Fundamental Thermofluid Experiments & Modeling

Subtask 3-1 of the DOE-Monbusho Collaboration Proposal

Responsible persons:

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Japan Monbusho / US DOE Collaboration
Washington, D.C., USA
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Joint Planning by Many Interested Scientists

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Thermofluid Task Objectives

1. Understand Underlying Science and Phenomena for Flibe (and other low conductivity liquid) Flow and Heat Transfer through:

    a. Conducting Experiments Using Flibe Simulants
    b. Modeling and Analysis of fundamental phenomena

2. Compare Experimental and Modeling Results to Provide Guidance and Design Database for both Flibe Blankets and Next Generation Stage of Larger Flibe Experiments.

3. Identifying and assessing new innovative techniques for enhancement of Flibe heat transfer (a major feasibility issue for Flibe blanket designs)

Main Areas of Collaborative Scientific Interest

Hydrodynamics near liquid/vacuum interfaces and at solid walls of Flibe simulants flowing on flat and curved plates, and in closed channels and swirl pipes, with and without MHD effects

Heat transfer at liquid/vacuum interfaces and at solid walls of Flibe simulants flowing on flat and curved plates, and in closed channels and swirl pipes, with and without MHD effects

Sub-areas of Interest for Collaborative Efforts

Identification of instrumental and experimental techniques: Radiant heating, laser and ultrasonic surface topology reconstruction, infra-red temperature measurements, laser Doppler anemometry, others.

Development and benchmarking of new modeling techniques: MHD turbulence interactions and turbulence/free surface or wall interactions in k-e, DNS, LES

Need for Coupled Modeling Effort

Explanation:

Fusion designs require practical computational models that must utilize input data from more elaborate theory and experiments. (* Note that theory implies Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS).)

Collaboration:

1. Enhance LES and DNS numerical techniques to:

- **understand near-wall and near-surface turbulence structures in magnetic fields**
- **help clarify experimental observations**
- **provide input data for practical computational models needed for fusion component design**

2. Develop practical computational models using input from experiments, LES and DNS.

Task 3-1 Negotiations: Present Status

After the Makuhari workshop in February, 2000, the research plan of subtask 3-1 research for 6 years was negotiated and the principles of the plan as a whole were agreed to by J and US.

Further discussions between Japan-U.S. are still necessary to firmly establish details of research plan

- **Personnel exchanges**
- **Before or after the two workshops held in Washington D.C. and in Yuta. (e.g. Prof. Toda will go to UCLA ~2 times to provide input to constructing/modifying experimental facility and confirming the final experimental plan)**

Personal exchange program in 2000 FY (Preceding start of US-Japan collaboration), has been arranged to allow Japan-U.S. joint work on design, construction, modifcation, and test equipment for Flibe simulant loops, FLI-HY and HiTeC. (Schedules are tentative, and need more negotiations.)

- **K. YUKI (Tohoku) and S. SATAKE (Toyama) to go to UCLA**
- **M. Abdou and A. Ying (UCLA), to go to Tohoku U.**

Thermofluid Task

Experimental Schedule Breakdown

Prior beginning of collaboration:

- **FliHy Loop construction at UCLA and shakedown tests**
- **Shakedown of initial diagnostic techniques: e.g. fast photography, ultrasonic fluid height, thermocouples, pressure transducers**

Thermofluid Task Plan Breakdown

- **The plan is broken into two 3-year phases, Phase I without MHD effects and Phase II with MHD effects.**

- **The US is interested in running 3 primary free surface experiments during Phase I (US-1,2,3) – each of which can have many variations and "fine-tuning" as the experimental data is acquired and analyzed.**

- **Japan is interested in running 5 primary closed channel experiments during Phase I (J-1,2,3,4,5) – each of which can have many variations and "fine-tuning" as the experimental data is acquired and analyzed.**

- **At the end of phase I, the US will re-evaluate Flibe as a potential free surface liquid before proceeding to Phase II. In case of negative evaluation – primary US work will shift to LM.**

- **The FliHy Water/KOH Loop, the HiTeC High Prandtl Number, High Temperature Organic Oil Loop, and the LM-MeGA Loop are available for this collaboration (they have been described in detail in previous presentations)**

