented at the ANS Fusion Topical Meeting [6].

8.) *Participation in relevant workshops and conferences.*

Have participated actively at all meetings

Summary of Other Work

The following section summarizes work related to the original contract, but was not specifically called out.

Thermal Effects of CO₂ Cleaning

The work was motivated by the very large refrigeration effect that CO₂ cleaning can generate, and the very tight thermal parameters for the NIF target chamber (i.e. 0.5 °C variation allowed). This work involved model development for the thermal response of first-wall panels to direct cooling by a CO₂ jet, benchmarking of the model against experimental data for panel temperatures generated at LLNL, identification of key cooling mechanisms including direct cooling by the jet and indirect cooling due to inefficiency of the pellet capture system, and discussion of the design requirements for a radiant heating system to balance the CO₂ cooling effect.

Modeling of Silica Vapor

As a result of the x rays emitted from a NIF target, silica will be ablated from the target chamber beam dumps. This vapor will expand into the chamber and deposit onto various surfaces. It is likely that while the silica vapor is in transit through the chamber, silica particles will form in the vapor. Deposition of these particles on to the debris shields may inhibit the performance of these optics for subsequent shots. Gerry Wilemski has developed a nucleation model that estimates the rates and sizes of these particles as they form in the vapor. Gerry has also prepared a SESAME-style equation of state for silica that describes the behavior of silica vapor in the metastable gas phase. The metastable phase is the state the ablated vapor passes through as it expands from the surface. Both of these models have already been incorporated into a version of the TSUNAMI code to specifically address the dynamics of the SiO₂ vapor plume. We intend to add a particle tracking code and Andy Anderson's ABLATOR code to TSUNAMI as well. Those tasks are pending completion.

Presentations

The following pages are from presentations given at LLNL regarding the tasks mentioned in the summary section of this report. The list of presentations is as follows

- Feb. 12, 1996 -- NIF Frost Protection Systems Review Meeting
- Apr. 22, 1996 -- NIF Frost Protection Systems Review Meeting
- Apr. 29, 1996 -- NIF Frost Protection Systems Review Meeting
- Jun. 18, 1996 -- Experiments and Analysis of Ablation and Condensation on NIF First Wall Materials
- Jul. 1, 1996 -- NIF CO₂ Cleaning Thermal Response
- Jul 30, 1996 -- Mini-chamber Status Report/ICE Meeting
- Oct. 21, 1996 -- NIF CO₂ Cleaning Thermal Response
- Dec. 13, 1996 -- NIF CO₂ Cleaning Thermal Response
- Dec. 13, 1996 -- TSUNAMI Status Report
- Dec. 13, 1996 -- Mini-chamber Status Report

References

1. A.T. Anderson, R.A. Managan, M.T. Tobin, and P.F. Peterson, "X-Ray Emission from National Ignition Facility Indirect Drive Targets," Fusion Topical, ANS Summer Meeting, Reno, Nevada, June 16-20, 1996.
2. H. Jin and P.F. Peterson, "Stopping of Target Debris in Ablated Materials in ICF Chambers," Fusion Topical, ANS Summer Meeting, Reno, Nevada, June 16-20, 1996.
3. A.T. Anderson, "X-Ray Ablation Measurements and Modeling for ICF Applications" Ph.D. Dissertation, U.C. Berkeley (1996).
4. A.T. Anderson, A.K. Burnham, M.T. Tobin, and P.F. Peterson, "Modeling and Experiments of X-Ray Ablation of National Ignition Facility First Wall Materials," Fusion Topical, ANS Summer Meeting, Reno, Nevada, June 16-20, 1996.
5. H. Jin, P.F. Peterson, R.E. Turner, and A.T. Anderson, "Experiments and Analysis for Ablation and Condensation of NIF First Wall Materials," Fusion Topical, ANS Summer Meeting, Reno, Nevada, June 16-20, 1996.
6. P.F. Peterson and J.M. Scott, "The Mini-Chamber, An Advanced Protection Concept for NIF," Fusion Topical, ANS Summer Meeting, Reno, Nevada, June 16-20, 1996.

Appendix

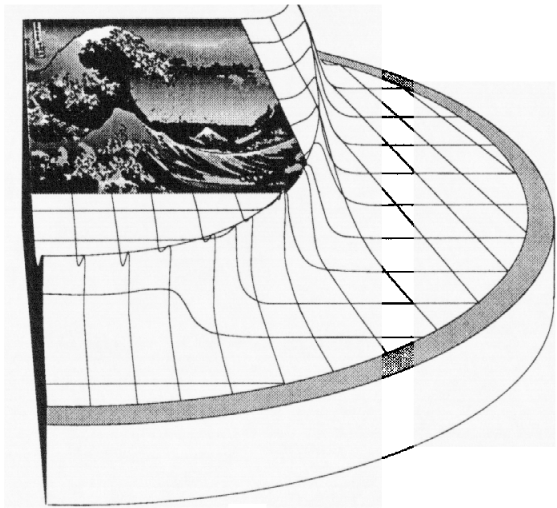
The following pages contain copies of relevant presentations through the year.

NIF Frost Protection Systems Review Meeting

**Per F. Peterson
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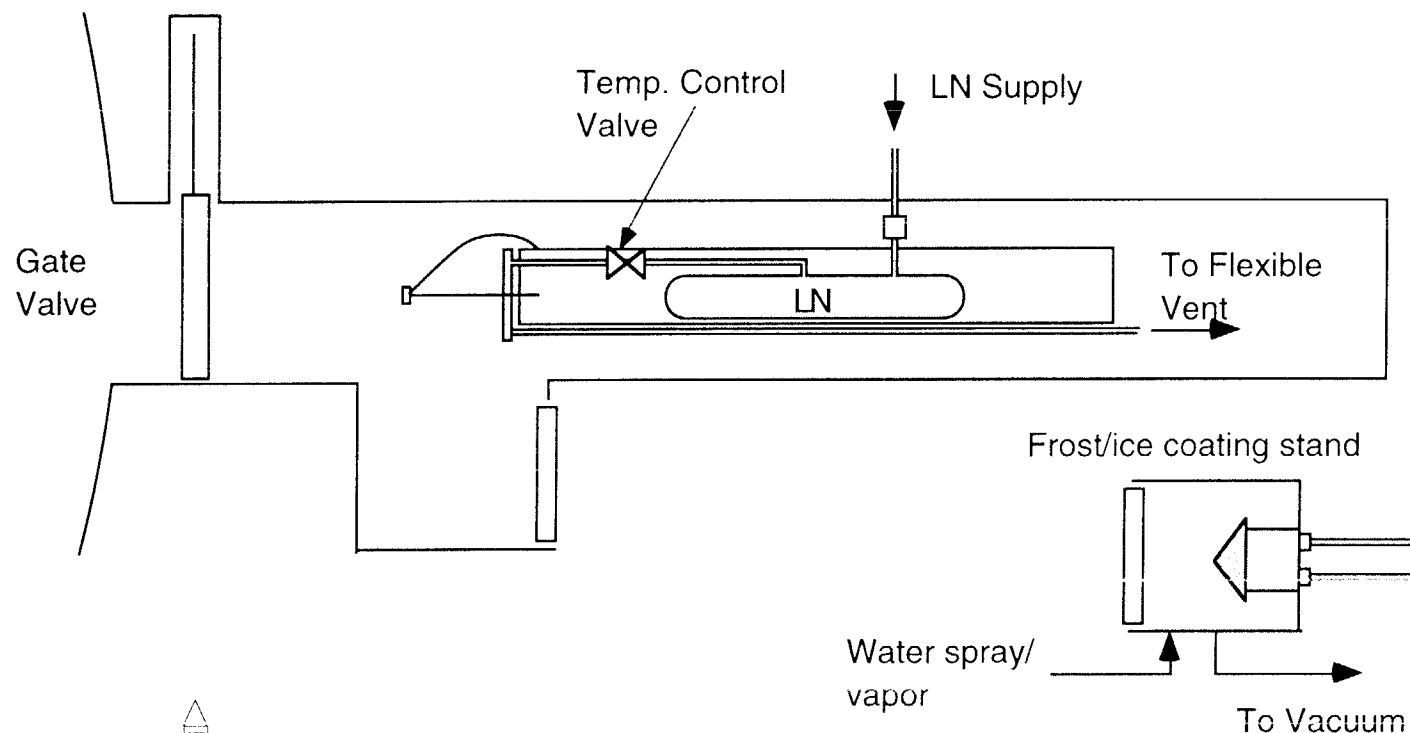
**Lawrence Livermore National Laboratory
February 12, 1996**

- **Design requirements for the NIF Target Positioner
Frost Protection System**



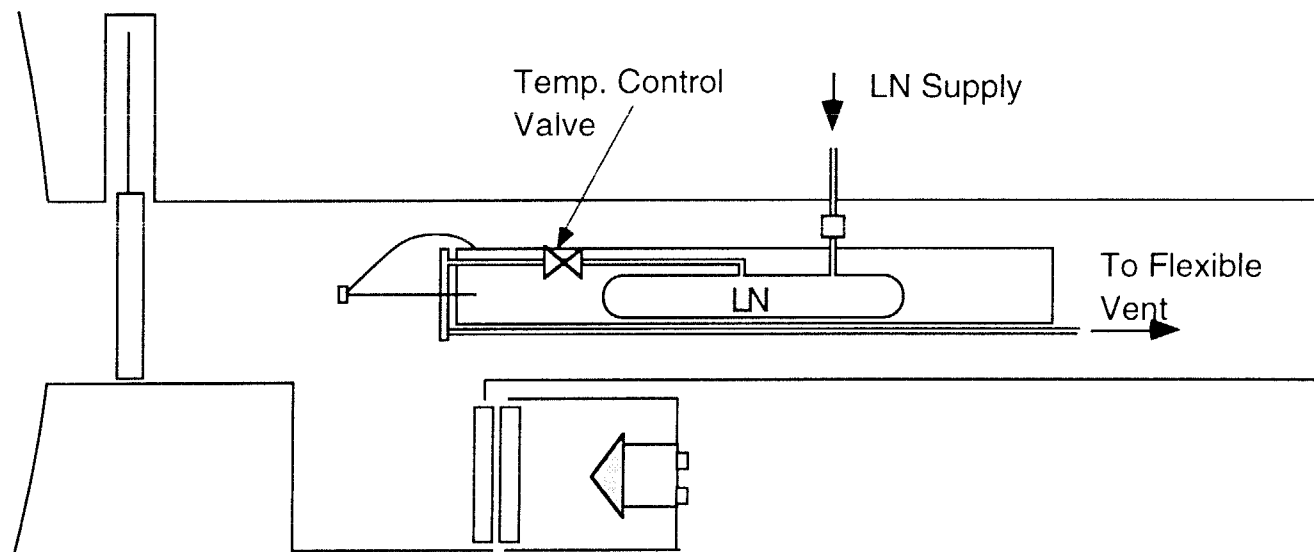
Schematic Positioner System - 1

- Pull vacuum, fill LN dewar, chill support plate
- Coat frost/ice on cylinder/cone under vacuum in coating stand



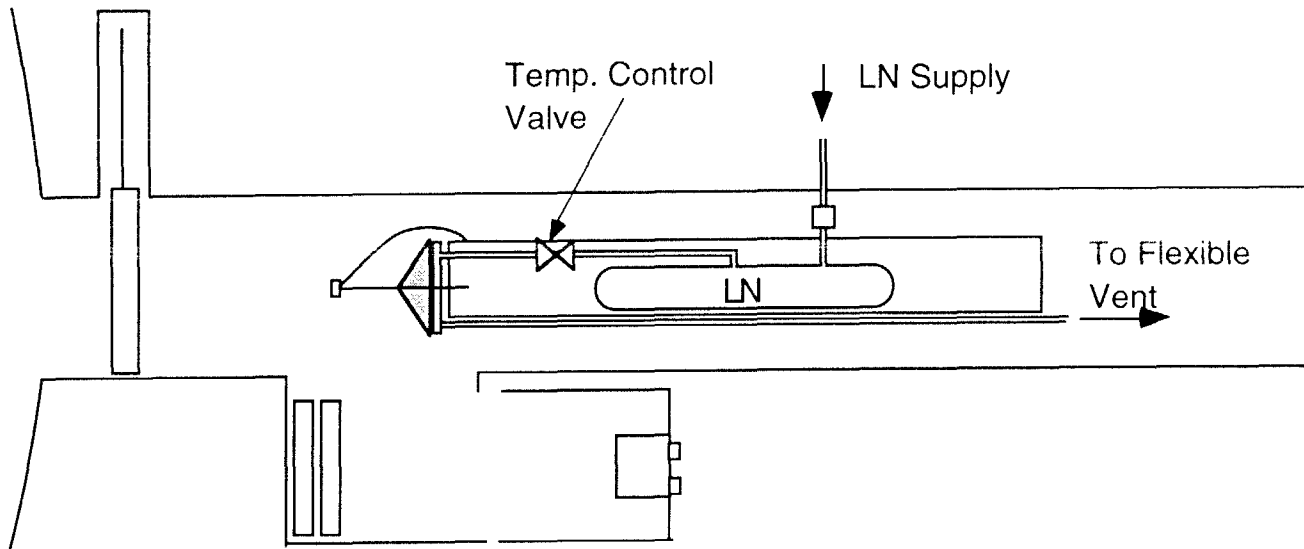
Schematic Postioner - 2

- Dock coated cone/disk container



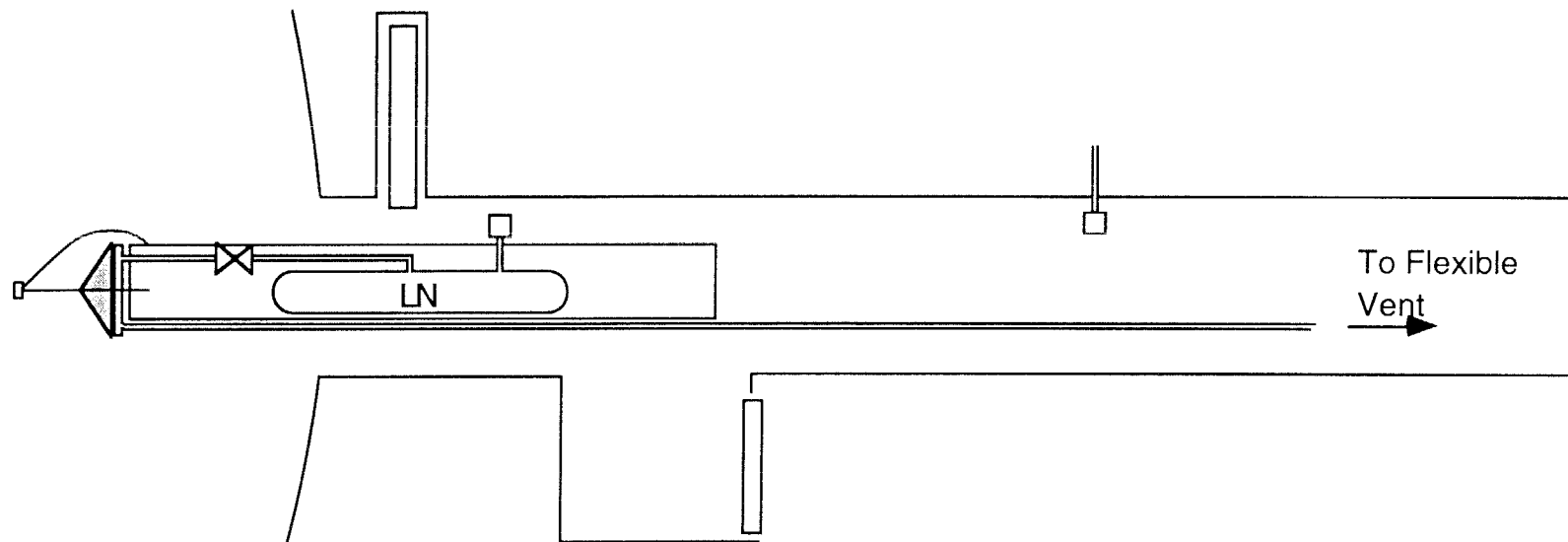
Schematic Postioner - 3

- **Transfer coated disk/cone to target positioner**



Schematic Postioner - 3

- Break LN supply connection
- Insert positioner



Major Frost System Design Constraints - 1

- **Positioner Thermal Distortion**

- Changing thermal environment will cause thermal distortion of positioner
- Solution:
 - » Frost protection system should be integral to positioner
 - » Chill frost/ice support system early
 - » Frost or ice coated disk or cone clips to integral positioner support system
 - » Make positioner thermal environment same in withdrawn and extended positions (thermal radiation most important)

