# Investigation of Mist Cooling for the Electra Hibachi

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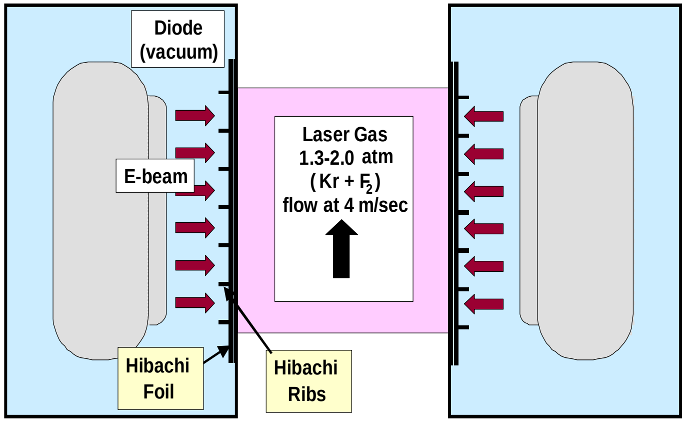
# *The Electra Hibachi*

- **The Electra hibachi structure supports the thin foil(s) separating the laser gas (at a pressure of 1.3 to 2.0 atm) from the hard vacuum of the electron beam diode**




Generic Single-Foil Hibachi Structure – Top View

- **Design requirements for the hibachi include**
  - lifetime >$10^8$ shots
  - electron beam transmission efficiency >75%
  - cooling power requirement <2.5% of the overall laser system input power

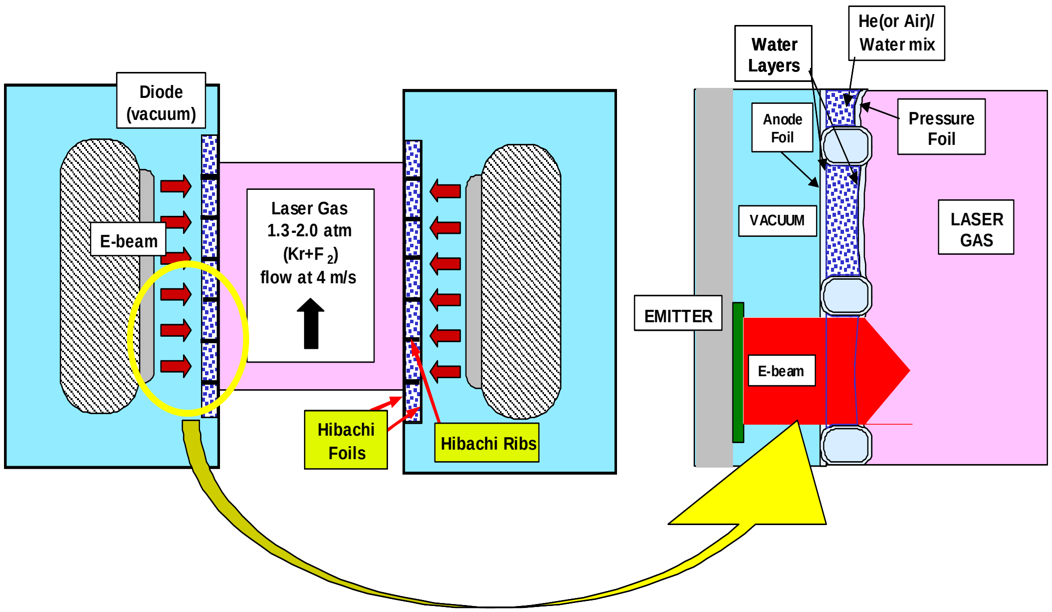
# *Cooling the Electra Hibachi*

**Several cooling schemes have been proposed**

- Cooling the pressure foil with the laser gas
- Cooling the foils by conduction to water-cooled support ribs
- Radiative cooling
- Cooling the entire hibachi assembly by flowing high pressure gas (helium at 20 psi) between two foils
- Pulsed spray cooling of the foils with spray nozzles mounted on the hibachi rib structure
- Cooling the entire structure with a flowing gas/liquid mist at an intermediate pressure (~1 atm) between the two foils