Thermofluid Collaboration Phase I: US-1

US-1: "Classification of surface wave and surface mixing structure for sub- and super-critical free surface flow regimes"

- **Purpose: Experimentally investigate and classify the types of surface waves and natural mixing expected in an idealized geometry with similar Re, Fr, We numbers as the APEX needs**
- **Time: Collaboration Year 1 (overlap from Year 0), J-Fiscal 01**
- **Test Section: Long (4m), straight transparent test section with adjustable angle of inclination**
- **Diagnostics: Dye/Camera Technique and Ultrasound Flow Height Transducers**
- **Modeling: Simulate flows with various tools (Japan/Pathfinder, US/Flow3D, Telluride, UCLA-k,e model)**

Thermofluid Collaboration Phase I: J-1

J-1: "Mixing intensification by fins in forced flow closed channels"

- **Purpose: Pipe flow experiments with the complicated inner wall surface like fins are performed to develop an advanced technology of high heat flux removal applied for the High-Pr. fluid system.**

- **Time: Collaboration Year 1, J-Fiscal 01**

- **Test Section/Apparatus: Pipe test section on improved FliHy with transparent structure and windows, and with functions of inclination or rotatory movement.**

- **Diagnostics: Visualization with dye method, time-series PIV system.**

- **Modeling: Experimental results are compared with the modeling code for the complicated-shape pipe flow clarified from the view point of internal turbulent structure and mixed convection.**

Extensions needed to FliHy for pipe flow test sections will be done during US-1 experimentation, and, hereafter, this improved loop is referred to as "improved Fli-Hy"

Thermofluid Collaboration Phase I: J-2

J-2: "Free surface flow on porous walls"

- **Purpose: Evaluate the stability and mixing due to surface movement of Flibe flow with a free surface utilizing porous walls**
- **Time: Collaboration Year 1, J-Fiscal 01**
- **Test Section/Apparatus: Rotatable porous block on HiTeC organic oil loop**
- **Diagnostics: Ultrasonic wave system, PIV, high speed photography**
- **Modeling: Pathfinder, Telluride, Flow-3D to model flow profiles and stability behavior.**

Thermofluid Collaboration Phase I: US-2

US-2: "Quantification of near-surface turbulence and heat transfer"

- **Purpose: Experimentally measure turbulent fluctuations near the free surface interface and their effect on heat transfer.**
- **Time: Collaboration Year 2 and 3. J-Fiscal 02,03**
- **Test Section: Same as above, with added surface heaters, backwall heaters, liquid bulk temperature control. Several heating scenarios are possible.**
- **Diagnostics: Ultrasound Flow Height Transducers, Backscatter LDA, PIV, IR camera, Thermocouples, Calorimetry**
- **Modeling: Simulate flows with turbulence modeling techniques being developed in the US and Japan (Japan & UCLA-k,e model, Japan/DNS model)**

Thermofluid Collaboration Phase I: US-3

US-3: "Investigation of complex APEX flow geometries and effect on hydraulic behavior of liquid flow"

- **Purpose: Experimentally simulate scaled flow conditions anticipated in APEX liquid walls designs and measure developing free surface height and visualize free surface conditions.**
- **Time: Collaboration Year 2 and 3, J-Fiscal-02,03**
- **Test Section: Specially designed test sections for: inverted flow on a curved backwall, flow around a specially-shaped penetration, expanding and contracting flow area, and breakup of film flow over a ledge.**
- **Diagnostics: Ultrasound Flow Height Transducers (provided by US), High Speed Camera (US)**
- **Modeling: Simulate flows with various tools (Japan/Pathfinder, US/Flow3D, Telluride, UCLA-k,e model)**

Thermofluid Collaboration Phase I: J-3

J-1: "Heat transfer intensification by fins and swirl in forced flow closed channels"

- **Purpose: Continuation of J-1 pipe flow experiments with the complicated inner wall surface like fins with inner wall heating and temperature measurements (based on the experimental results obtained by the pipe flow using molten salt, HTS)**
- **Time: Collaboration Year 2, J-Fiscal-02**
- **Test Section/Apparatus: J-1 test section on improved FliHy with inner wall heating and overall loop temperature control**
- **Diagnostics: Visualization with dye method and PIV system, calorimetry, infrared camera, fine thermocouples**
- **Modeling: Experimental results are compared with the modeling code for the complicated-shape pipe flow clarified from the view point of heat transfer and mixed convection.**