- **Protection of cryogenic targets**

- Design frost system to handle either noncryo or cryo targets
- Apply frost or ice to disk or cone in separate vacuum chamber, install via airlock

Major Frost System Design Constraints

- **Coated cone/disk thermal coupling**
 - Contact resistance between cone/disk and cooled substrate is important
 - To prevent frost buildup on support system surface, must cool system after pulling vacuum
 - Therefore frost or ice coated cone/disk inserted under vacuum conditions

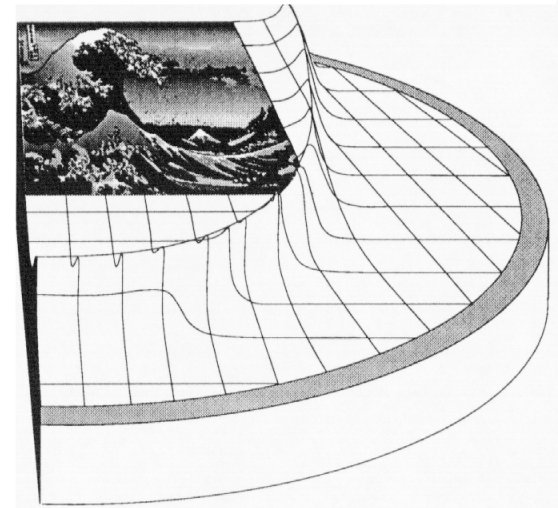


NIF Frost Protection Systems Review Meeting

**Per F. Peterson
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Department of Nuclear Engineering
University of California, Berkeley**

**Lawrence Livermore National Laboratory
April 22, 1996**

- Frost Protection System Topics**



Water Budget

- Compare water from frost to initial water in chamber
- At 1 atm, 20°C, 50% relative humidity:
 - Water vapor pressure = 1.17 kPa
 - Water specific volume = 115.6 m³/kg
 - Water inventory in chamber = 4.54 kg
- Vacuum system must handle much larger inventory of water than would come from frost ablation (i.e. 2 grams)



Frost Layer Growth Rate

- Growth rate controlled by water vapor pressure, increase growth rate by increasing vapor pressure.
- Optimal dendritic morphology achieved at 3-7 torr vapor pressure:
 - growth rate of 10 - 20 mm/hr
 - density of 0.1 g/cm³



Target Positioner Options

- Ice coated metal foam cooled to LN temperature
- Thick-frost coated surface cooled to LN temperature
- Small diameter (30-mm) solid positioner tip
 - promising, particularly for non-yield targets
 - potential materials: graphite, boron, silica
 - must shield entire positioner, including the effect of finite hohlraum radius
- Ambient-generated frost on LN cooled surface
 - Aluminum substrate cooled to LN temperature, with frost coating generated by condensation of ambient background gas (primarily water vapor).

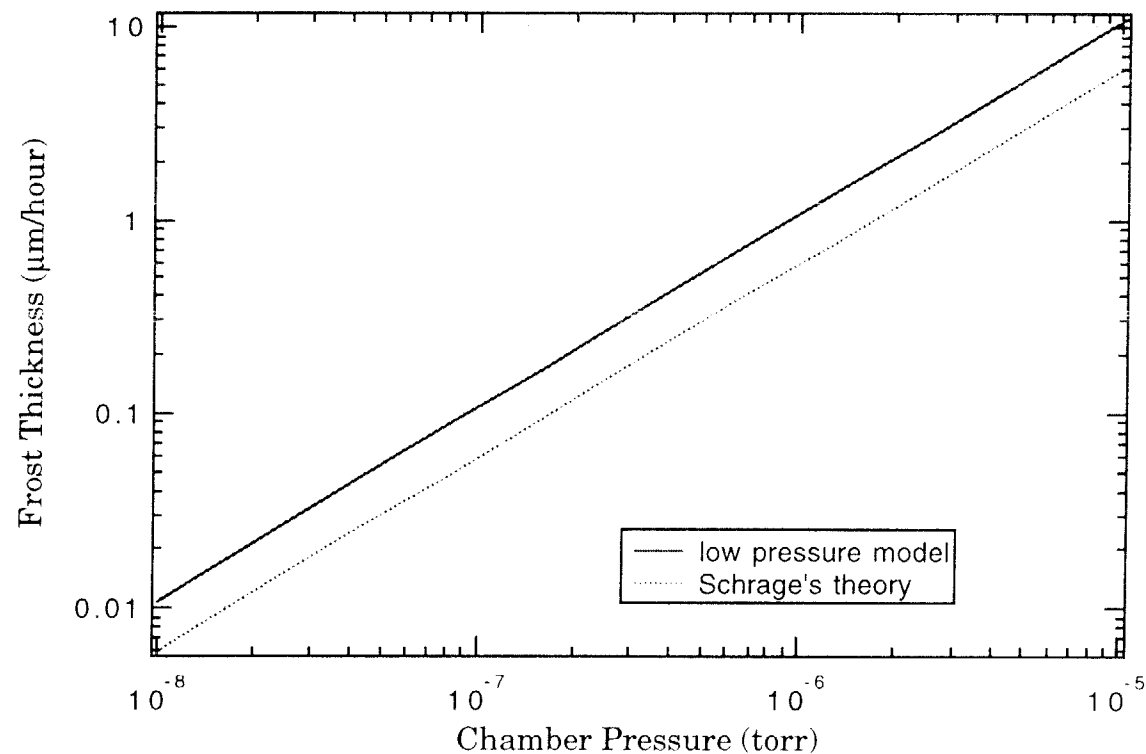
Solid Non-frost-coated Positioner

- Ablation at 10-cm standoff, no yield, 1.8 MJ noncryo hohlraum, giving 400 J/cm^2 to cone with half angle of 45° :
 - Silica (2.2 g/cc): $3.6 \text{ }\mu\text{m}$ fully vaporized
 - Boron (2.35 g/cc): $1.4 \text{ }\mu\text{m}$ fully vaporized, 3.5 mm to incipient vaporization
- 30-mm diameter cone-shaped positioner tip (45° half angle) has an area of 10 cm^2
- Approximate ablated masses (fully vaporized depth):
 - Silica: 0.0079 g
 - Boron: 0.0033 g
- Small diameter solid positioner gives acceptable vapor generation: Must fully shield target positioner.



Ambient Frost-coated Positioner

- Chill surface and allow ambient background gas to condense, generating noncondensable-gas frost layer



NOVA 2-beam shock experiments

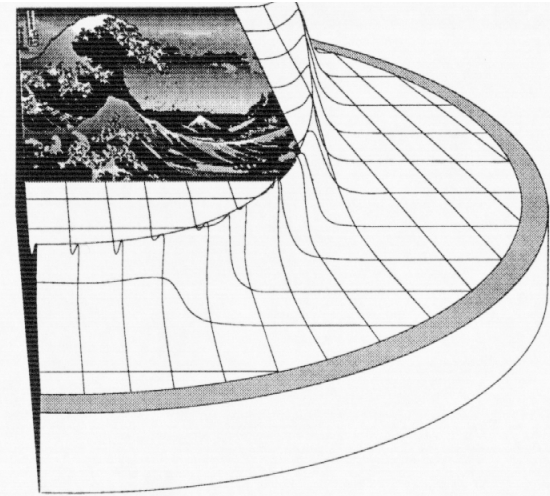
- **Use lasers to generate shocks similar to target-facing surfaces**
- **Greg Dipeso looking at design calculations for plastic-coated metal foam**
- **Also look at solid positioner materials (graphite, boron, silica) in conical geometries, catch debris on polished fused silica to study debris effects on damage threshold.**
- **Coordinate with work on Beamlet beam-dump experiments.**



NIF Frost Protection Systems Review Meetings

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**Lawrence Livermore National Laboratory
April 29, 1996**



- **Ablation from Non-Frost-Coated Positioner Components**



Solid Non-frost-coated Positioner

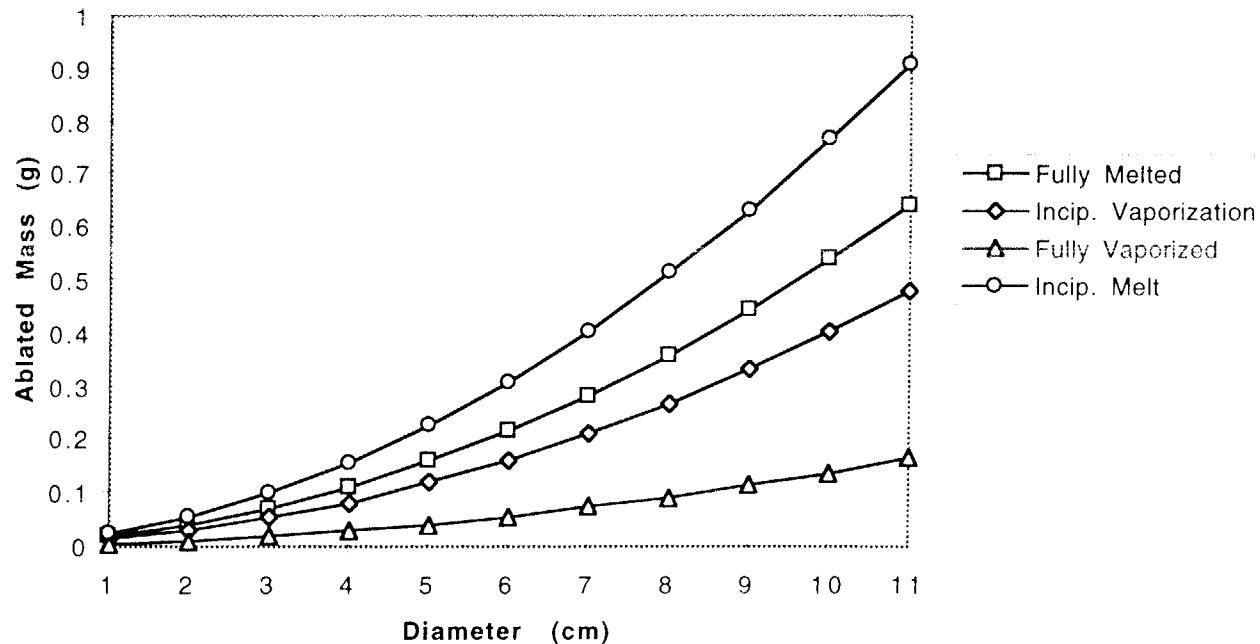
- **Boron:**
 - full vaporization energy: 14,148 cal/g
 - incipient vaporization energy: 3524 cal/g
- **Ablation thickness for 20-MJ cryo target, 10-cm standoff distance**

orientation	normal	45 degrees
total melt	24.1 μm	17.0 μm
incipient vapor	18.0 μm	12.6 μm
complete vapor	6.2 μm	4.6 μm



Boron Ablation Mass

- 20 MJ Yield Shot, 10-cm stand-off (1720 J/cm^2)
- Vary diameter of surface facing target



Compare Cryo and Non-cryo targets

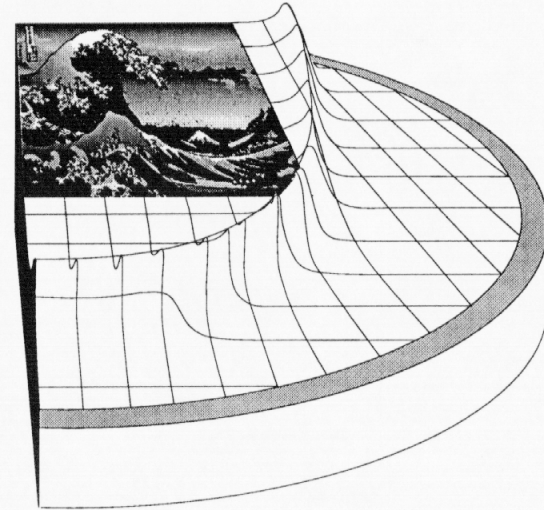
- Ablation at 10-cm standoff, no yield, 45° cone half angle
 - 1.8 MJ noncryo hohlraum (400 J/cm² normal to x rays)
 - » Boron (2.35 g/cc): 1.4 μm fully vaporized, 3.5 μm to incipient vaporization
 - 20 MJ cryo hohlraum (1720 J/cm² normal to x rays)
 - » Boron (2.35 g/cc): 4.6 μm fully vaporized, 12.6 μm to incipient vaporization



Experiments and Analysis of Ablation and Condensation on NIF First Wall Materials

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University of California, Berkeley

Robert E. Turner and Andrew T. Anderson
Lawrence Livermore National Laboratory



June 18 , 1996

- **Introduction to NIF Chamber Dynamics**
- **NOVA Chamber Damage Observations**
- **X-Ray Ablation/Condensation Experiments**
- **TSUNAMI Modeling**



Introduction

- **NIF laser debris-shield contaminants**
 - Target debris
 - X-ray ablation from target positioner/diagnostics
 - First wall and beam dumps for high-yield shots
 - Remobilized contamination from first wall
 - Shine-shields and other near-target objects
- **Important physical processes**
 - Target x-ray and debris emission
 - X-ray ablation
 - Near-target ablative shock response
 - Gas dynamics and transport
 - Condensation
 - Debris shield response to contamination



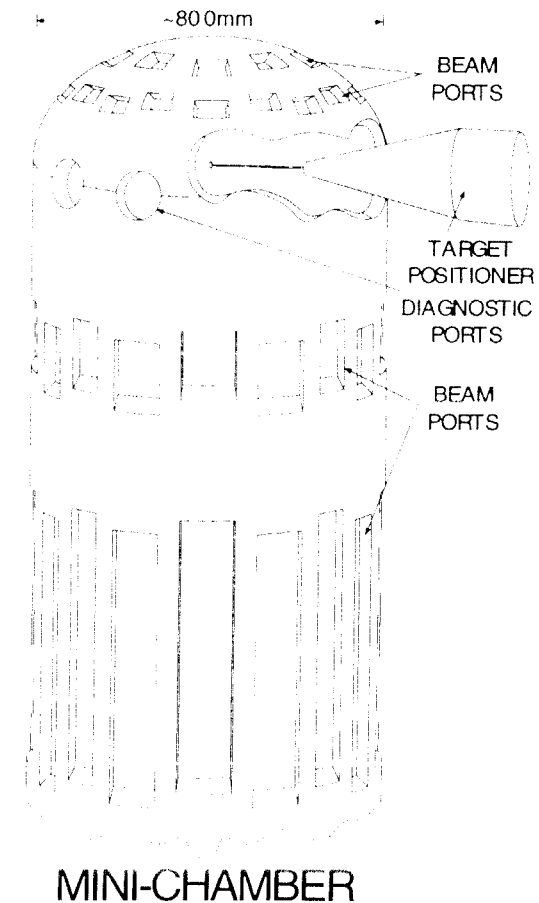
NIF and NOVA x-ray fluence comparison

	Near Target (10 cm)	First Wall (2.2 m, NOVA) (5.0 m, NIF)
30-kJ NOVA no yield	18.5 J/cm ²	0.05 J/cm ²
1.8-MJ NIF 0.1-MJ yield	1400 J/cm ²	0.6 J/cm ²
1.8-MJ NIF 20-MJ yield	5000 J/cm ²	2.0 J/cm ²