# *Mist Cooling - Concerns*

- Uniform Coverage?
- Explosive Boiling?
- Foil wettability?
- Accommodating E-Beam hot spots?
- Loss of E-Beam transmission efficiency
- Cooling power requirements




Generic Two-Foil Hibachi Structure – Top View

Preliminary calculations by NRL (S. Swanekamp) suggest that the transmission efficiency in a full-scale IFE system with mist cooling, including a 40μm water layer on each foil, can be greater than 75%

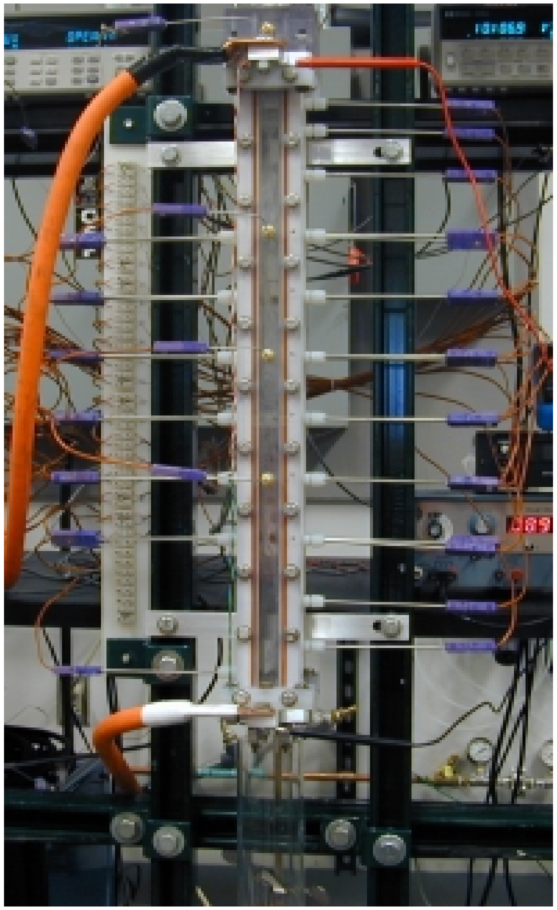
# *Objectives*

**Investigate effectiveness of flowing gas/liquid mist as a means of cooling the Electra hibachi structure**

- Quantify effect of various design parameters on mist cooling effectiveness
- Develop and validate a mechanistic model to predict the response of mist-cooled hibachi foils under prototypical pulsed operating conditions
- Design and construct a prototypical mist-cooled hibachi test module for Electra
- Conduct on-site experiments of mist-cooled test module performance under prototypical pulsed operating conditions (5 Hz) in Electra