Thermofluid Collaboration Phase I: J-4

J-4: "Free surface flow on porous walls and effective heat transfer"

- **Purpose: Continuation of J-2 experiment with surface and backwall heat transfer**
- **Time: Collaboration Year 2, J-Fiscal-02**
- **Test Section/Apparatus: Rotatable porous block on HiTeC organic oil loop modified for liquid free surface and porous backwall heating**
- **Diagnostics: Ultrasonic wave system, PIV, high speed photography, calorimetry, infrared camera, fine thermocouples**
- **Modeling:. quantitative evaluation of turbulent structures and heat transfer are carried out with J/Pathfinder, US/Telluride, Flow-3D**

Thermofluid Collaboration Phase I: J-5

J-4: "Heat transfer in flow through metallic packed bed"

- **Purpose: To explore pressure drop vs. heat transfer enhancement achieved in slow, high Pr. flow through a dense packed bed.**
- **Time: Collaboration Year 2, J-Fiscal-03**
- **Test Section/Apparatus: circular and rectangular test channel in HiTeC loop, filled with metal particles at various densities, inner wall heated**
- **Diagnostics: Calorimetry, infrared camera, fine thermocouples**
- **Modeling: Comparison with encouraging calculations of J/Hashizume code**

Thermofluid Task Phase 2

- **At this time a high field magnet being constructed for both LM and Flibe MHD experiments will be transferred to FliHy loop.**
- **The US is interested in studying the effect of MHD forces on the turbulent structures and secondary flows (US-4) that contribute to surface heat and mass transfer. (Contingent on positive evaluation of Flibe work to date)**
- **Japan is interested in studying the effect of MHD forces on the turbulent structures and secondary flows (J-6) that contribute to channel flow heat and mass transfer.**
- **Some additional time is reserved in Year 3-6 for additional US and J led experiments – to be defined.**
- **The FliHy Water/KOH Loop, and the LM-MeGA Loop are available for this collaboration**

Thermofluid Task Phase 2: US-4, J-6

US-4, J-6: Repeat experiments US-1, US-2, J-1, J-3 with high magnetic field of various orientations

- **Purpose: Experimentally measure turbulent fluctuations and heat transfer in a strong magnetic field near the free surface interface and in complex shaped closed channels**

- **Time: Collaboration Year 4-6, J-Fiscal 04-06**

- **Test Section: Same as US-1,2 and J-1,3 with added strong field magnetic and power supply systems**

- **Diagnostics: Ultrasound Flow Height Transducers, Backscatter LDA, IR camera, fine thermocouples, calorimetry, PIV**

- **Modeling: Simulate flows with turbulence modeling techniques being developed in the US and Japan, UCLA-k,e-MHD model, Japan DNS-MHD model.**

