# Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device (e.g. NSTX)

## Overview

**Presented by**
**Alice Ying**
**UCLA**

**APEX Meeting**
**May 10, 2000**
**ANL**

# Participant Support is the Key to Accomplishing this Task

## Thanks given to the following Task Performers

UCLA: Neil Morley, Sergey Smolentsev, Tom Sketchley
PPPL: Bob Kaita, Bob Woolley
ORNL: Brad Nelson, Rajesh Maingi
SNL: Mike Ulrickson, Richard Nygren
INEEL: Kathy McCarthy
ANL: Ahmed Hassanein

**Thanks also given to M. Youssef who does not allow me to cancel any conference calls!!!**

# Task I Presentations

**Overview** — **Alice Ying**

**Proof-of-principle liquid wall experiments on NSTX** — **Bob Kaita**

**Proposed experiments on the LMMHD facility** — **Bob Woolley**

**New MHD Multi-component Code Development and its Application to APEX/NSTX** — **Sergey Smolentsev**

**Open Discussions**

## Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device (e.g. NSTX)

**Total Effort** **$450 k (allocated in Nov. 99)**
**Preseent allocation: $415 k (due to reduced contribution from SNL)**

### Scope

**This task is for development of and agreement upon a technology-physics integrated mission to conduct flowing liquid wall tests in a major operating plasma device, performing research to identify and characterize design options and key issues of such flowing liquid walls, and development of an R&D plan.**

### Approach

**The approach to executing this task must remain flexible and evolve over time based on updated technical results and information available. An appropriate approach to undertake this task involves the following elements:**

1. **to establish close interactions with the current programs of operating plasma devices and plasma physicists**
2. **to understand and convey the benefits of performing such a test**
3. **to characterize the issues and assess the R&D required for conducting flowing liquid wall tests in a major operating plasma device.**
4. **to start with NSTX as an example of an experimental physics facility.**

# APEX FY 2000 Task I: Explore options and issues for implementing a flowing liquid wall in a major experimental physics device (e.g. NSTX)

**I.1 Characterization of projected plasma operating conditions in NSTX (30k)**

**I.2 Design and analysis of flowing liquid wall options in NSTX and other operating plasma devices (195k⇒190k)**

- **a) Configuration**
- **b) Divertor Integration**
- **c) Hydrodynamics and Heat Transfer**
- **d) Safety and Off-normal events**

**I.3 Plasma-Liquid Interactions**

The data from Task II should help identify issues concerning plasma-liquid wall interactions such as:

- a) Surface Interactions and Edge Physics (LLNL, under C.C. Task A)
- b) Bulk Plasma-Liquid (PPPL, covered under Task II)

**I.4 LM-MHD initial exploratory experiments with magnetic field gradients and applied currents (145 k⇒120 k)**

**I.5 Identification of key issues and Development of an R&D plan for implementing liquid walls in NSTX and other operating plasma device (80k⇒75k)**

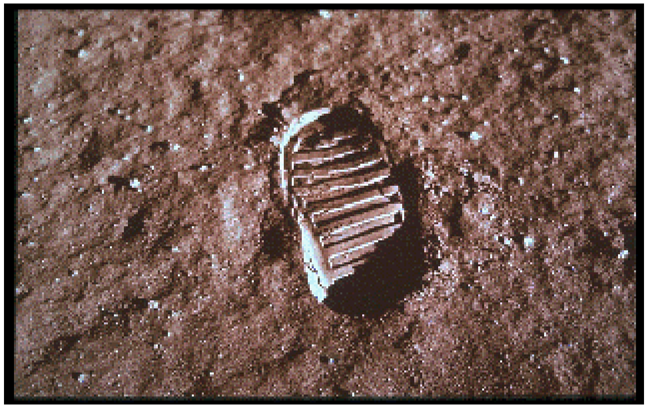
# General Observation

**Conducting a flowing liquid wall in an experimental physics device:**

- **It provides an excellent opportunity to enhance the cooperation between the physics and technology communities.**

- **It can serve as "one" mechanism for physicists to explore more attractive plasma operating regimes and can allow technologists to begin work on technology in a "real" machine (get their feet wet).**

**It is an important "small" step toward fusion chamber technology development. However, it can not be viewed as technology development for fusion energy.**



*Neil Armstrong's first step onto the Moon*

## Operating a flowing lithium wall in a major experimental physics device (e.g. NSTX)

## *"Romance" or Reality?*

**Benefits**

**A list of physics benefits was developed before the NSTX Research Forum.**

**Risks**

**The existing experimental devices are not built to accommodate "unforeseen and unexpected" complexity and dangers (meaning chemical reaction).**