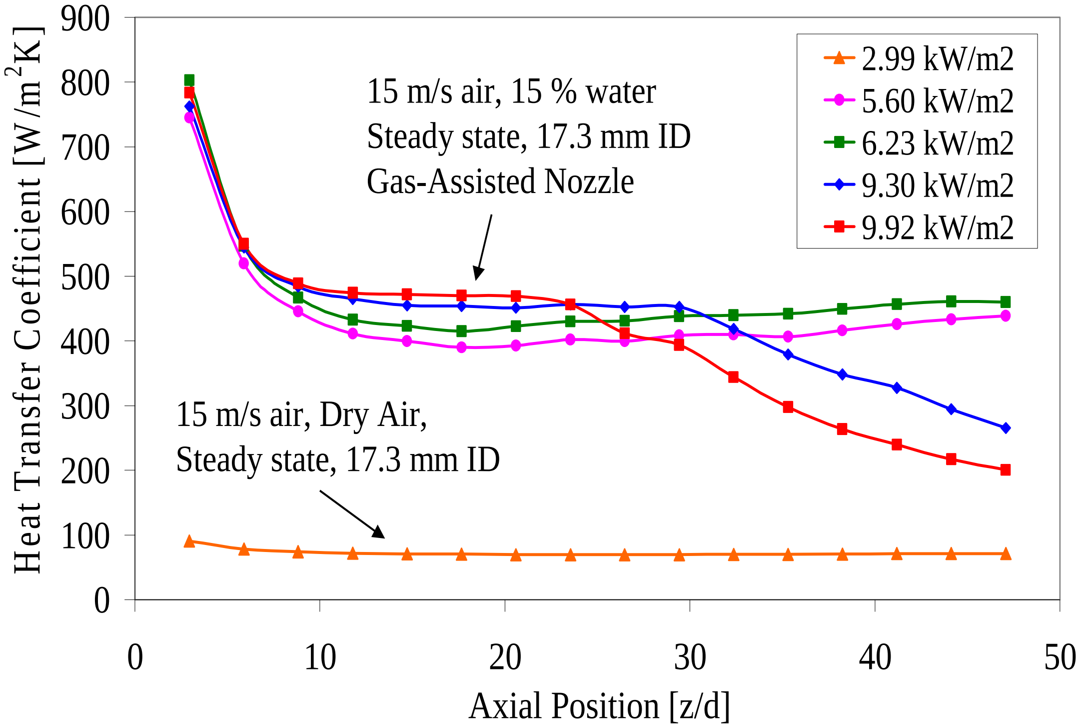
# *Georgia Tech Experimental Test Facility*

- Three instrumented, electrically-heated, channels
- Air/water or helium/water downward mist flow at controlled velocity, liquid fraction, droplet size (nozzle design) and heat flux
- Wall temperature distribution measured along channel
- Local heat transfer coefficient determined from measured heat flux (power) and wall temperature



Rectangular test sections
(insulation removed)