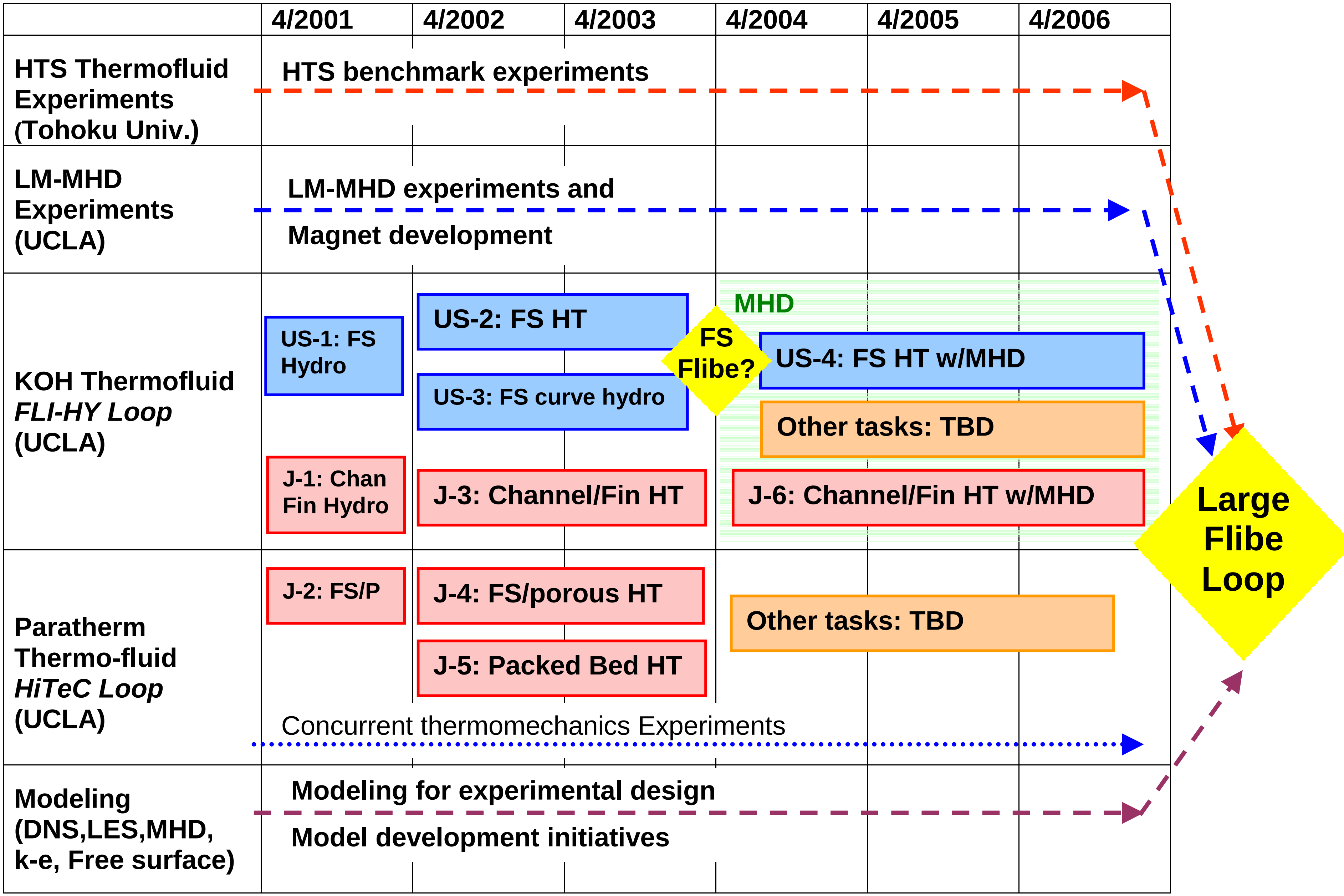
Significant Costs

loop costs **(US capital investment > $1M)**

- **Operation and maintenance of FliHy and HiTeC Loops - $150k/yr**
- **Deployment of high field magnets – Estimate $400k**

diagnostics

- **LDA systems, backscatter type, 2D – approx. $200k, Source: undecided (Years 2-6, intermittent)**
- **Time series analog PIV system: (Japan laser Co. Model B-4000S) – approx. $400k, Source: Japan (Years 1-6)**
- **IR Camera systems and surface heaters – approx. $80k, Source: US (Years 2-6, intermittent)**
- **High Speed Camera, 500 to 4000 frame/sec – approx $100k, Source: US (Years 1-6)**
- **10 unit Ultrasound Transducer array – approx $30k, Source: US (Years 1-6)**


4/2001
4/2002
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HTS Thermofluid Experiments (Tohoku Univ.)
HTS benchmark experiments
LM-MHD Experiments (UCLA)
LM-MHD experiments and
Magnet development
KOH Thermofluid *FLI-HY Loop* (UCLA)
US-1: FS Hydro
US-2: FS HT
US-3: FS curve hydro
FS Flibe?
MHD
US-4: FS HT w/MHD
Other tasks: TBD
J-1: Chan Fin Hydro
J-3: Channel/Fin HT
J-6: Channel/Fin HT w/MHD
Large Flibe Loop
Paratherm Thermo-fluid *HiTeC Loop* (UCLA)
J-2: FS/P
J-4: FS/porous HT
J-5: Packed Bed HT
Other tasks: TBD
Concurrent thermomechanics Experiments
Modeling (DNS,LES,MHD, k-e, Free surface)
Modeling for experimental design
Model development initiatives