Fluences near holraum axis, fluences are lower on
hohiraum waist by factor of 2 to 4

NIF Chamber X-ray Protection

- **Near target (positioner/diagnostics)**
 - Cryogenic (liquid nitrogen cooled) water frost/ice coated surfaces
 - Crushable foam/frost for shock mitigation
 - Tapered geometries
- **First wall**
 - Refractory-coated panels (i.e. boron, boron carbide, ...)
 - Fused-silica beam dump cover
- **Advanced protection methods**
 - For beyond-design-basis shots (direct drive, large near-target masses)
 - Frost-coated mini-chamber -->



NOVA Chamber Damage Observations

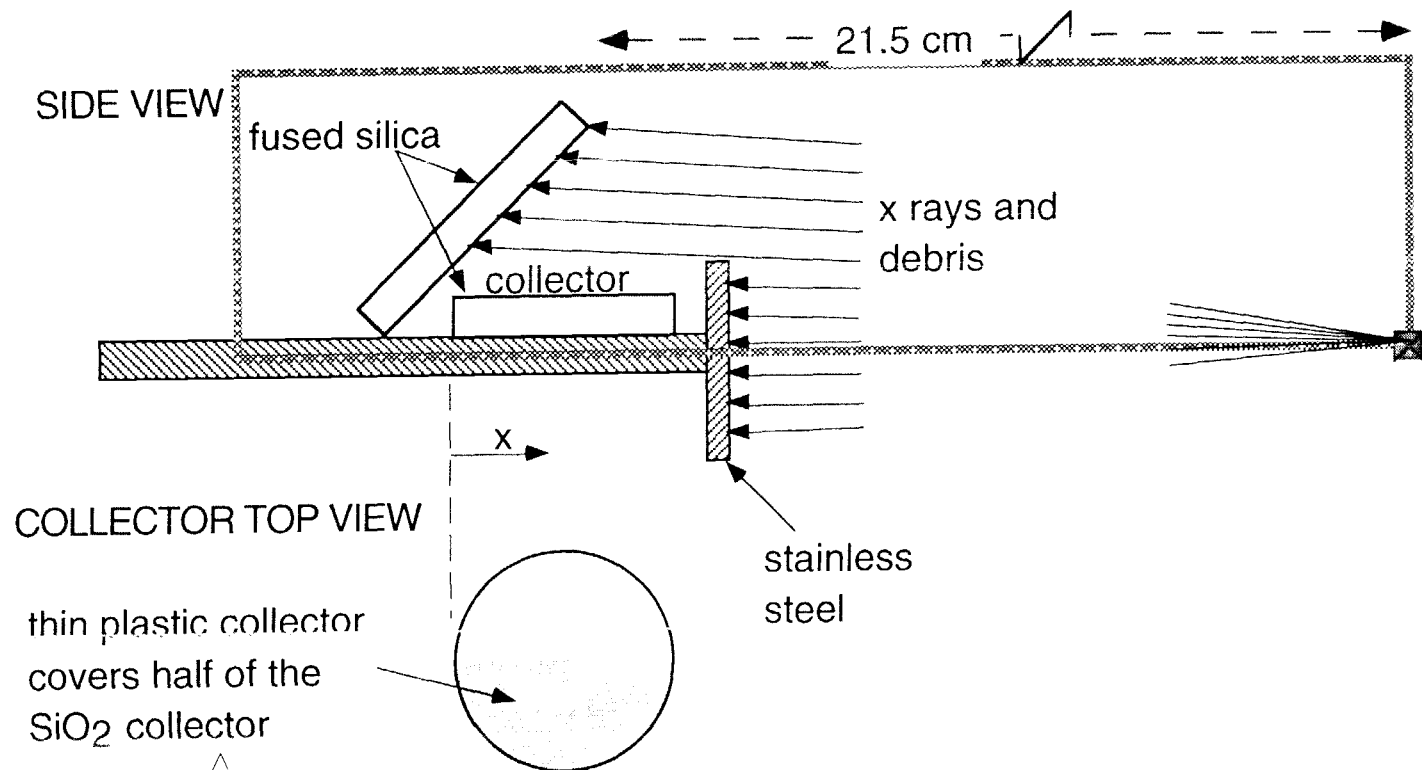
- **One decade of NOVA operation provides insight for debris generation, transport and deposition**
 - Photos of chamber damage
- **NOVA has provided x-ray fluences characteristic of NIF first-wall fluences for NIF experiments**
 - NOVA used as test bed for NIF chamber-response experiments
 - Samples placed in six-inch manipulator tube and placed close to NOVA target (i.e. 10-cm to 80-cm standoff)
 - See also papers in the NIF poster sessions



NOVA Ablation/Condensation Experiments

- **Experiment Configuration**

- Initial study for fused-silica beam dumps
- Goal to study debris-shield degradation from ablated contaminants



Experiment Parameters

- **Fused silica blanks exposed to x-rays**
 - Optical quality (flat to a tenth wave or better)
 - 50-mm diameter
- **Nova laser-heated hohlraum targets**
 - hollow gold cylinders, 2.8 mm long and 1.6 mm diameter
 - laser light focused through the open ends and onto the interior walls
 - 10-beam laser delivered 30 kJ of 0.35-mm light in a 2.3-ns pulse
- **Experiment orientations (21.5-cm standoff)**
 - **Case 1:** 25° away from target's axis of symmetry (gives it a good “view” of the x-rays from the hot interior gold walls)
 - » 200-eV black-body, 4 J/cm²
 - **Case 2:** normal to the hohlraum axis, thin hohlraum walls
 - » 100-eV black-body, 2 J/cm²



Experiment Results

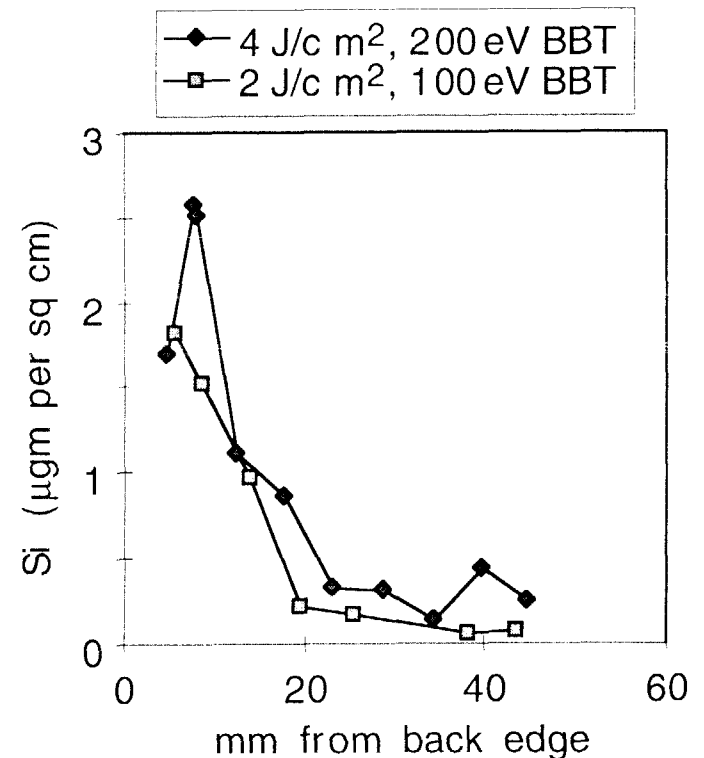
- Ablation (model* predicts well):

- Case 1: $0.28\ \mu\text{m}$ ($4\ \text{J}/\text{cm}^2$)
- Case 2: $0.18\ \mu\text{m}$ ($2\ \text{J}/\text{cm}^2$)

- Condensation

- collected on a thin CH (plastic) foil
 - » analyzed by x-ray fluorescence
- collected on polished fused silica
 - » laser damage threshold measured
 - » contaminated silica damaged with $0.35\text{-}\mu\text{m}$ light at significantly lower threshold (of order $1.5\ \text{J}/\text{cm}^2$, rather than $> 10\ \text{J}/\text{cm}^2$)

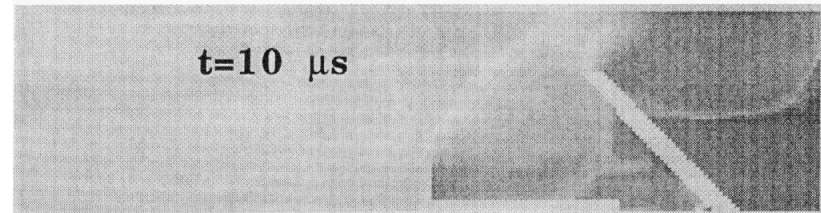
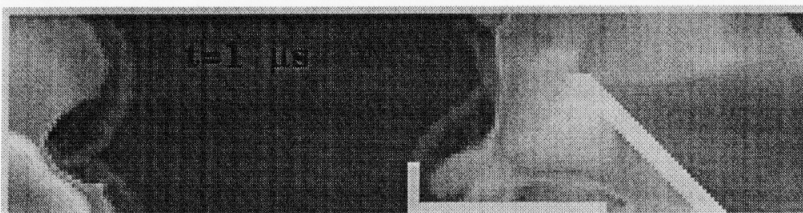
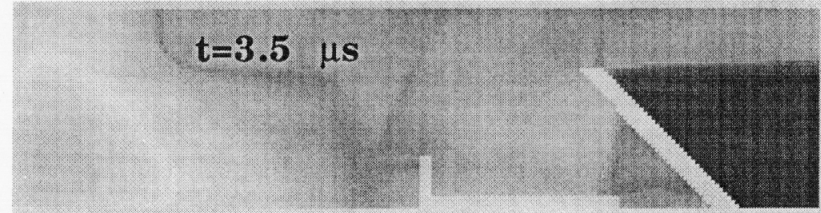
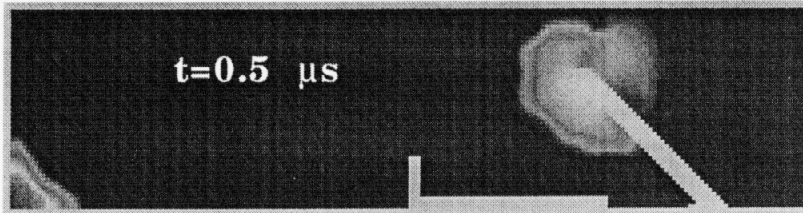
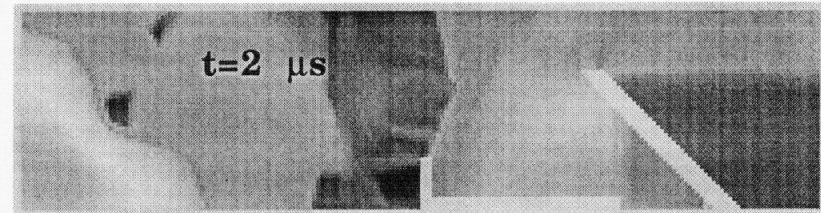
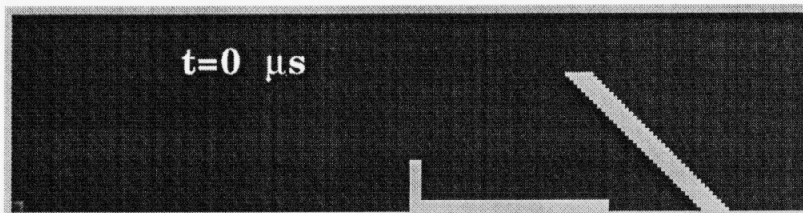
Condensed Si on CH sample



* see "X-Ray Emission from National Ignition Facility Indirect Drive Targets," Anderson, Managan, Tobin, and Peterson

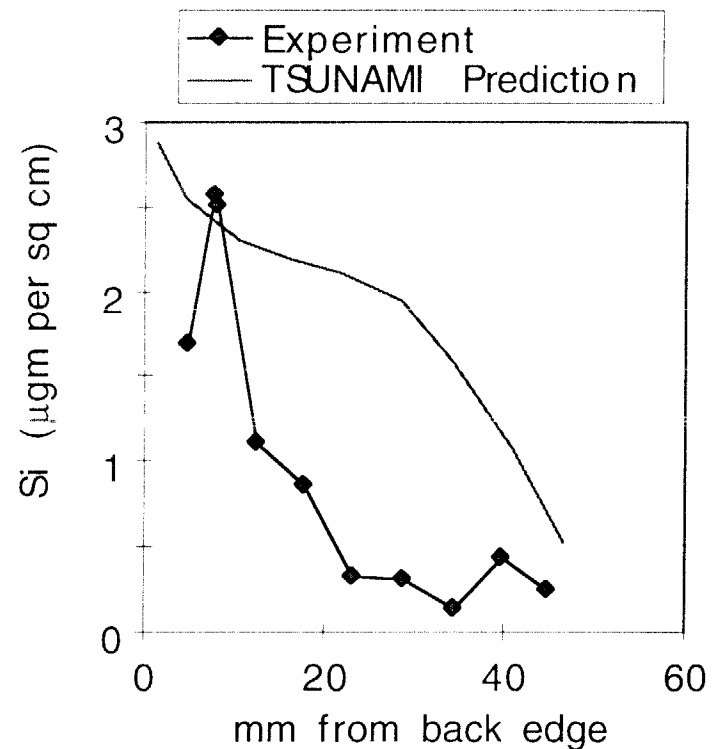
TSUNAMI 2-D Simulation

- Condensing surface model developed
 - heating of surface reduces condensation rate
 - compare with using open boundary for condensing surface



Condensation Predictions

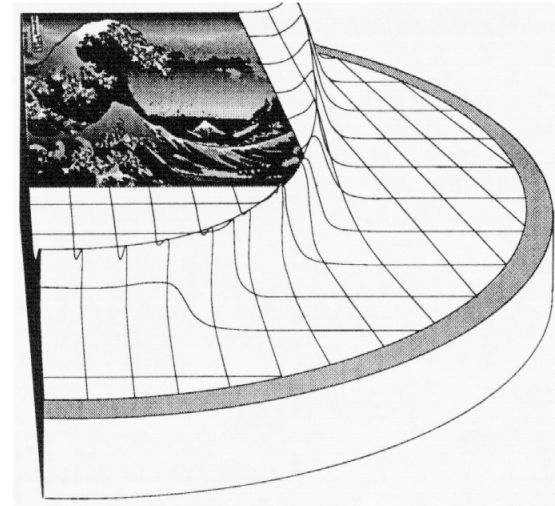
- TSUNAMI results are **conservative**; predict **thicker layer condensed**
- **Reasons:**
 - 2-D versus 3-D flow effects
 - Equilibrium assumption in condensing model
 - Vaporized SiO_2 chemical state (dissociates to SiO and O_2)