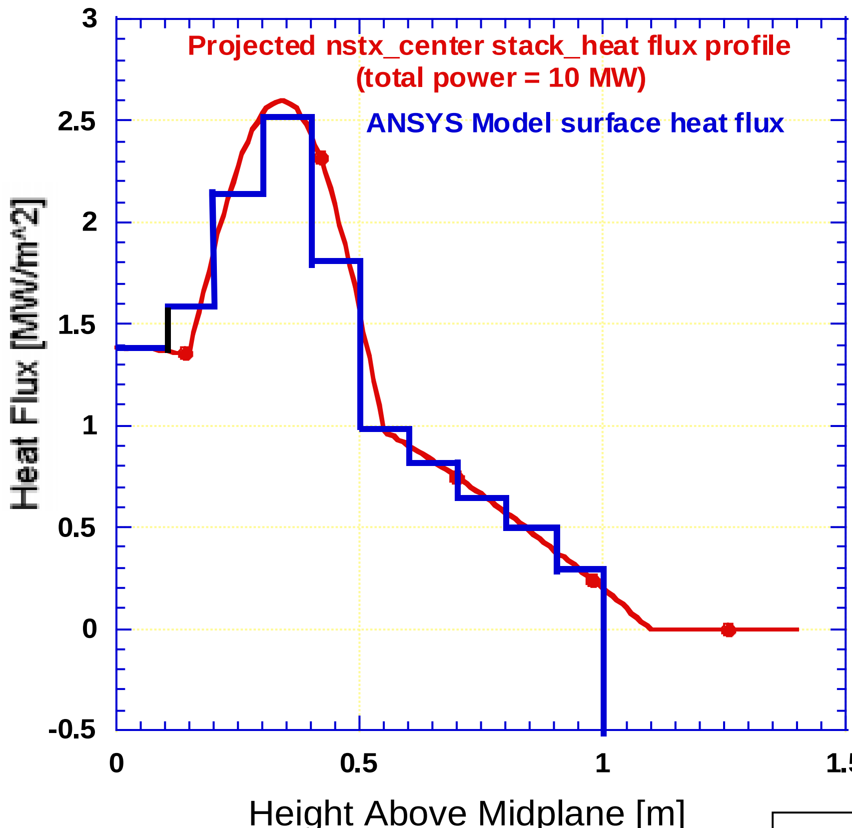
**Cost (Impact)**

**What is the minimum diagnostics required for plasma to operate appropriately?**

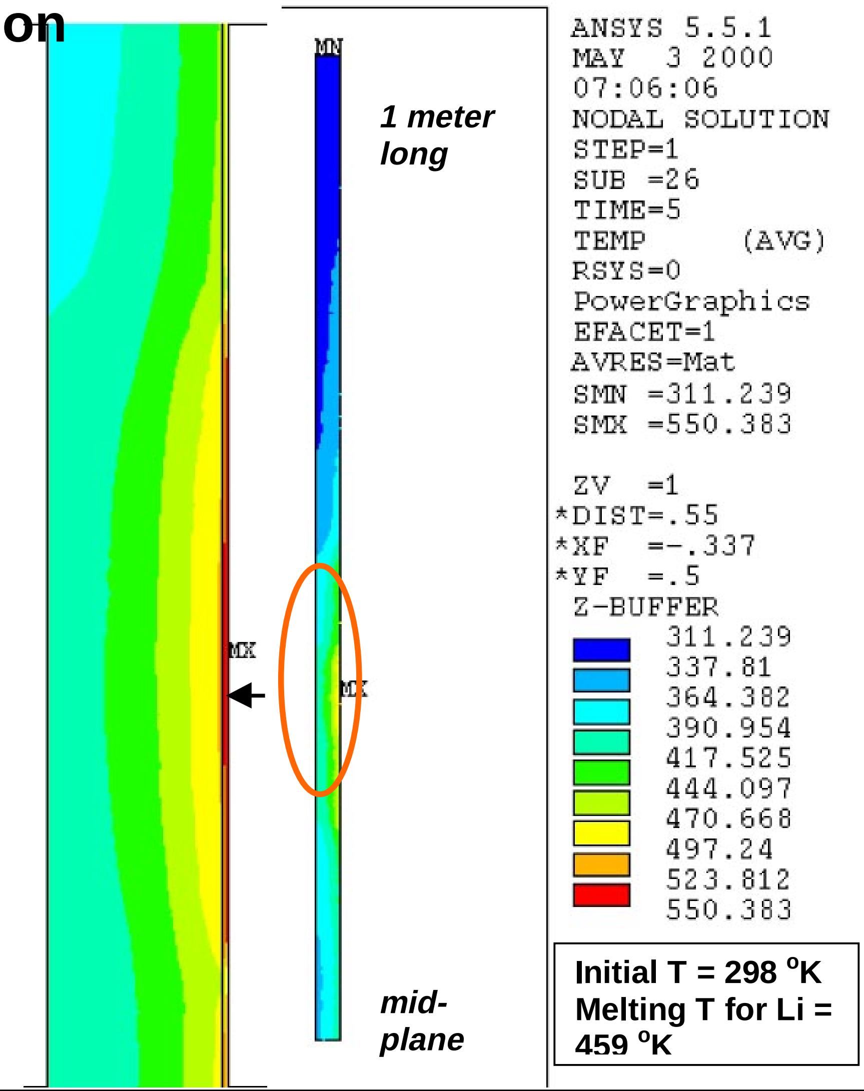
***It is part of the nature of man to start with romance and build to a reality.***
***- Ray Bradbury***

# Lithium coating is an inexpensive scheme to explore the effects of lithium surface on plasma operation

**Q: Can the lithium surface maintain a solid state under the projected surface heat load conditions without active cooling?**




$K_{cu}$ = 322 W/mK
$K_{Li}$ = 50 W/mK




**Temperature (K) distribution of 1 mm solid lithium on a 2.5 cm thick copper substrate over a 5-second burn**

## Benefits of a Flowing Lithium Wall over a Solid Lithium Coating

- **A flowing lithium wall can solve the problems (melting and evaporation) of solid lithium surface heat removal**

- **A flowing lithium wall can also solve the problem of hydrogen saturation on a solid lithium surface**

- **A flowing lithium wall with a magnetic Reynolds number greater than 1 provides wall stabilization effects (need to understand the relative impact of different lithium locations)**

- **Provide opportunities for multiple-long burns, which may not be possible even an active cooling exists for center stack graphite tiles**