UCLA Experimental Plans and Capabilities in Thermofluids Research

Thermo-fluid capabilities at UCLA

Laboratory Thermofluid Facilities

- **Multiple flow loops**
- **Multiple magnets and high current power supplies (from PPPL and MIT)**
- **High bay space and high load crane**

Special materials handling capabilities (Be, Flibe)

- **Glovebox and enclosure facilities**
- **Approval for large scale Be handling (PISCES and Solid Thermomechanics experiments)**
- **Flibe qualification underway for vaporization/condensation experiments for IFE**

UCLA Capabilities (Continued)

Thermofluid Instrumentation

- **Laser doppler velocimetry**
- **Micrometer & ultrasonic flow depth probes**
- **Bubble/dye flow visualization and fast digital photography**
- **Holographic temperature profiling**

Computational Tools

- **DNS/LES/MHD codes**
- **Free Surface Codes**
- **Parallel computing clusters and data visualization laboratory**

Interested UCLA faculty with worldwide reputations

- Vijay Dhir: Fluid heat transfer
- John Kim: DNS and MHD
- Robert Kelly: Free surface flow
- Nasr Ghoniem: Fusion materials

UCLA Fusion Science and Technology Group experience

- **Magnet design and construction**
- **Thermofluid/MHD experimentation**
- **MHD/free surface modeling**

Key Thermofluid Facilities Proposed for Collaboration

Fli-Hy: Flibe Hydrodynamic Simulation Facility

- **Water/KOH Discharge System and High Field Magnet**
- ***Status: Design and Construction***

HiTeC: High Temperature Cycling Experiment

- **Paratherm High Termperature, High Prandtl Organic Oil Loop**
- ***Status: Operating since 1993***

MeGA-Loop

- **Liquid Metal Flow Loop Coupled with Large Volume Magnetic Field Facility for open and closed channel MHD experiments**
- ***Status: Operating since 1992, Upgrade to toroidal magnet in progress***

➢ **These operating facilities can accommodate the needs of the collaboration**

Flibe Hydrodynamic Simulation Facility, or *Fli-Hy*

***Facility role:** flexible Flibe simulant loop for a variety of hydrodynamic, magnetohydrodynamic, and heat transfer experiments for MFE and IFE*