NIF CO₂ Cleaning Thermal Response

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Lawrence Livermore National Laboratory
July 1, 1996



- **Introduction**
- **CO₂ Cleaning Fin Model**
- **Conclusions**

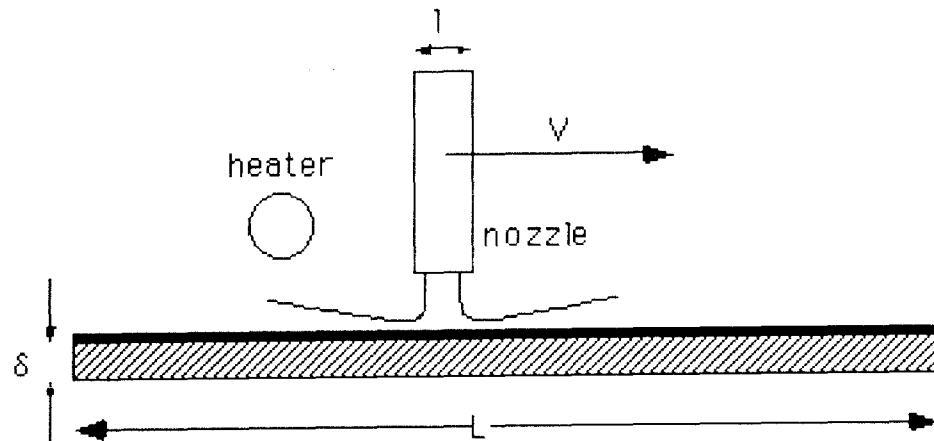


Introduction

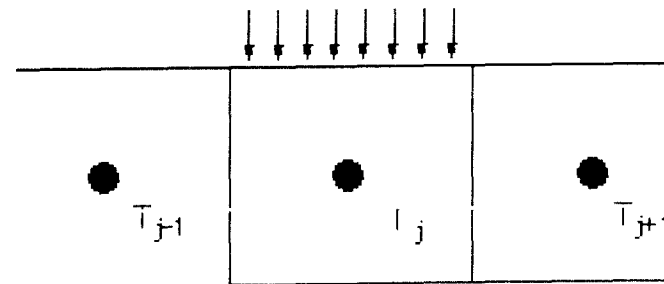
- Developed 1-D fin-equation-based model for for thermal cooling due to CO₂ cleaning
- Obtained rough match of CO₂ cleaning test experimental results
- Most important issue for CO₂ cleaning is cooling of chamber aluminum shell and concrete
 - 0.5 m thick concrete thermal time constant is 100 hr
- Any bypass CO₂ flow has substantial refrigeration effect
- Heat transfer by convection (not conduction) from panels to chamber wall is important
- Providing air flow behind panels can mitigate any convective heat transfer

1-D Fin-Based CO₂ Cleaning Model

System schematic



Numerical Grid



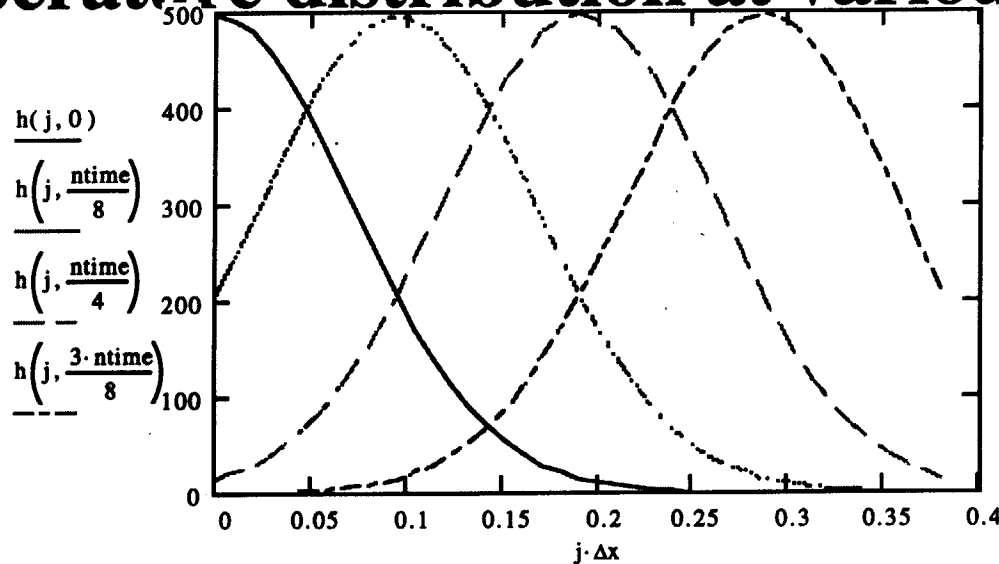
Cleaning Model Assumptions/Parameters

- **Used Sun and Chen, Journal of Heat Transfer, Vol. 117, pp 1028, 1995, particle heat transfer correlation**
- **Uncertainty in CO₂ particle velocity, size, flow rate**
- **Ended up doubling heat transfer coefficient to better match experiments**
- **Used normal distribution for heat transfer coefficient, adjusted cooled area width to match experiments**

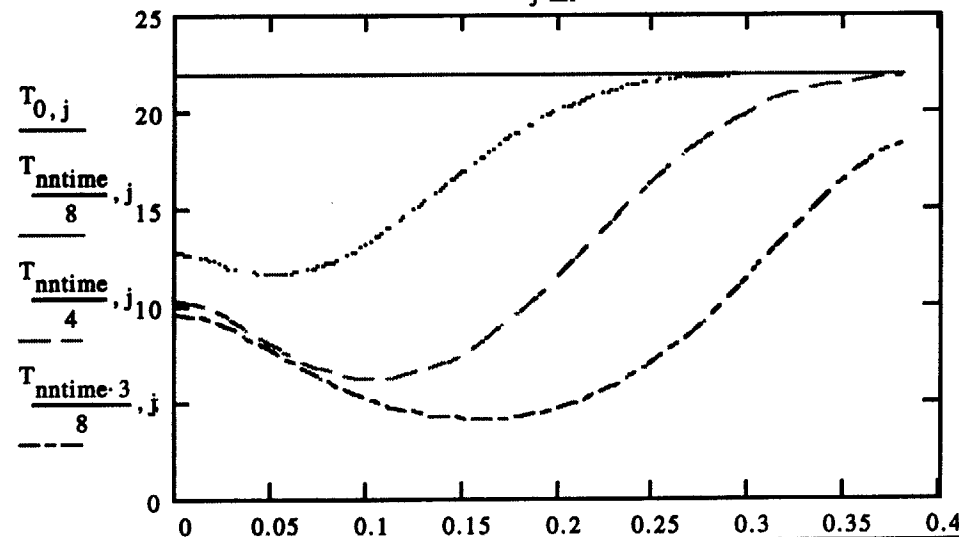


Heat transfer coef. distribution, resulting temperature distribution at various times

$h, \text{W/m}^2\text{C}$



$T, ^\circ\text{C}$

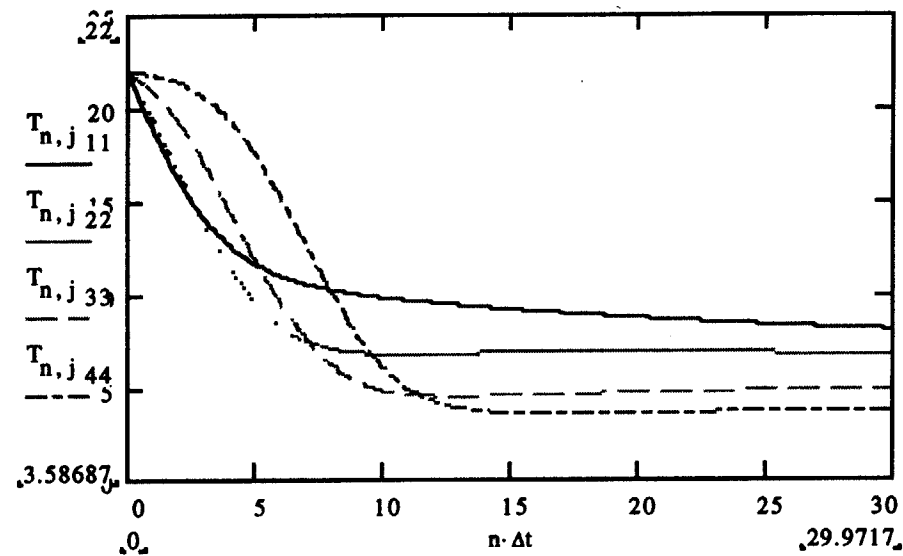


$j \cdot \Delta x$

Heat transfer coefficient distribution, resulting temperature distribution at various times

Temperature history predicted at four points

$T, ^\circ\text{C}$



Time, seconds



University
of California



Nuclear Thermal Hydrogen

Conclusions

- width over which cooling occurs is much larger than cleaning width
- significant cooling continues after CO₂ cleaner has passed off of sample
- properly designed vacuum system should reduce cooling significantly by reducing cooled area
- plastic brush material will be damaged by heaters, consider a spring-loaded sliding metal
- consider mechanism for air flow behind panels to prevent convective heat transfer to chamber wall



Minichamber Status Report

Per F. Peterson

John M. Scott

July 30 , 1996

Lawrence Livermore National Laboratory

ICE meeting

**Berkeley
Engineering**



**University
of California**



Nuclear Thermal Hydraulics

Overview

- **NIF design requirements for fielding mini-chambers**
- **Minichamber key issues**
 - mechanical response (Will it break?)
 - debris capture effectiveness and optimization
 - water burden on vacuum system
 - effectiveness of frost as a beam dump
 - demonstration of frost growth
 - TSUNAMI calculations
 - interface for chamber protection with large experiment packages



Minichamber impact on NIF design

- **Need to make sure to have enough vertical clearance to fit minichamber on the lift.**
- **Will need lockdown hardware for the minichamber attachment to main chamber when the lift is withdrawn.**
- **Will need hookups for instrumentation packages, LN supply, and vent lines.**
- **Impact appears to be relatively small, but needs to be considered during design process**



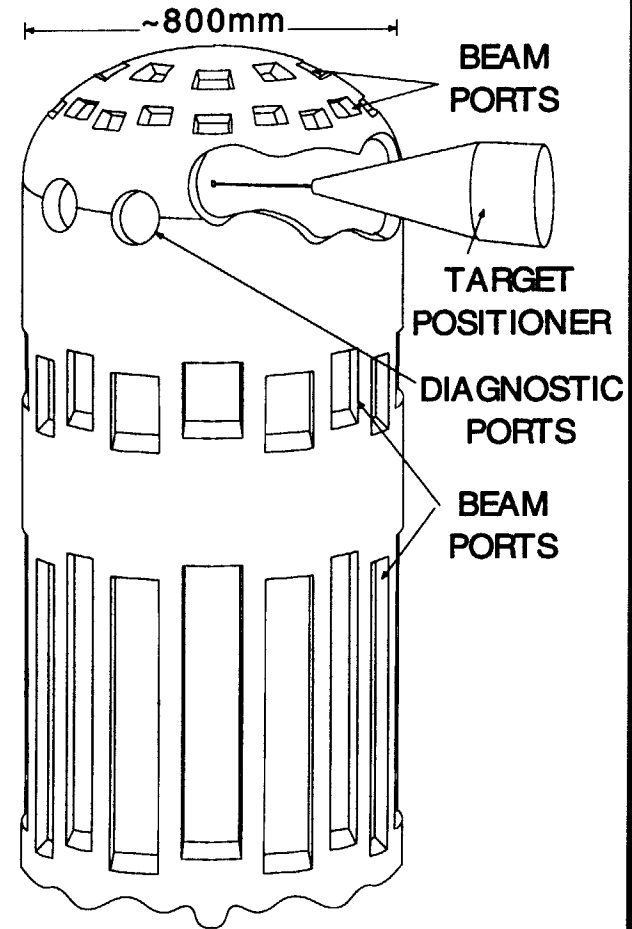
Minichamber Analysis

- **Mechanical Response**

- Need to evaluate the response of the cylindrical minichamber.
- An initial study of the spherical design indicated the pressure loading could be accommodated.

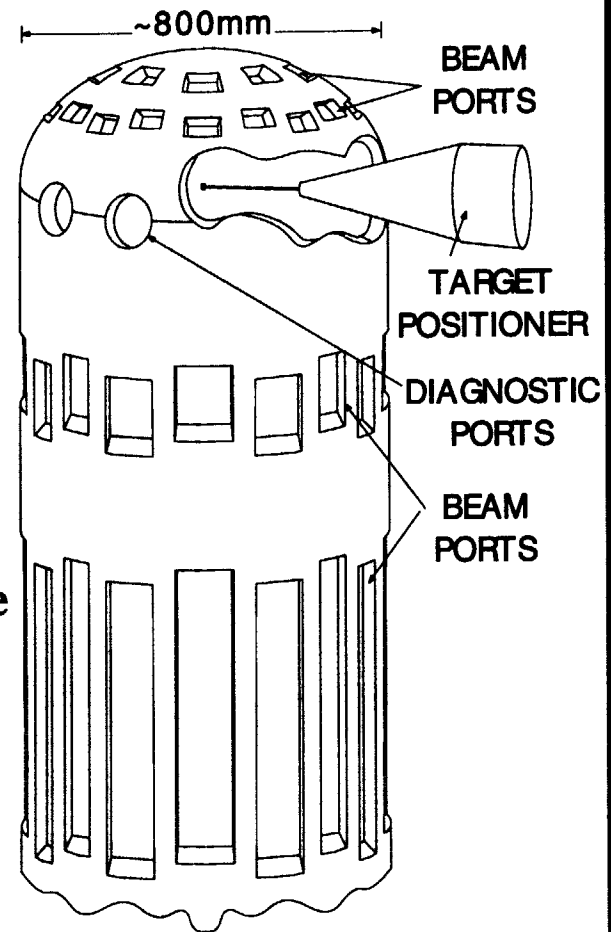
- **Debris Capture Effectiveness**

- Will ablated frost effectively 'close' the laser ports so that debris cannot pass through?
- Study of the optimum size and bevel angle of ports to capture debris.
- Optimization of the shape of the minichamber head to force debris to the bottom of the minichamber.
- Will debris escape out the large ports at the bottom of the minichamber? What fraction?