- **Provide data for the next machine (e.g. DTST)**

**Note: Time frame for possible implementation of flowing lithium walls in NSTX is about 2004.**

## Areas that have been performed under Task I Prior to the APEX Electronic Meeting

- A list of potential benefits of flowing liquid lithium walls on plasma performance was documented
- Various conceptual flowing liquid wall options in NSTX were identified
- 1.5 D magnetohydrodynamics and heat transfer analysis have identified possible operating conditions for axisymmetric annular flowing lithium film for the NSTX center stack.
  - 3-D modeling to investigate MHD interactive effects among multi component magnetic fields is under development
- Design of LMMHD Facility and R&D Plan

## Areas Being Investigated under FY2000 Scope

- **Better understand the risks and impact on the machine**
  - **- Explore designs that use less lithium**
- **Search schemes for lithium evacuation**
- **Model the effects of VDEs on flowing lithium walls**
- **Model the effects of a pulsed magnetic field on flowing lithium MHD**
- **Begin documenting the ongoing tasks**

# MHD and Heat Transfer Analysis for Flowing Lithium Walls in NSTX

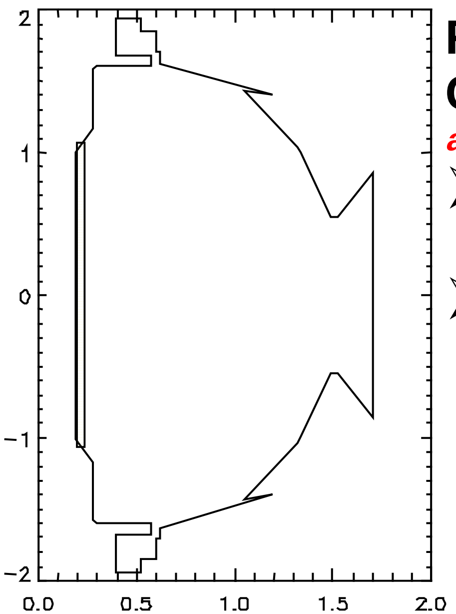
## Objectives of MHD and Heat Transfer Analysis

- ❑ Identify the operating regimes that satisfy system requirements
- ❑ Define and understand issues that require further explorations
- ❑ Establish a database for design options
- ❑ Define meaningful experiments for R&D

## Findings prior to APEX Electronic Meeting

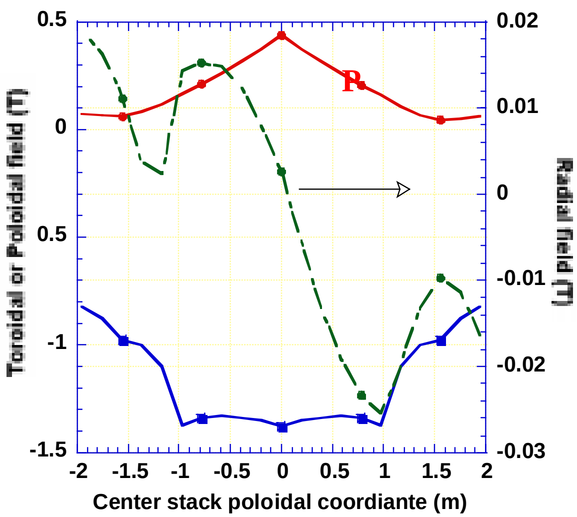
- ❖ Flow damping as a result of the MHD drag from the radial field appears acceptable, which results in about a $\pm$ 10% change in the flow thickness (and the corresponding velocity) at initial flow velocities of ~ 5 to 10 m/s.
- ❖ The MHD flowing lithium surface temperatures over the center stack and inboard divertor can be maintained below than 400 $^{o}$C at a velocity of about 2 m/s due to good thermal conduction, a short flow path and manageable heat loads.

**New results show MHD interaction may cause some micro instability in the flow (Somolentsev)**

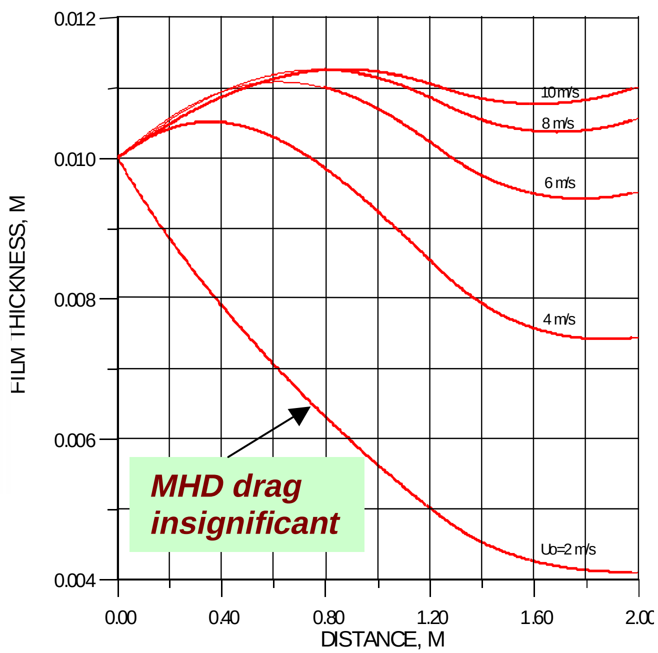



# Results of 1.5 D MHD and Heat Transfer Calculations for NSTX Center Stack *(The effect of the poloidal field on the flow characteristics is not taken into account)*