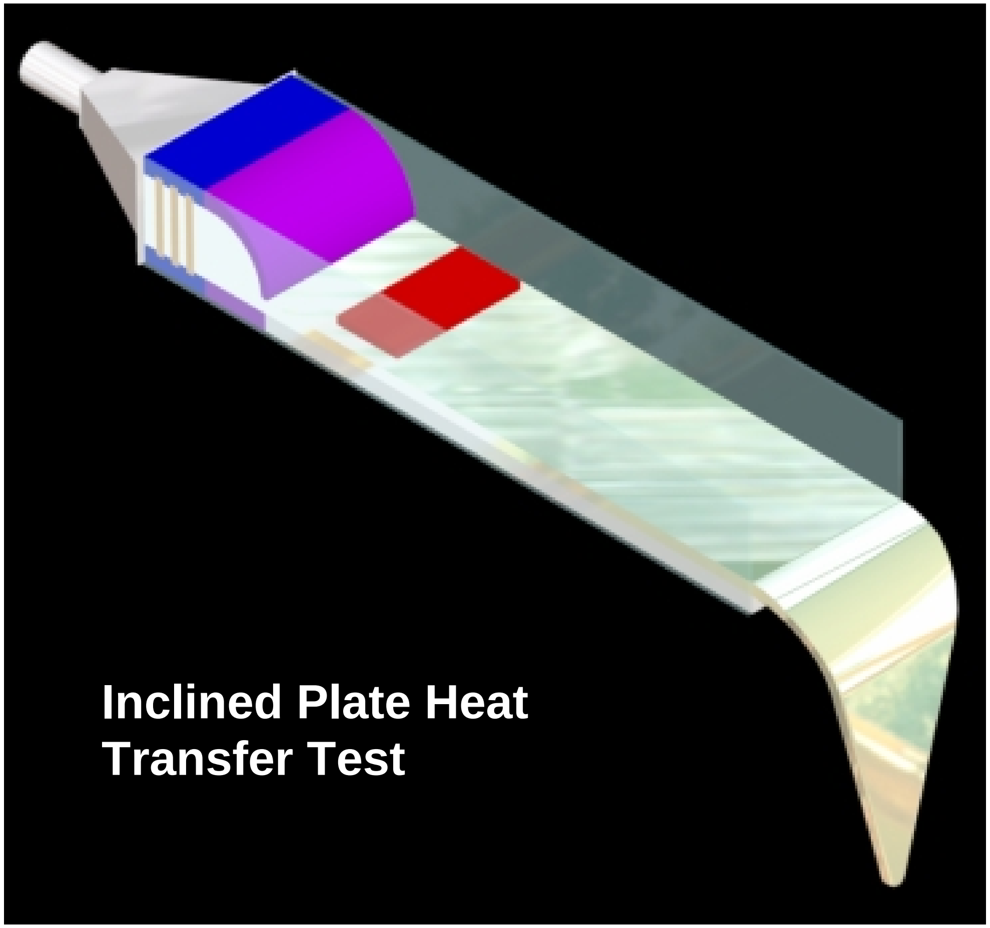
Current facility design specifications

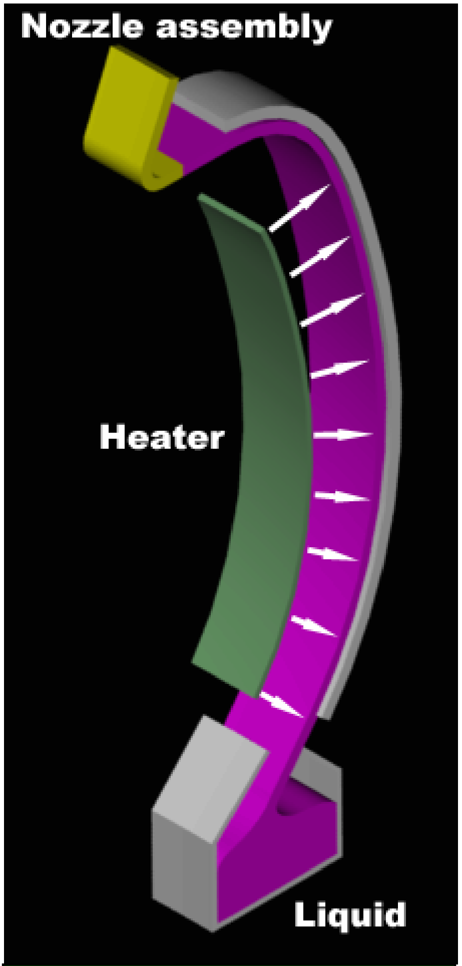
- **Switchable water or water/electrolyte working liquid**
- **Discharge or continous operating modes**
- **316SS and CPVC components for electrolyte compatabilty**
- **>2 m^3 working volume**
- **>100 l/s maximum flowrate capability (in discharge mode)**
- **>10 m/s flow velocity**
- **Temperature control from 4 to 50C**

Status:

- ➢ **Design phase underway**
- ➢ **Construction phase awaiting final design review at UCLA**

Fli-Hy Example Test Sections





Curved Plate
Heat Transfer Test

Features of Flibe Simulation with Aqueous KOH Solution

Advantages:

- Low cost for working liquid
- Low operating temperature
- Wide material compatibility and low material cost
- Large flow volumes and flow rates possible for free surface flow tests
- Transparent medium for optical flow measurements
- Scaling favors reduced size and flow velocity tests
- Relatively high electromagnetic parameters for simulation of MHD/turbulence interactions