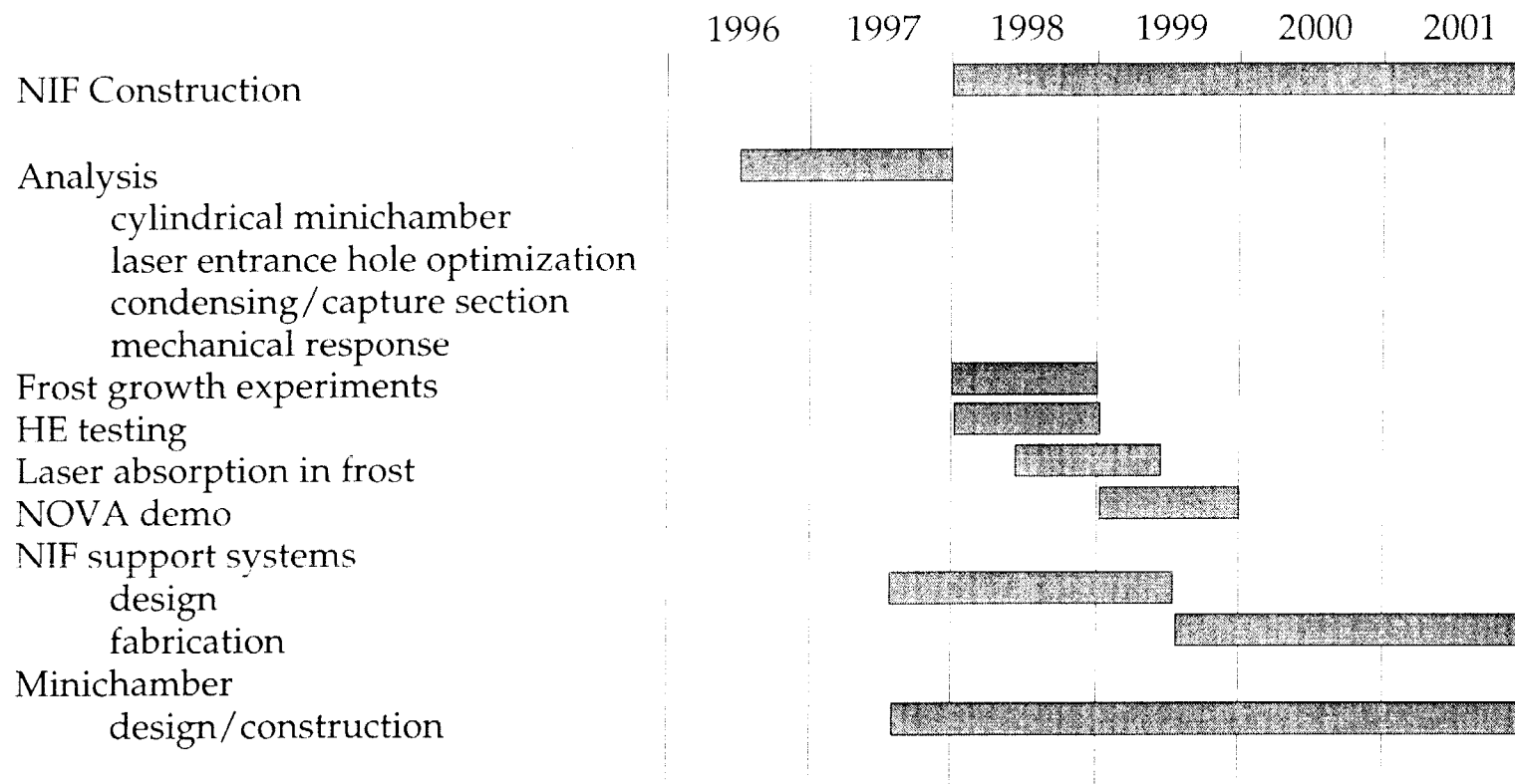


Minichamber Analysis

- **Water burden on vacuum system**
 - Frost thickness required
 - Fraction of frost to be regenerated each shot
- **Effectiveness of frost as a beam dump**
 - Thickness of frost required to effectively attenuate 1ω and 2ω laser light
 - The 3-D effects of the laser ablated frost on the system
- **Frost growth experiments**



Tentative Timeline

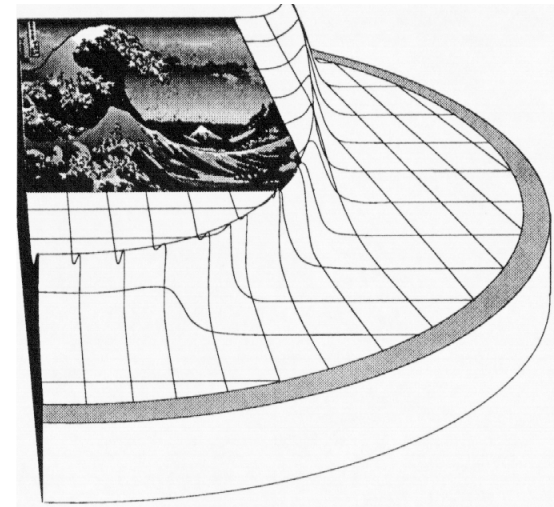


• **Integrate into the current NIF project schedule.**

NIF CO₂ Cleaning Thermal Response

Per F. Peterson
Associate Professor
Department of Nuclear Engineering
University of California, Berkeley

Lawrence Livermore National Laboratory
October 21, 1996



- **Introduction**
- **CO₂ Cleaning Fin Model**
- **Conclusions**

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Nuclear Thermal Hydraulics

Introduction

- **Most important issue for CO₂ cleaning is cooling of chamber aluminum shell and concrete**
 - 0.5 m thick concrete thermal time constant is 100 hr
 - Tentative criteria - do not cool concrete by more than 0.5°C
 - For a 24-hr cleaning duration, 0.1- m thick concrete Fourier and Biot numbers are:
 - » $Fo = t\alpha/L^2 = (8.6 \times 10^4 \text{ sec})(7 \times 10^{-7} \text{ m}^2/\text{s})/(0.1 \text{ m})^2 = 6$
 - » $Bi = hL/k = (4 \text{ W/m}^2\text{K})(0.1 \text{ m})/(1.4 \text{ W/mK}) = 0.3$
 - » Biot around unity implies detailed thermal analysis needed
- **Bypass CO₂ flow has substantial refrigeration effect**
 - For 5000 cfm ventilation rate, to maintain 2.0°C air temperature change requires a capture efficiency of 94% when the pellet flow rate is 20 lb/hr.



Compare In- and Ex-Chamber Cleaning

- **In-Chamber negatives**

- In-chamber requires close fitting panels to prevent pellet escape
- In-chamber requires strategy to move cleaning head around beam ports and diagnostics without excessive pellet escape
 - » question of radiant heater performance and thermal stress when cleaning head is rotated.
- In-chamber cleaning generates some thermal perturbation of chamber wall, detailed thermal design required to minimize effect

- **Ex-chamber negatives**

- Ex-chamber panel removal rate may be too slow
 - » Consider a scheduled cleaning strategy, remove fraction of panels during each weekly maintenance period?



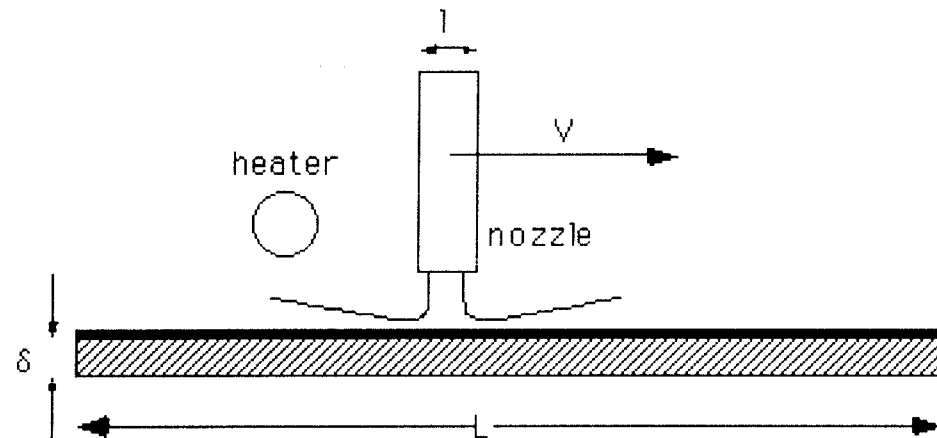
1-D Chamber Cleaning Model

- Developed 1-D fin-equation-based model for for thermal cooling due to CO₂ cleaning
- Obtained rough match of CO₂ cleaning test experimental results
- Used Sun and Chen, Journal of Heat Transfer, Vol. 117, pp 1028, 1995, particle heat transfer correlation
- Uncertainty in CO₂ particle velocity, size, flow rate
- Used normal distribution for heat transfer coefficient, adjusted cooled area width to match experiments

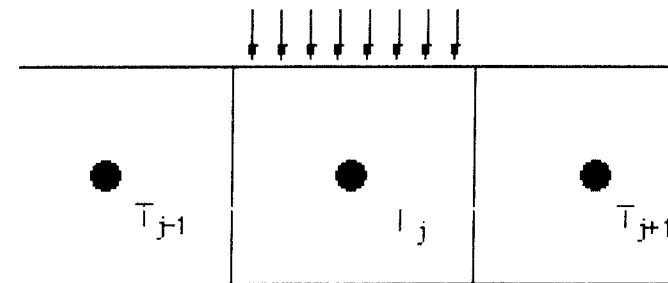


1-D Fin-Based CO₂ Cleaning Model

System schematic

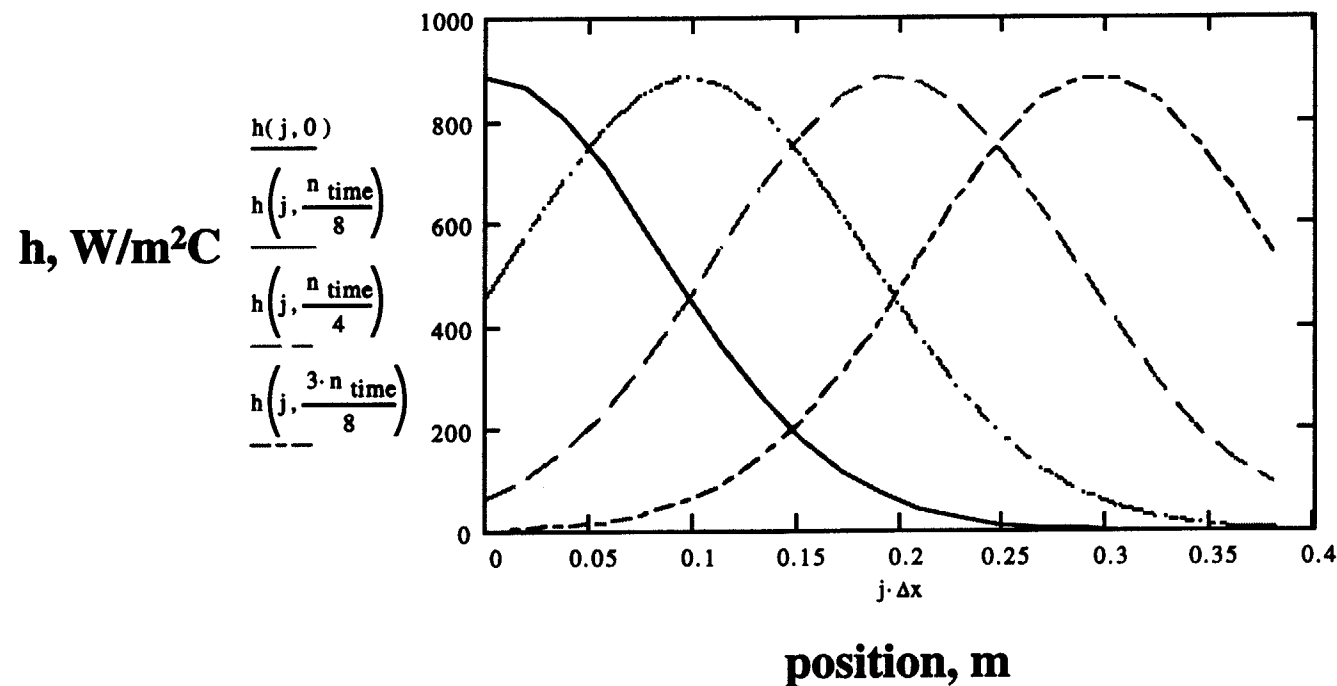


Numerical Grid



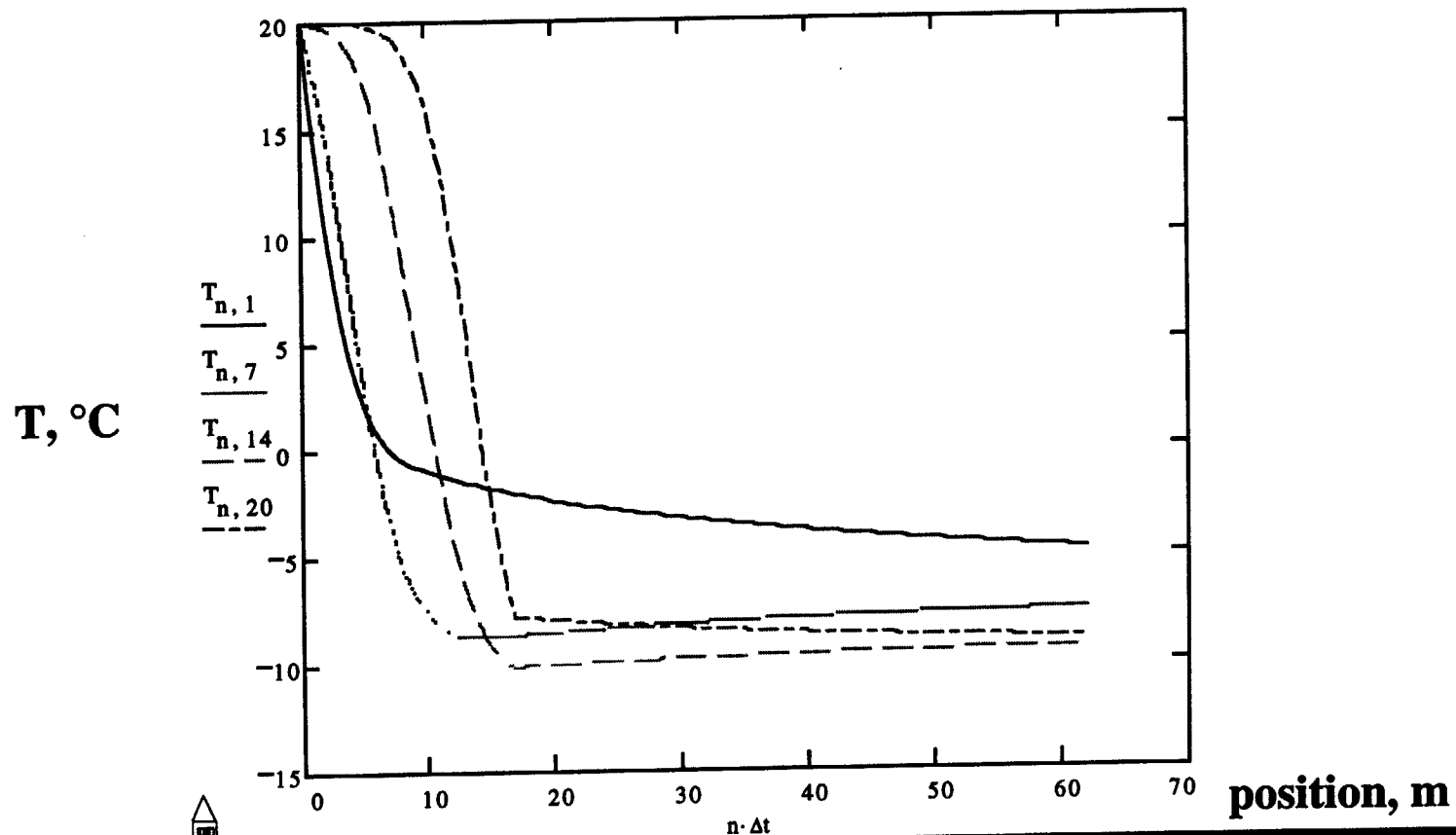
Heat Transfer Coefficient

- Surface heat transfer coefficient ($\text{W/m}^2\text{°C}$) distribution (m) at four different points in times as the jet rasters across the surface.