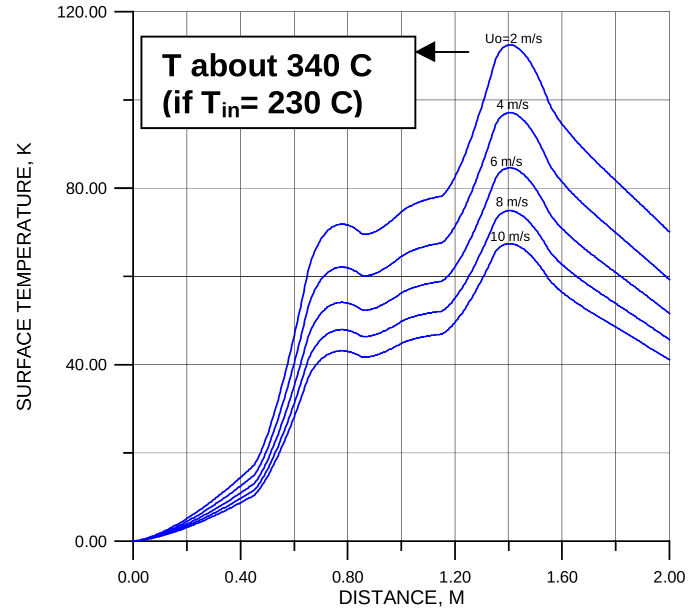
- **Flow damping occurs as a result of the MHD drag from the radial field.**
- **However, during normal operation, lithium appears to have reasonable surface temperatures along the NSTX center stack.**




**Film thickness varies as flowing lithium proceeds center stack downstream as a function of velocity**




**Lithium surface temperature increases as flow proceeds downstream as a function of lithium inlet velocity**



## Technical Challenges (Cont'd)

# NSTX Thermal loads

(R. MAINGI)

**(Original Requirements/Design Criteria)**

***Heating Power = 5 MW ?***

Normal Operation, peak surface flux

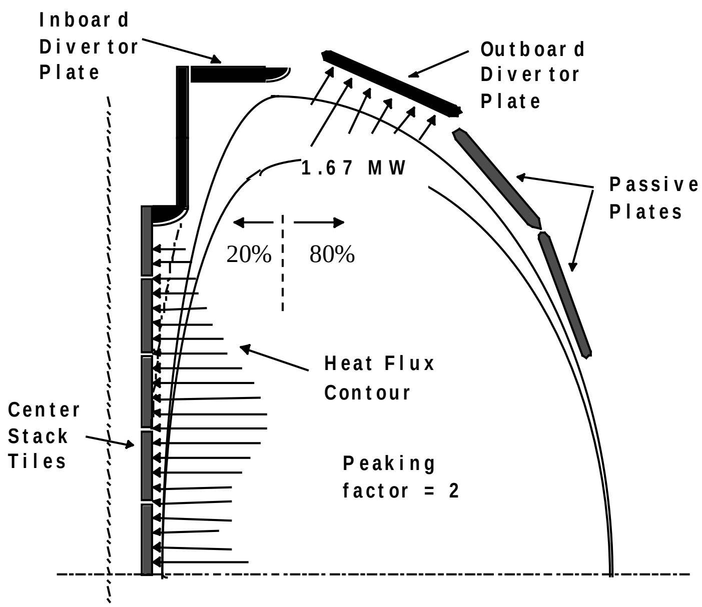
- **Center stack ~ 200 W/cm² peak**
- **Inboard divertor**
  **~ 700 W/cm² for single null**
- **OB divertor**
  ~ 1100 W/cm² for $\lambda = 3$ cm
  ~ 1700 W/cm² for $\lambda = 1.5$ cm

(peak from calc = 1400 W/cm²)