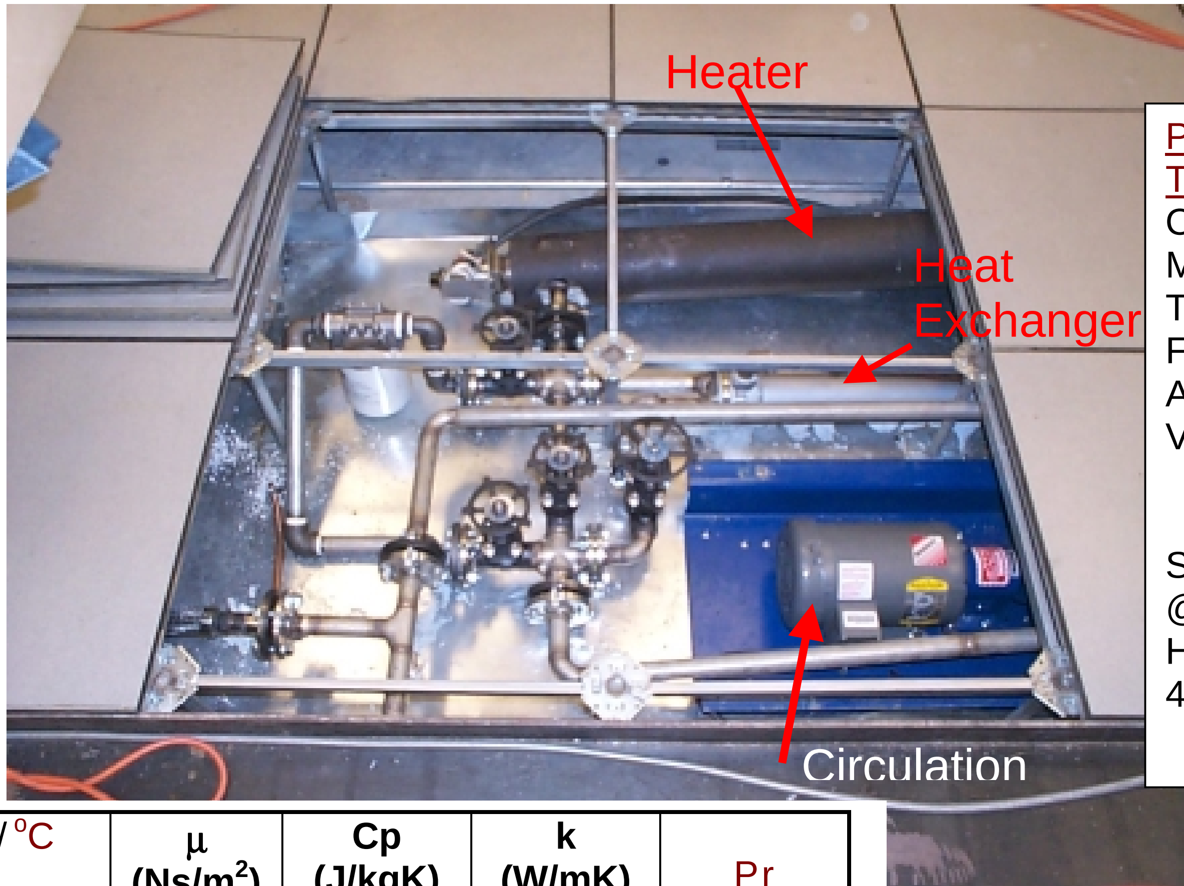
Concerns:

- Some health hazard and corrosive characteristics, but good materials and safety procedures have already been identified.
- High vapor pressure at elevated temperatures

HiTeC Paratherm NF Thermal-hydraulics Loop

Main Purpose: as a coolant for high temperature solid breeder material system thermomechanics experiments