Surface temperature history

- four thermocouple locations, for raster rate of 1 in/sec.

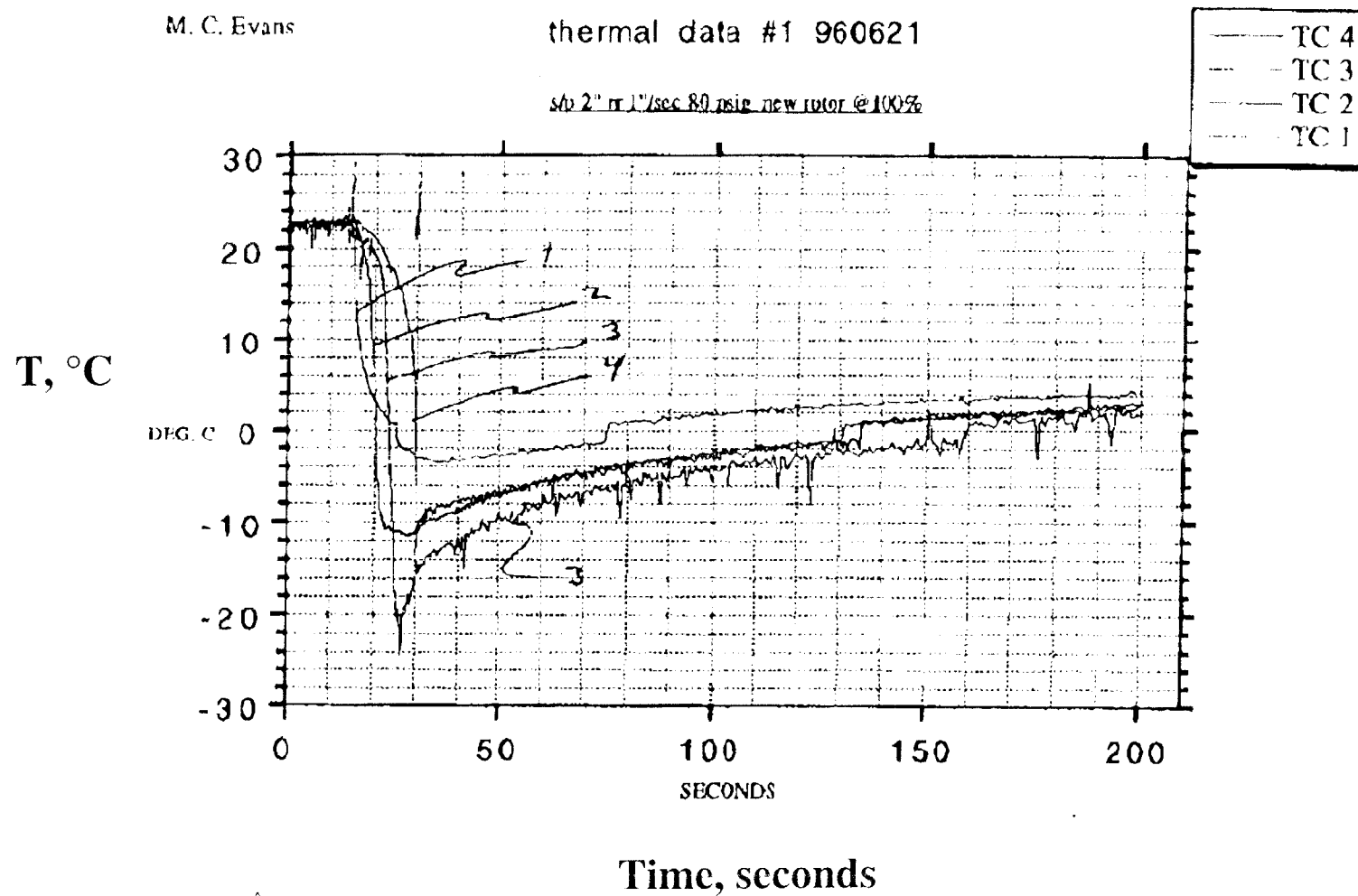


Measured temperature history

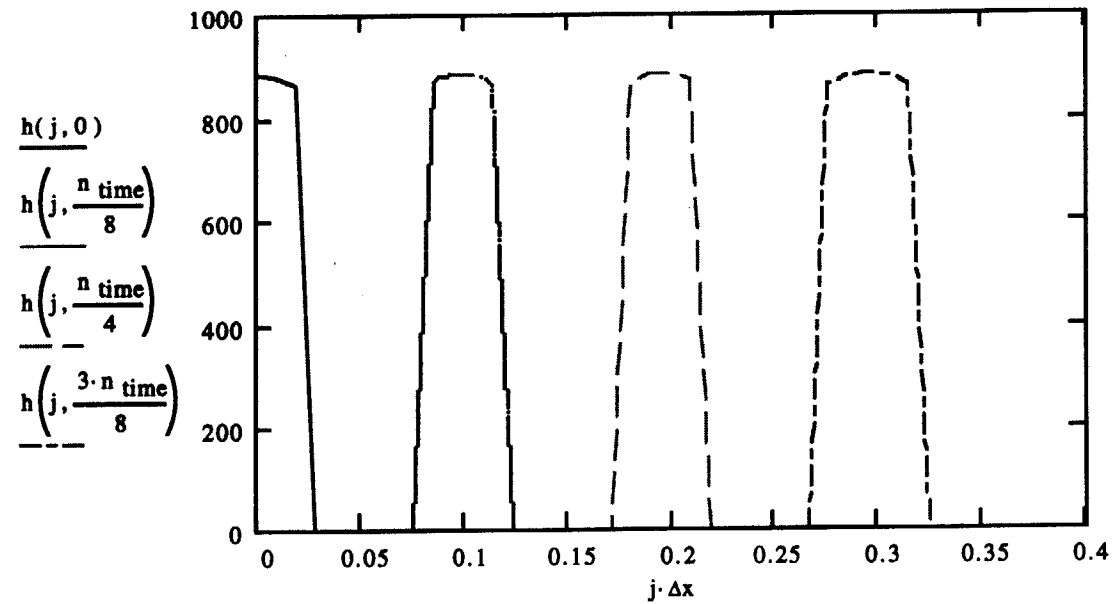
M. C. Evans

thermal data #1 960621

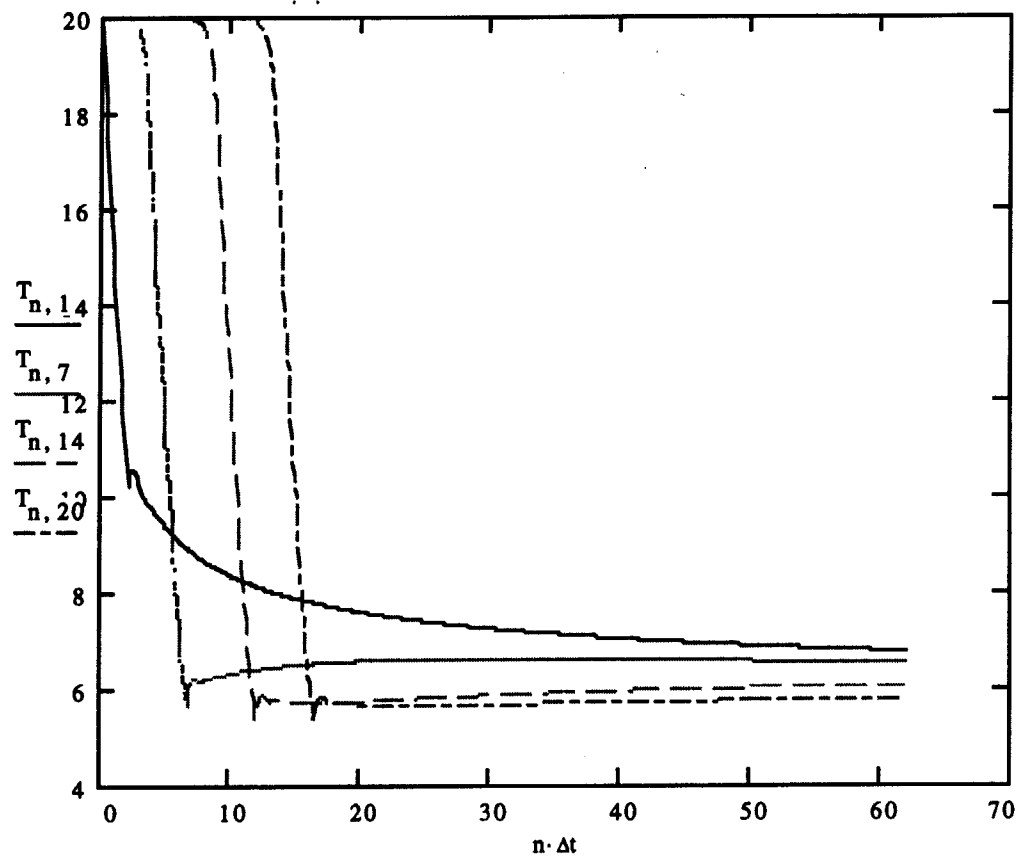
shd 2" r 1" / sec 80 psig new rotor @ 100%



Effect of capture system



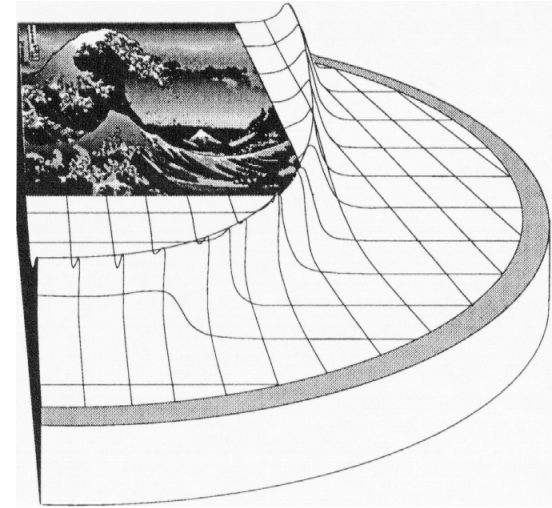
Effect of Capture System



NIF CO₂ Cleaning Thermal Response

Per F. Peterson
Associate Professor
Department of Nuclear Engineering
University of California, Berkeley

Lawrence Livermore National Laboratory
December 13, 1996



- Introduction
- In-chamber vs. ex-chamber cleaning issues
- Localized cooling: CO₂ Cleaning Fin Model
- Global cooling: CO₂ Pellet Bypass
- Conclusions



Conclusions

- width over which cooling occurs is much larger than cleaning width
- significant cooling continues after CO₂ cleaner has passed off of sample
- properly designed vacuum system reduces cooling significantly by reducing cooled area
- plastic brush material will be damaged by heaters, consider a spring-loaded sliding metal
- capture system efficiency is important
- ex-chamber cleaning may offer advantages



Introduction

- **Most important issue for CO₂ cleaning is cooling of chamber aluminum shell and concrete**
 - 0.5 m thick concrete thermal time constant is 100 hr
 - Tentative thermal distortion criteria - do not cool concrete by more than 0.5°C
 - For a 24-hr cleaning duration, 0.1- m thick concrete Biot number is:
 - » $Bi = hL/k = (4 \text{ W/m}^2\text{K})(0.1 \text{ m})/(1.4 \text{ W/mK}) = 0.3$
 - » Biot around unity implies detailed thermal analysis needed
- **Localized cooling effect from CO₂ jet**
 - Mitigate using radiant heaters
- **Global cooling from bypass CO₂ pellet flow**
 - Requires active thermal control of chamber interior

Compare In- and Ex-Chamber Cleaning

- **In-Chamber negatives**

- In-chamber requires close fitting panels to minimize pellet bypass
- In-chamber requires strategy to move cleaning head around beam ports and diagnostics without excessive pellet escape
 - » question of radiant heater performance and thermal stress when cleaning head is rotated.
- In-chamber cleaning generates some thermal perturbation of chamber wall, detailed thermal design required to minimize effect

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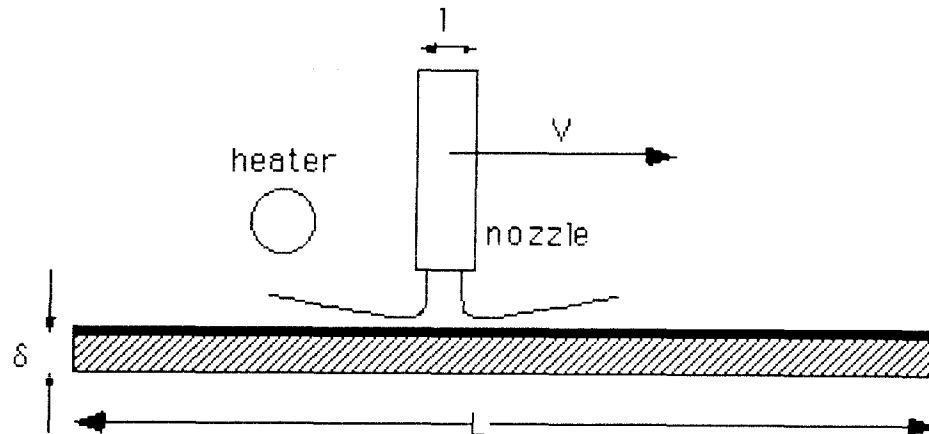
1-D Cleaning Model-Localized Cooling

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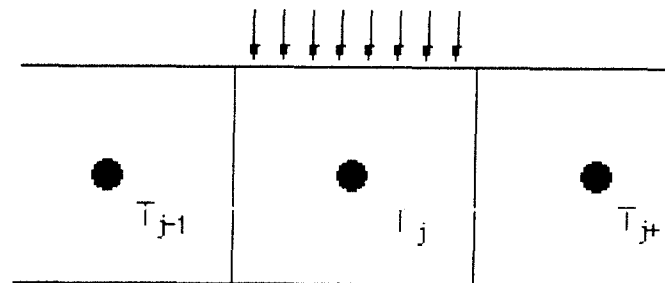