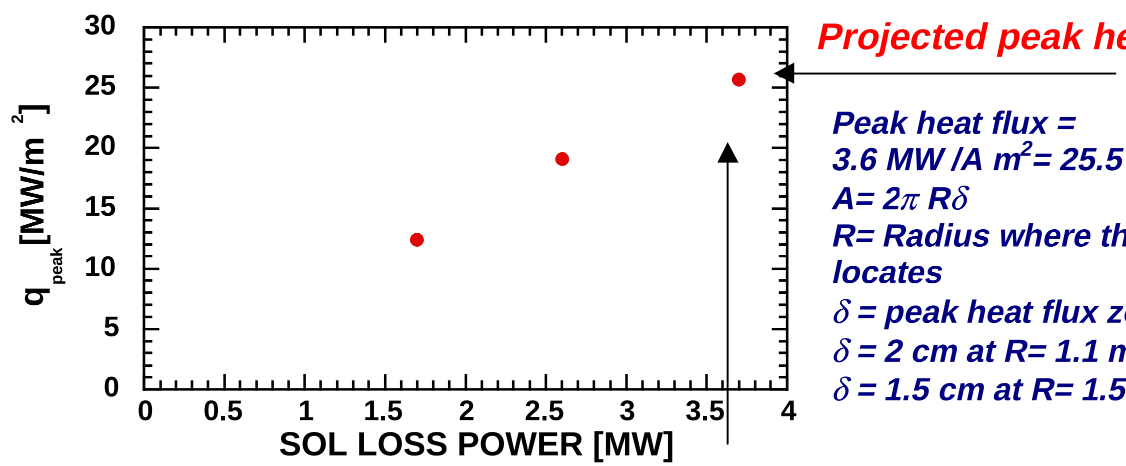
- **Passive plates** ~10 W/cm²

• **Disruption**

- Peak surface flux: TBD




**PEAK HEAT FLUX INCREASES LINEARLY WITH HEATING POWER**




***Projected peak heat flux***

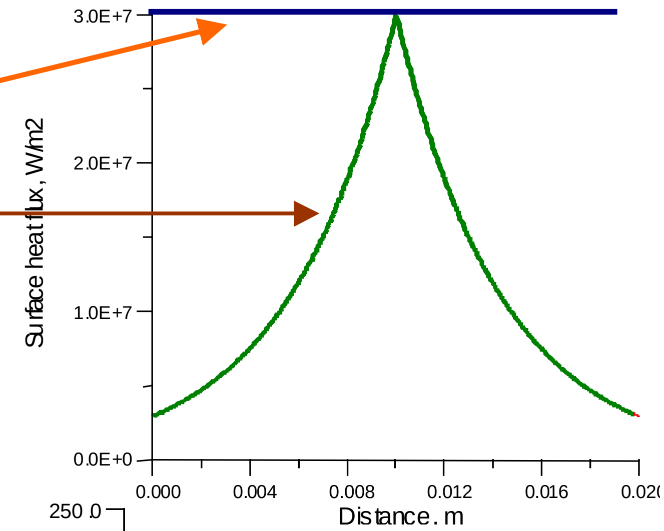
***Peak heat flux = 3.6 MW /A m² = 25.5 MW/m²***
***A = 2π Rδ***
***R = Radius where the peak locates***
***δ = peak heat flux zone***
***δ = 2 cm at R = 1.1 m***
***δ = 1.5 cm at R = 1.5 m***

**Nominal operating point is 1.8 MW (Heating power = 5 MW);**
**3.6 MW operating point corresponds to heating power ~10 MW**
**Peak heat flux decreases linearly with divertor radiation until plasma begins to detach from divertor (radiation ~ 1 MW)**

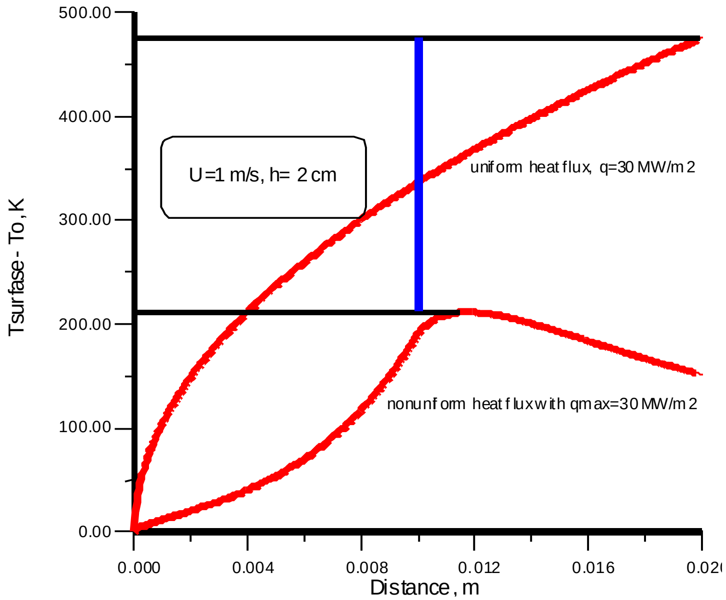
## *Technical Challenges (Cont'd)*

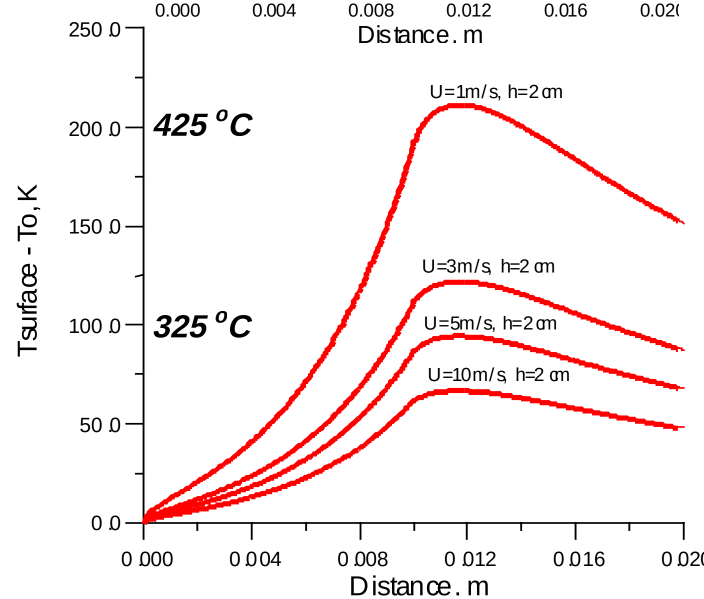
# Lithium Surface Temperature Rises Under Maximum "Projected" Peak Heat Load Conditions

- A uniform heat flux distribution of 30 MW/$m^2$
- A non-uniform heat flux distribution with a peak heat flux value of 30 MW/$m^2$




**Lithium velocity = 1 m/s**
**δ = heat flux zone = 2 cm**
**Peak heat flux = 30 MW/$m^2$**




**Finding: The minimum velocity required for projected outboard divertor surface heat removal, yet without exceeding temperature limit of 400 °C is about 2 m/s**