Alternative use: as a simulant for fluid having high Prandtl numbers



Paratherm NF: A Non-Fouling, Non-Toxic Heat Transfer Fluid

Optimum Use Range 49 to 316 °C

Maximum Recommended Film Temperature 338 °C

Flash point 168 °C

Atmospheric Boiling Point 343 °C

Vapor Pressure psia

@	200 °F	0.0005
	300 °F	0.003

Surface Tension

@ 760 mm Hg/25 °C 28 dynes/cm

Heat transfer coefficient at 2” sched. 40 pipe @ 2.44m/s = 1891 W/m^{2}K

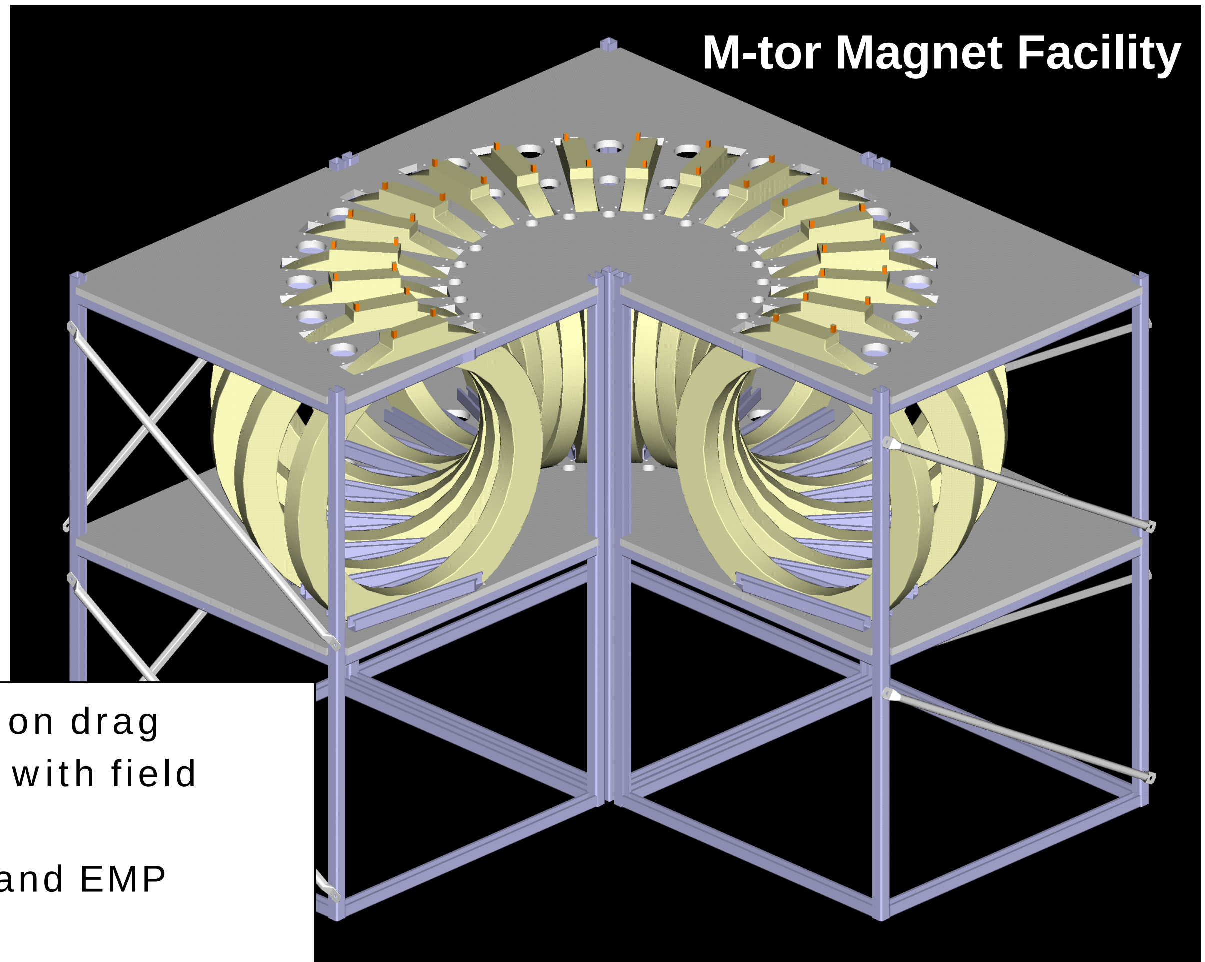
°F/ °C	µ (Ns/m^2)	Cp (J/kgK)	k (W/mK)	Pr
100/37.8	16x10^{-3}	1926	0.13156	234
200/93.3	3.5x10^{-3}	2135.4	0.128	58.39
300/148.9	1.6x10^{-3}	2344.7	0.12378	30.3
400/204.4	0.92x10^{-3}	2554	0.1194	19.68

Magnet Upgrade in MeGA-Loop

Tara coils are currently being fashioned into a torus for investigation of relevant field gradients on LM free surface flow

Status:

- ***all 24 magnets acquired***
- ***power supply acquired from PPPL***
- ***support structure under construction***



1. Field gradient effect on drag
2. Magnetic Propulsion with field gradients
3. Other forms of EMR and EMP
4. Two layer MHD flow
5. NSTX simulation (pulsed fields)

M-Tor Experimental Hardware

Development of high field magnet options

- ***Design using iron** gives up to 2 T field, large working volume and easily accessible test area*
- ***High current air core solenoid** design has potential for higher fields with existing power capabilities*

Status:

- Design of small, low cost 4T, air core coil underway in collaboration with PPPL