1-D Fin-Based CO₂ Cleaning Model

System schematic

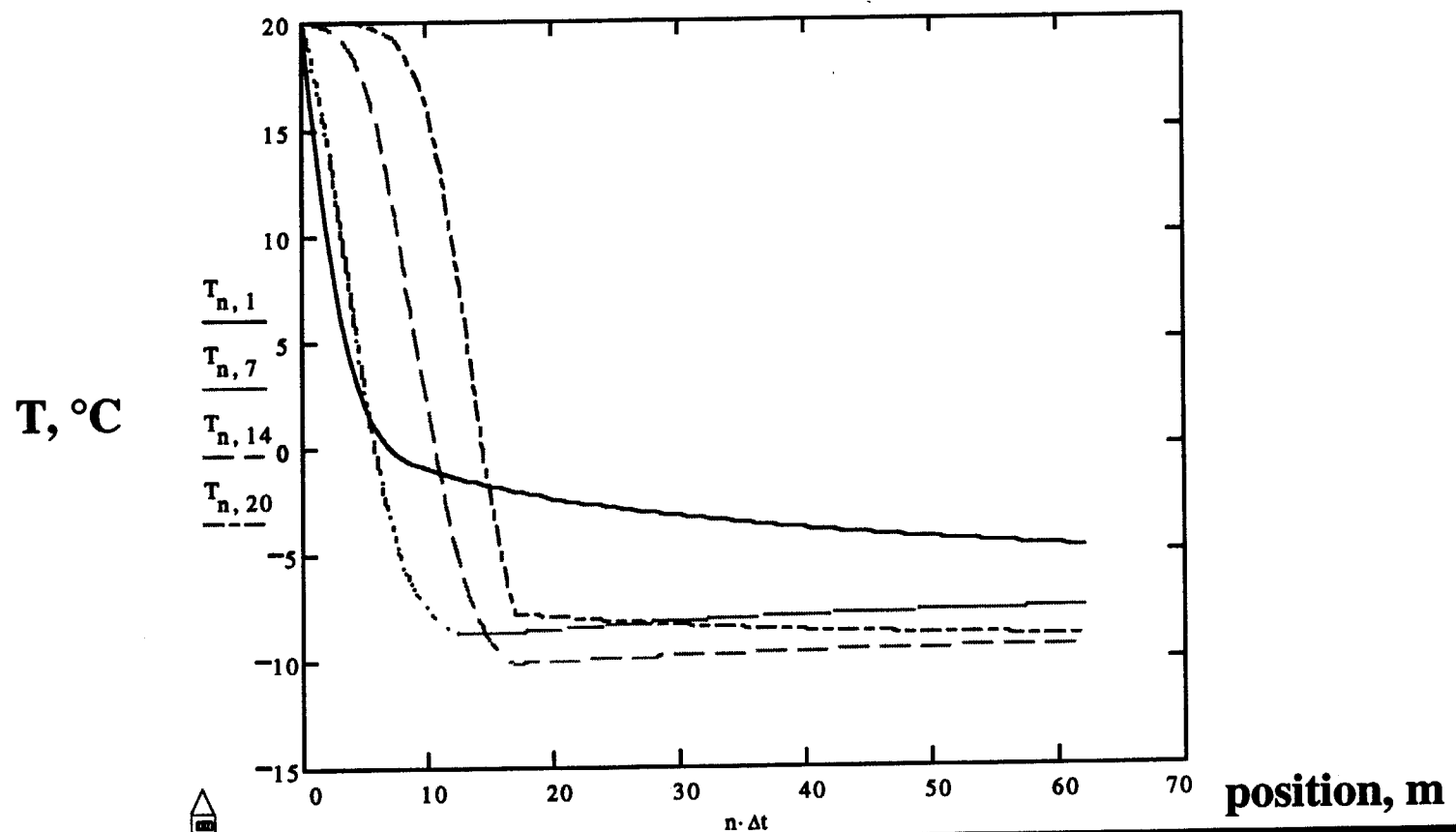


Numerical Grid



Surface temperature history

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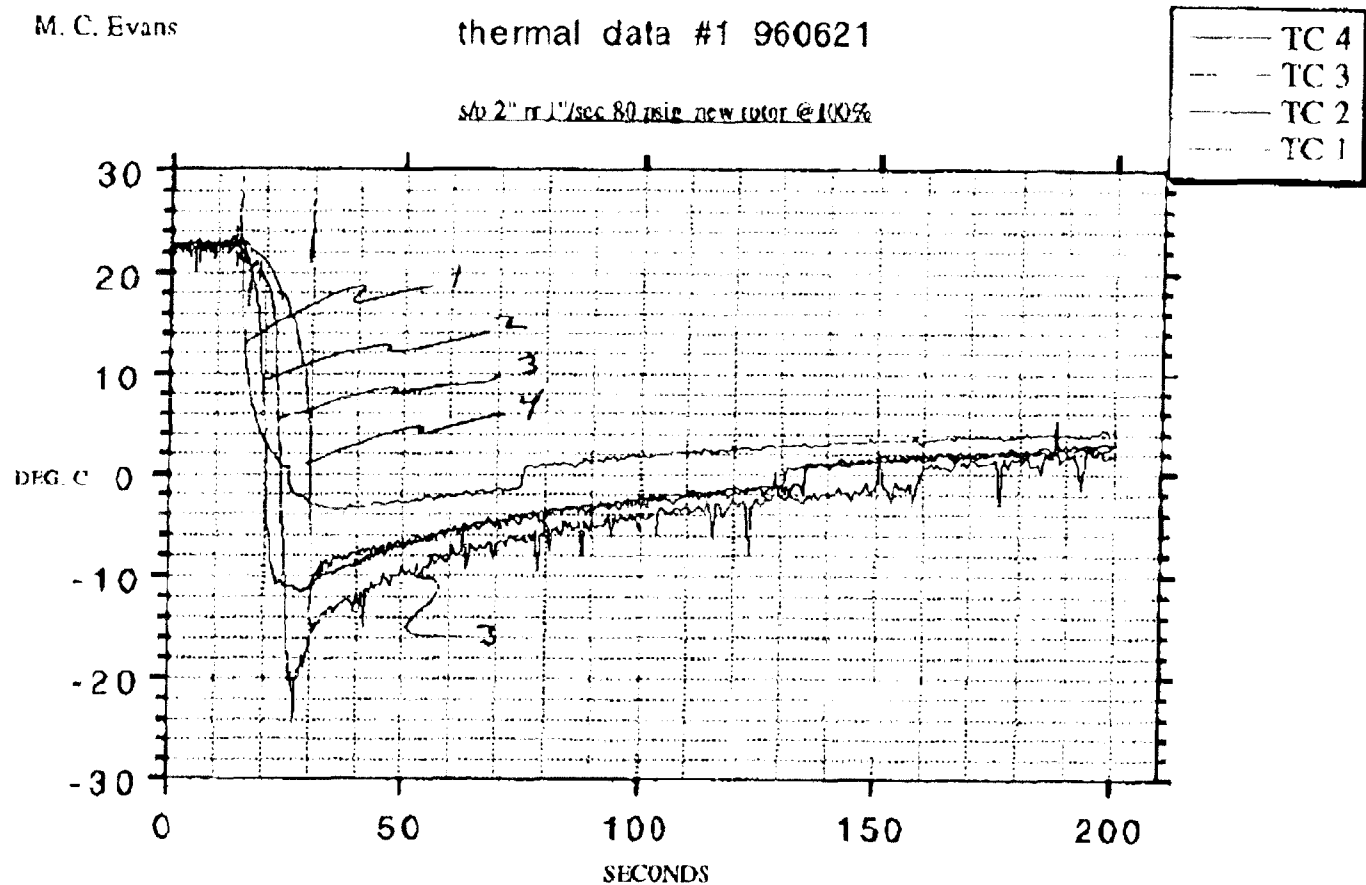
Measured temperature history

M. C. Evans

thermal data #1 960621

slp 2" rr 1"/sec 80 msig new tutor @ 100%

T, °C



Time, seconds

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Nuclear Thermal Hydraulics

Global Cooling Effect

- Localized cooling by pellet impact mitigated with radiant heating
- Primary refrigeration effect comes from CO_2 pellet bypass
- Active thermal conditioning of chamber inside wall can mitigate cooling
- Water flow rate may be substantial: 1 lb/min bypass \approx 50 gpm water flow for $0.1^\circ\text{C } \Delta T$
- Diverting water flow from final optics assemblies could provide ~ 500 gpm.



Conclusions

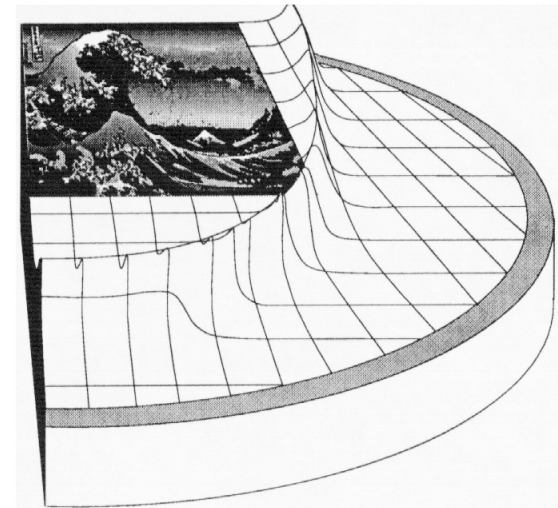
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- properly designed vacuum system reduces cooling significantly by reducing cooled area
- plastic brush material will be damaged by heaters, consider a spring-loaded sliding metal
- capture system efficiency is important
 - 1 lb/min bypass \approx 50 gpm water flow for 0.1°C ΔT
- ex-chamber/passive cleaning may offer advantages



TSUNAMI Status Report

**Per F. Peterson and John M. Scott
Department of Nuclear Engineering
University of California, Berkeley**

**NIF Target Chamber Development Review
December 13, 1996**



- **TSUNAMI and UCB-NIF Chamber Development Work**
 - Review and introduction
 - Example TSUNAMI calculations
 - Plan for upcoming year



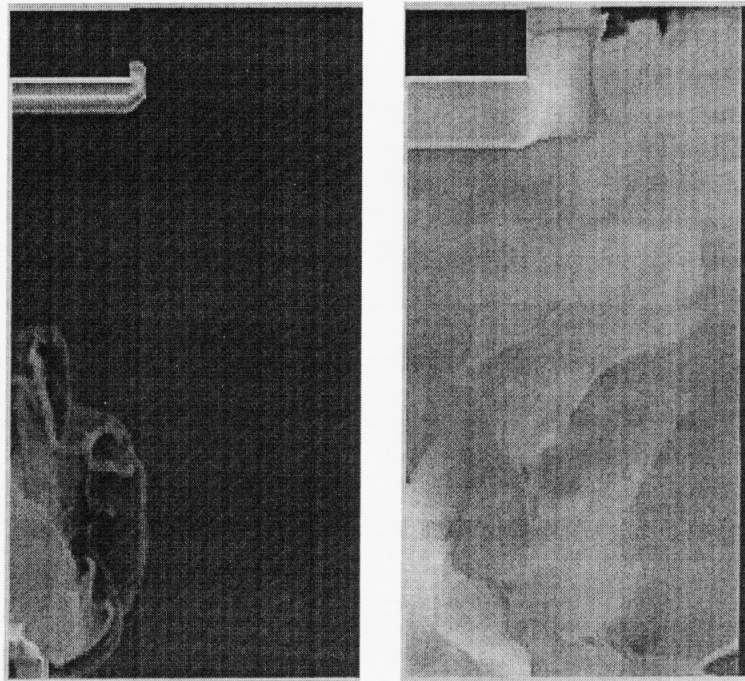
TSUNAMI Capabilities and Issues

- **Current features**
 - Complex geometry, gas dynamics, ablation/condensation, real gas treatment, multiple species
- **For the future**
 - Improved treatment of ablation, in flight condensation, 2-D radiation
- **Debris shield contamination drives development of TSUNAMI.**
- **Collaboration with Gerry Wilemski on SiO₂ behavior.**
- **We must properly model the ablation, 2-D transport processes, and condensation.**



Examples of TSUNAMI Applications

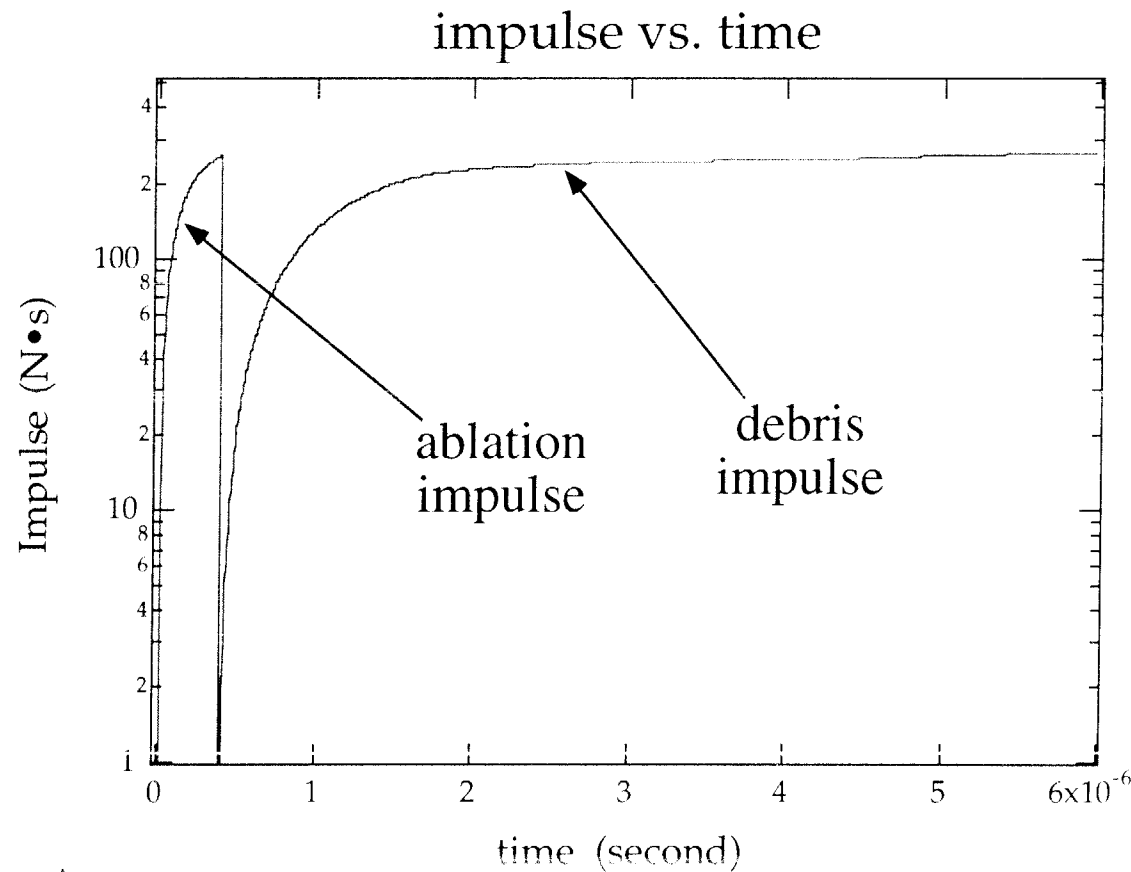
- **TSUNAMI has been utilized for:**
 - NOVA hohlraum and near target surface interaction
 - NIF target positioner calculations
 - Ablation/condensation experiment calculations
 - NIF target chamber debris distribution



NOVA hohlraum and ablated vapor interaction (benchmark example)

NIF Target Positioner Example

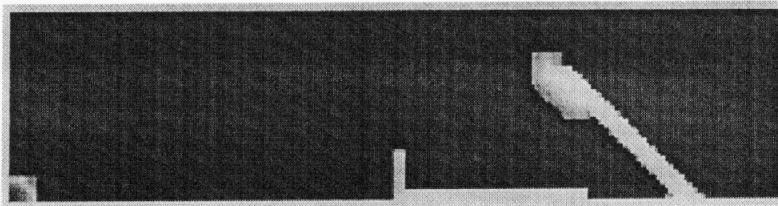
- Ablation impulse duration/magnitude compares well to LASNEX.
- Debris impulse, magnitude is same as ablation impulse.