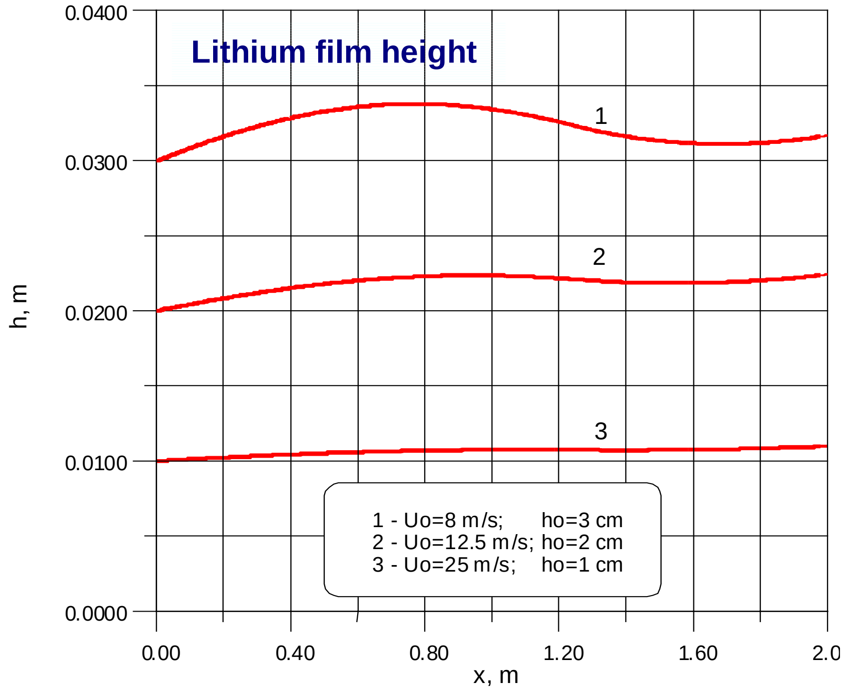
# Operating Conditions of Flowing Lithium Wall Options (May, 2000)

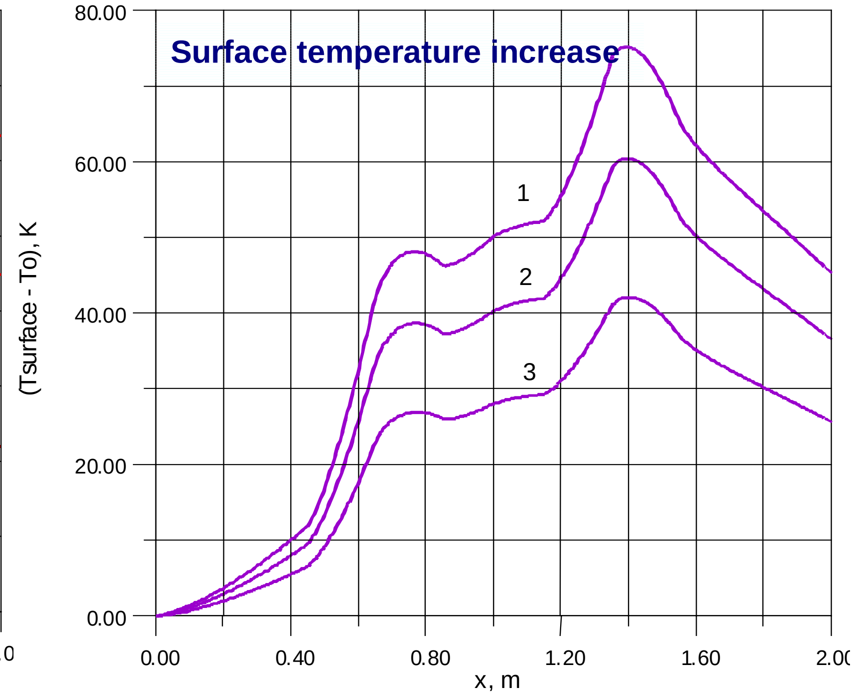
| Parameter | Base Design Option | Enhanced Design Option | Comments |
|---|---|---|---|
| Center Stack | Flowing Film | Flowing Film | Inlet manifold required for both options |
| Upper Passive Plate | Graphite tile or Solid lithium | Porous FW Infiltrated with LM | Inlet manifold required for enhanced design option |
| Mid-Passive Plate | Graphite tile or Solid lithium | Porous FW Infiltrated with LM | |
| Lower Passive Plate | Flowing Film | Flowing Film formed naturally from Mid- and Upper Passive Plates | Inlet manifold required for base design option |
| Inboard Divertor | Flowing Film from Center Stack | Flowing Film from Center Stack | Outlet removal system required |
| Outboard Divertor | Flowing Film from Lower Passive Plate | Flowing Film from Lower Passive Plate | Outlet removal system required |
| Inlet velocity, film thickness and temp. @ center stack * | 2 m/s and 0.5 cm at 230 $^{o}$C | 2 m/s and 0.5 cm at 230 $^{o}$C | Flow area expands as lithium approaches the inboard divertor |
| (Inlet) velocity and film thickness @ Lower passive plate * | 1 m/s and 0.2 cm at 230 $^{o}$C | 1 m/s and 0.2 cm at 230 $^{o}$C | Flow area contracts as lithium approaches the outboard divertor |
| Volumetric Flow Rate | 11.4 l/s @ inboard;<br>19 l/s @outboard | 11.4 l/s @ inboard;<br>19 l/s @outboard | |
| Lithium inventory* | 300 l | 300 l | |
| Time Frame | FY 2004 | FY 2005 | |

*** Numerical values will be evaluated further based on experimental data and modeling results taking into account of MHD due to multi-component fields, transient effects, plasma interaction, safety, etc.**

**To limit the field penetration for wall stabilization requires the operation of the flowing lithium wall with a Magnetic Reynolds number ($Re_m$= $\sigma\mu_o vh$) greater than 1** **[a much higher velocity than it is needed for heat transfer]**

***Question: How sensitive would the stabilization effect be as a function of the location of the flowing lithium wall (as in the inboard vs outboard)?***




**Note that:**

- **As developed, liquid metal magnetohydrodynamics mathematical formulation is valid with $Re_m$ <<1**
- **As $Re_m$ >1, the induced magnetic field is at about the same order of the applied magnetic field**

# NSTX liquid wall experiment: A few configuration issues

- **Concepts may only be compatible with single null configuration**

- **Helicity Injection Compatibility**

  **Li shorts out insulators, unless insulators are protected (via catch basin)**
  **Li is in contact with center stack, so piping must be insulated from vessel**