# *Experimental Data – Effect of Heat Flux*

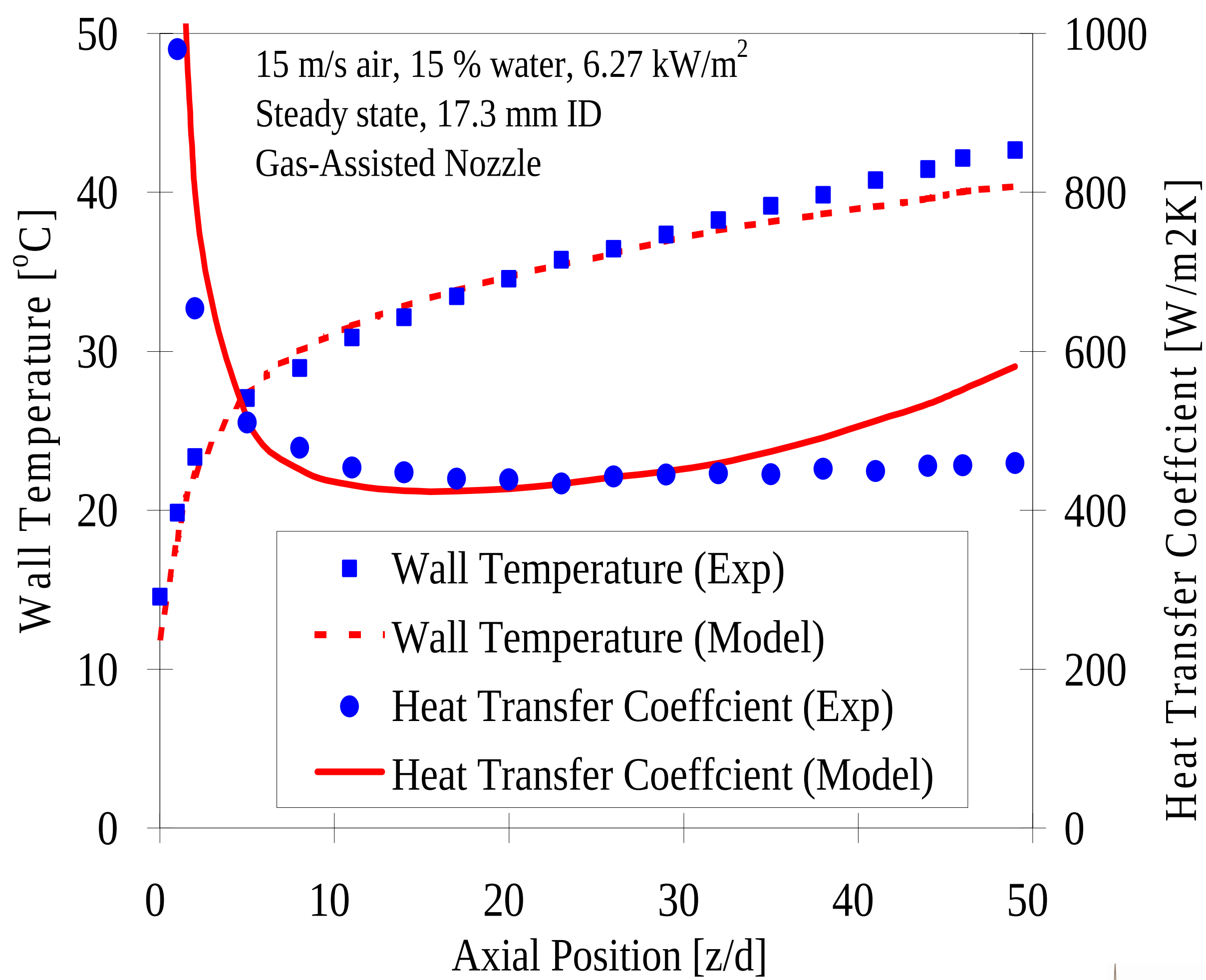



- Nearly an order of magnitude enhancement in heat transfer coefficient versus carrier gas (air) only
- Heat transfer coefficient increases with heat flux provided that the liquid film remains intact. It also increases with increasing water fraction

# *Georgia Tech Mechanistic Mist Cooling Model*

- Based on **KIVA-3** computer code developed by Los Alamos National Laboratory
- Can be applied to: transient, two- and three-dimensional, laminar or turbulent, subsonic or supersonic, single phase or dispersed two-phase flows with liquid films, and chemically reactive flows
- KIVA-3 was modified to accommodate nonzero heat flux and volumetric heating of the wall
- Model predicts
  - wall temperature distribution
  - gas temperature distribution
  - liquid temperature distribution
  - liquid film thickness
  - mixture density distribution