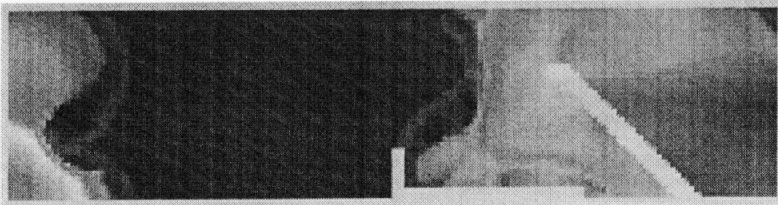
Ablation/Condensation Experiment

TSUNAMI output

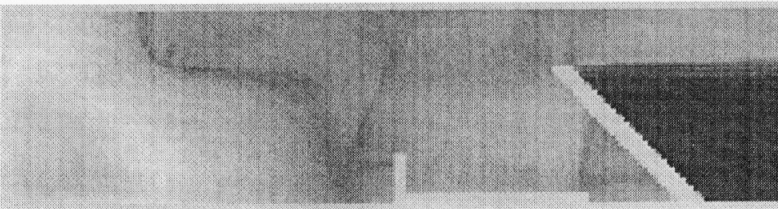
$t = 0 \mu s$



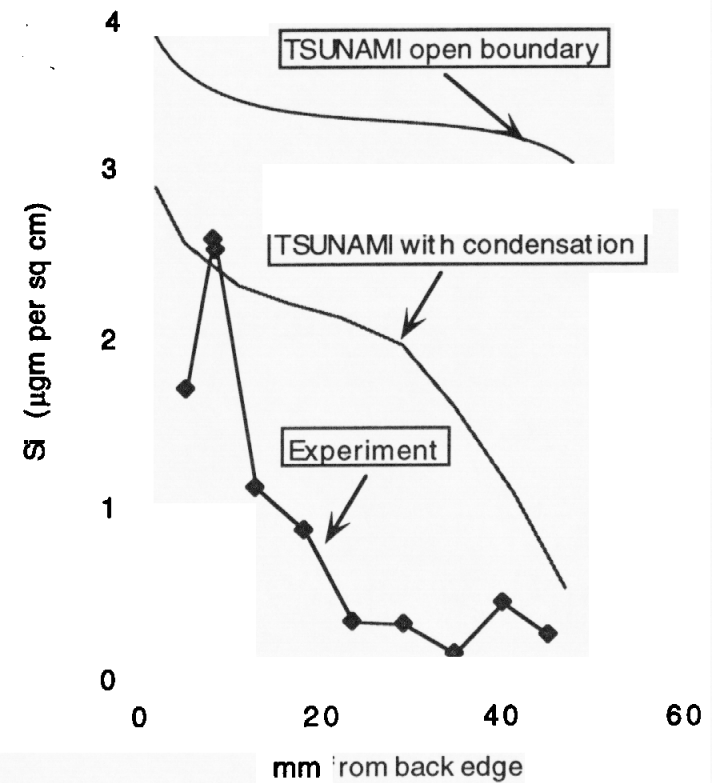
$t = .5 \mu s$



$t = 3.5 \mu s$



Comparison of TSUNAMI with experiment



1997 UCB-NIF Task Plan

- **Fundamental Topics**

- Completion of multiple species (Jan. 1997)
- In-flight chemical and condensation effects with G. Wilemski (Feb. 1997)
- Improved condensation model (Mar. 1997)
- Improved ablation model (Apr. 1997)
- NOVA ablation/condensation benchmarking experiments

- **Applications**

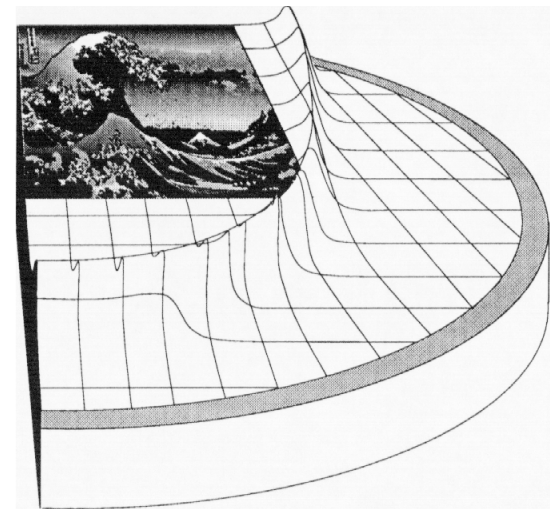
- Beam dump design and optimization
- Target positioner design and optimization
- Chamber debris deposition distribution studies and optimization
- Passive debris collection strategies (fate of remobilized first wall contamination)
- Advanced protection concept studies



Mini-chamber Status Report

Per F. Peterson and John M. Scott
Department of Nuclear Engineering
University of California, Berkeley

NI Target Chamber Development Review
December 13, 1996



• Advanced Protection: The Mini-chamber

- Introduction and overview
- Impact on NIF
- Development and goals



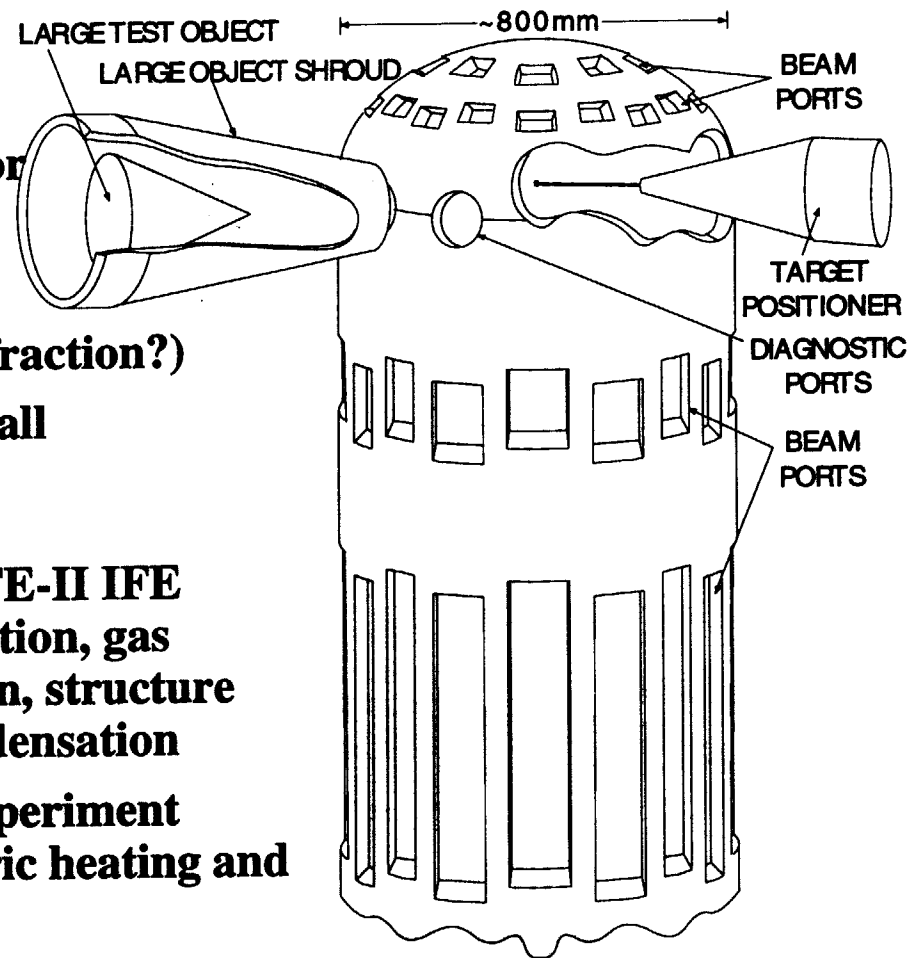
Frost Coated Mini-chamber Introduction

- **NIF Related Benefits**

- Capture target debris/ablated positioner and diagnostic vapor (~87% capture fraction)
- Oxidize hydrocarbons debris
- Stop shrapnel (~50% capture fraction?)
- Reduce x-ray fluence to first wall

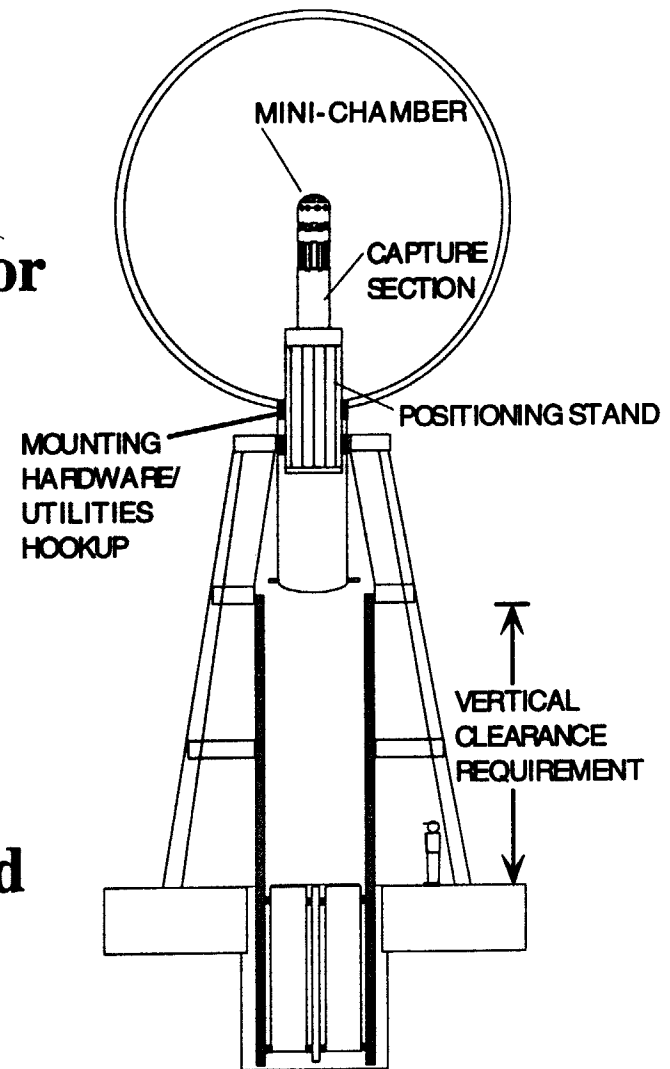
- **IFE Related Benefits**

- Generates prototypical HYLIFE-II IFE reactor conditions—x-ray ablation, gas dynamics, chemical dissociation, structure pressure loading, venting, condensation
- Allows fielding of large IFE experiment packages (i.e. liquid jet isochoric heating and disassembly experiments)
- Advantages for heavy ion demonstration facility

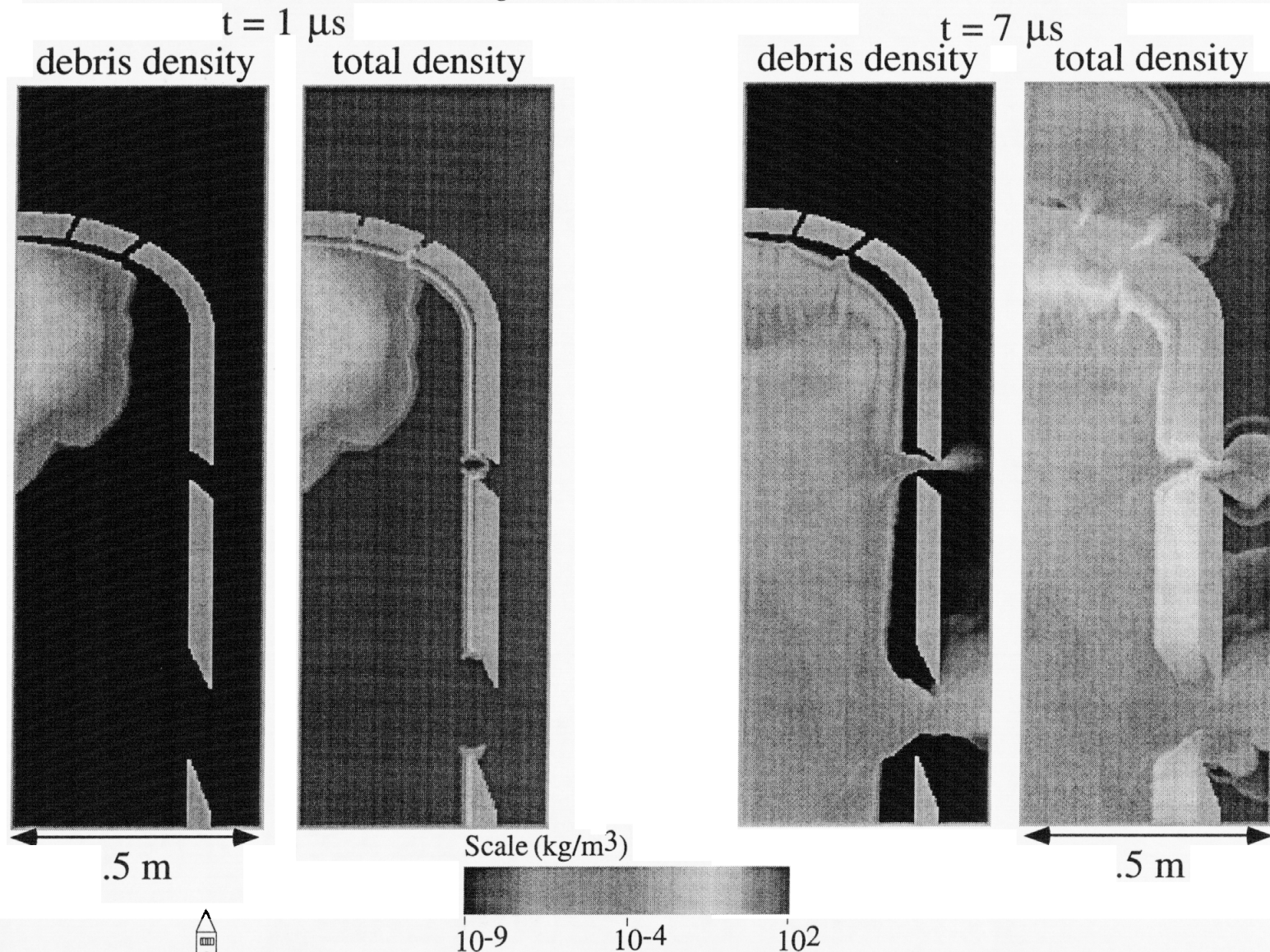


Minor Impact on NIF Design

- Need to make sure to have enough vertical clearance to fit minichamber on the lift.
- Will need mounting hardware for the minichamber attachment to main chamber when the lift is withdrawn.
- Will need hookups for instrumentation packages, LN supply, and vent lines.
- Impact appears to be relatively small, but needs to be considered during NIF chamber design process.



Mini-chamber Dynamics: TSUNAMI Results



Mini-chamber Development and Goals

- **Optimize geometry for debris/shrapnel capture**
- **Optimize frost growth and water recapture**
 - experiments to grow frost quickly and evenly
 - experiments to recapture water that is not vaporized
- **Small scale experiment using HE or micro-chamber demonstration on NOVA**
 - benchmark of TSUNAMI predictions
 - mechanical response
- **Coordinate with NIF design to provide capabilities for mounting large objects in target chamber**



Mini-chamber Development and Goals

- **Mechanical response calculations**
 - preliminary calculation from UW shows mechanical loading from fusion energy release is manageable
- **Collaboration with multiple user groups**
 - NIF chamber protection application - 80% debris capture
 - » 5x increase target/near target mass (unlimited hydrocarbons)
 - » 5x increase in shot repetition rate
 - » 1/5 frequency debris shield change out
 - » beyond-design-basis target yields (i.e. direct drive)
 - » Insurance for unanticipated chamber dynamics phenomena
 - IFE experimentation application
 - Protect DNA/other experiment packages/eliminate requirement for frost/ice protection

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