- **Limited space for exit flow piping**

  **Divertor plates will probably require modification, but should clear support rings**
  **Piping appears limited to about 4 inch I.D at 12 locations**

- **Smaller diameter (1.25 inch) inlet piping can be routed through instrument feed holes at top of center stack, but routing around the TF coil legs is still TBD**

- **Auxiliary heating penetration**

# Safety Considerations to Avoid Lithium Fire Hazard

**Background Information: US Test Blanket DDD (1997)-performed by INEEL**

- **Concerns: Lithium reacts exothermically with water and air.**
  - **Lithium-water interaction produces hydrogen leading to the potential for a flammable hydrogen-oxygen mixture in the torus.**

- **Design guidance to US ITER Test Program** **Applicable to NSTX**
  - **Limit inventory to < 35 kg to ensure that hydrogen produced from Li-water reaction < 5 kg**
  - **Design dump tank such that lithium spilled into the vault will drain quickly into the dump tank and reduce surface area available for reaction**
  - **Inclusion of a fast-acting valve that allows the Li loop to drain when a pressure loss is detected**
  - **Lithium loop pressure should be as low as possible to reduce speed of lithium spill**
  - **Minimize lithium loop (housed in a transporter with a dished-head ceiling and a controlled argon atmosphere)**
  - **Inert the vault atmosphere with Argon (Can a vault be built around NSTX vacuum vessel?)**

***Other possibility will be to use a fire-fighting compound that is being considered in the SNL lithium loop***

# Mechanisms to Evacuate the Lithium from the NSTX Chambers (Some modeling results will be shown by Smolentsev)

**Concerns:**

- **Excessive MHD drag near the divertor region due to multi-component field effects**
- **Flow damping reduces heat removal capability**
- **May flood the chamber under high flow rate conditions**

**If the combined inertia and hydrostatic head of the fluid is inadequate to move the liquid crossing the magnetic field (TBD):**

***Possible active evacuation mechanism***

**MHD pumping produced through jxB force by applying external currents**

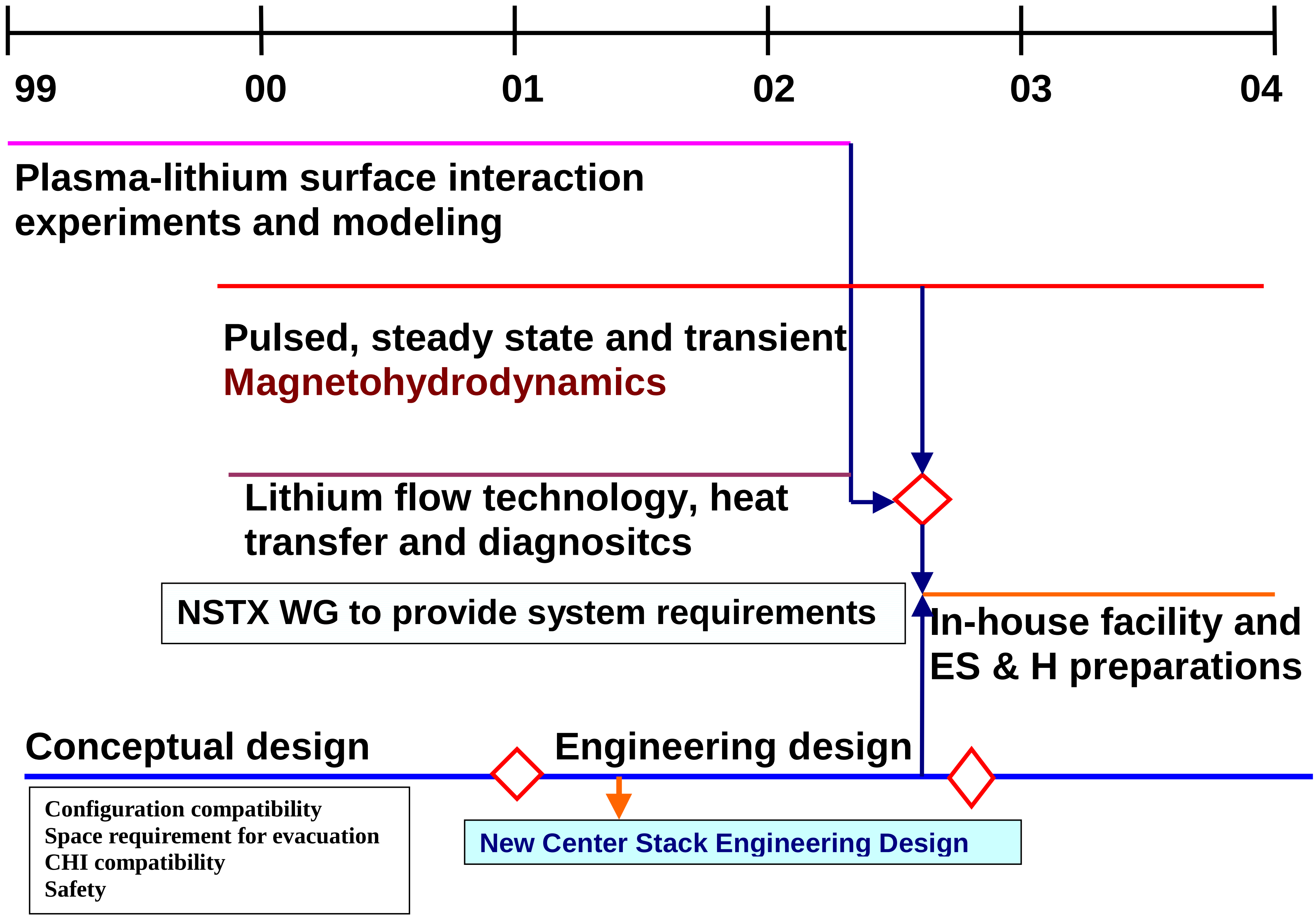
- **To apply radial currents to interact with the toroidal fields**
- **To use MHD propulsion from longitudinal currents interacting with decreasing toroidal field**

# Key Research Tasks Needed for Deployment of Flowing Lithium Liquid Wall Tests on NSTX

- Establishment and maintenance of stable flowing lithium walls in spatially and temporally varying magnetic fields
- Evacuation and removal of flowing liquid flows in regions with multi components magnetic fields and field gradients
- High heat removal capability without excessive concentrated vaporization and hot spots
- Material compatibility (liquid freezing, vacuum vessel baking temperature compatibility)
- Electrical insulation requirements for CHI operation
- Development of liquid handling and safety
- Plasma liquid wall interactions and plasma bulk interactions (gettering effects and helium pumping, start-up, transient effects)

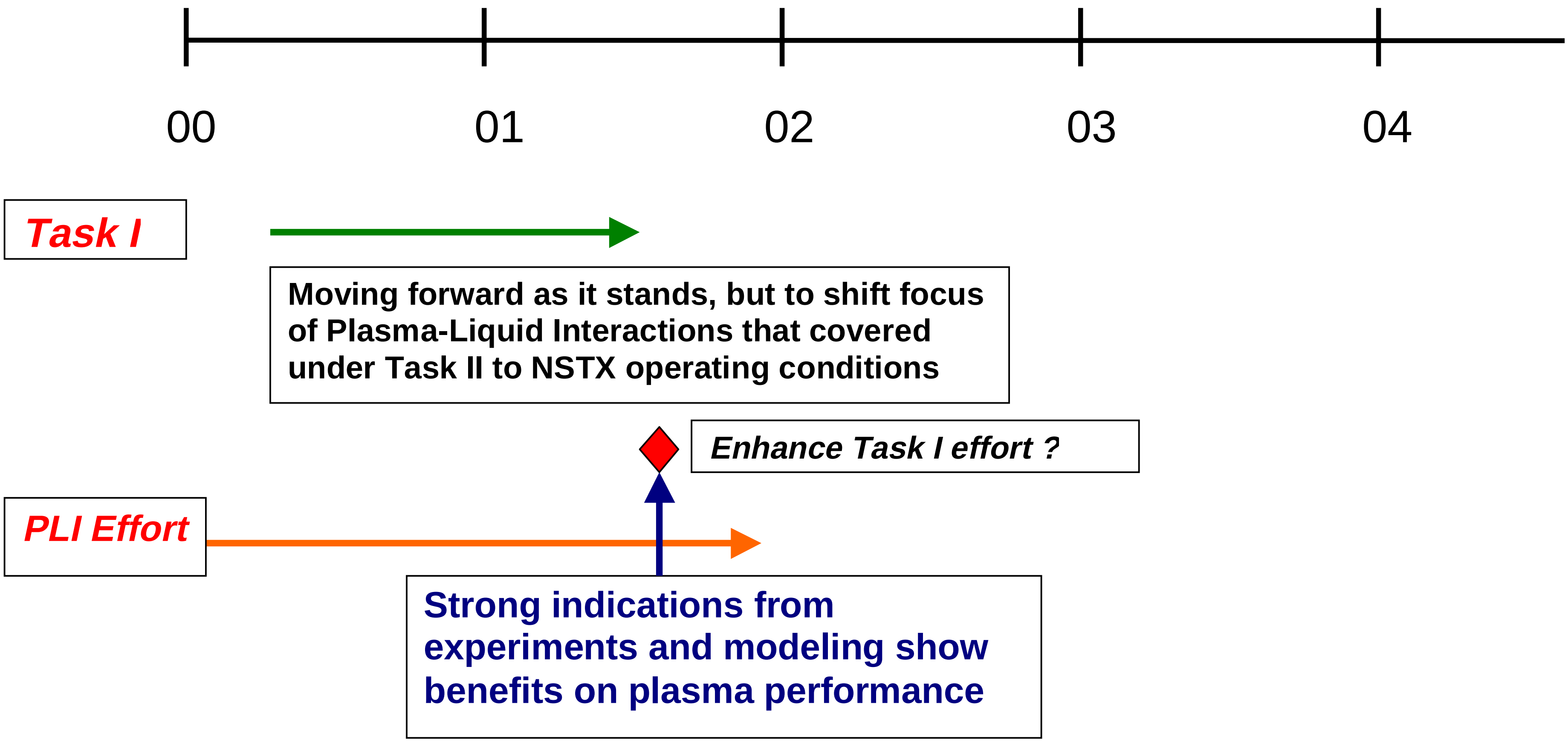
**Suggested Strawman for Discussions with Task I Group**

# Flowing Lithium Wall R&D Plan May Consist of 5 Key Elements



# Projected Pace of R&D (TBD)

***The approach to executing this task must remain flexible and evolve over time based on updated technical results and information available.***



# Task 1 Milestones

## Intermediate Milestones

- An integrated technology-physics mission statement 2/00
- Initial projected characterizations of operating plasma devices including operating conditions and configurations 2/00
- A draft R&D plan 5/00
- Design review of the laboratory experiment on MHD free surface 3/00
- Initial assessment of technology issues 5/00

## FY 2000 Deliverables

1) A Report of Recommendations
2) Document Issues Concerning Flowing Liquid Wall Tests in Operating Plasma Devices
3) A 4-year Plan Including Required R&D
4) Construction of laboratory facility for experiments with liquid metals in magnetic field