# Comparison between Experimental Data and Model Predictions

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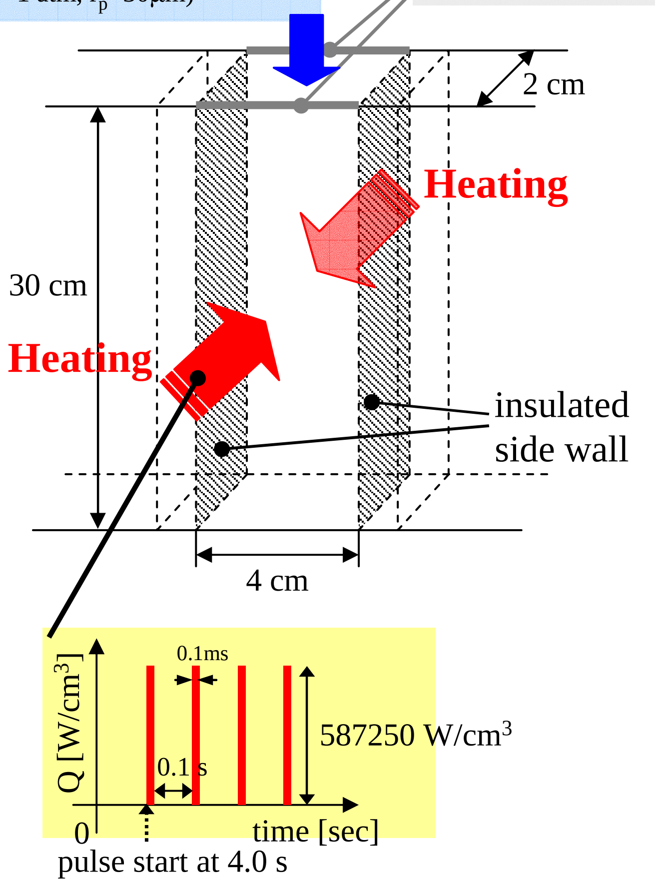
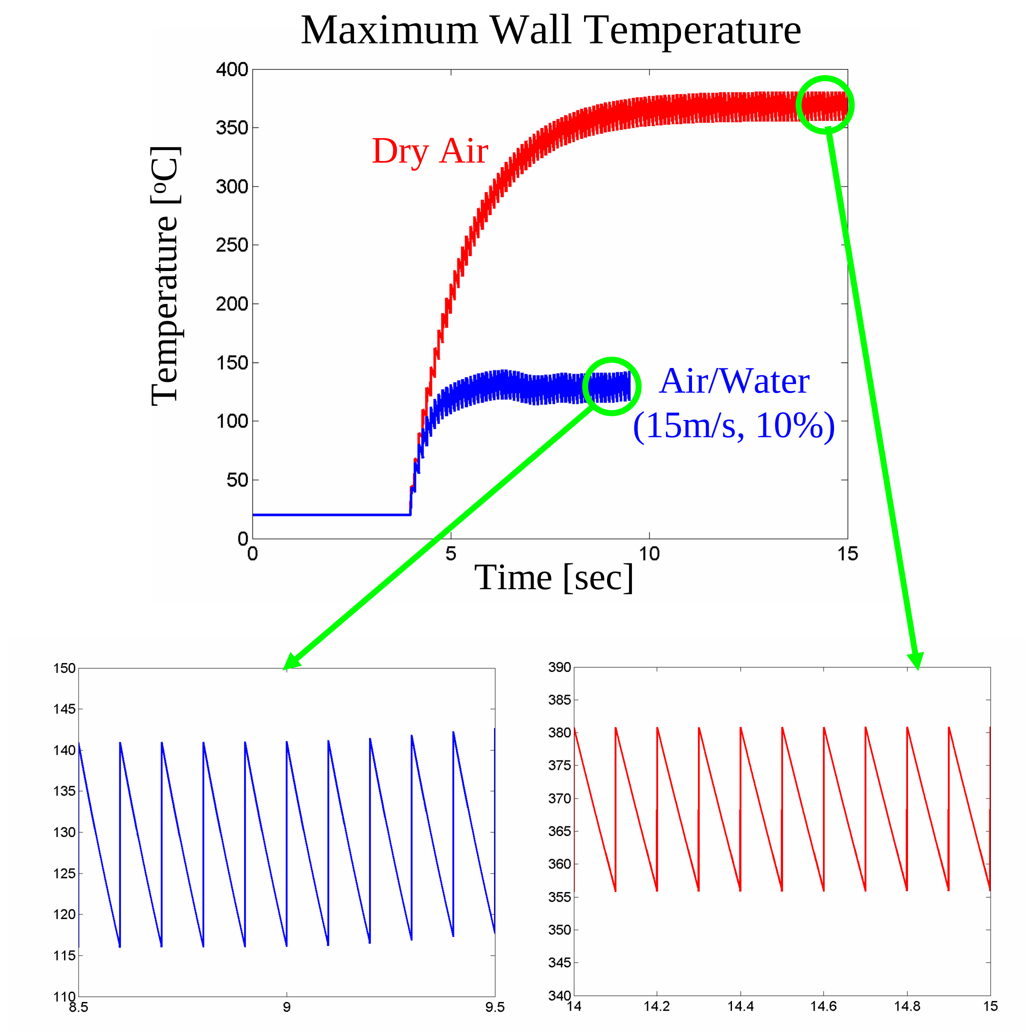
# Numerical Simulation
## Pulsed Heating (10Hz)

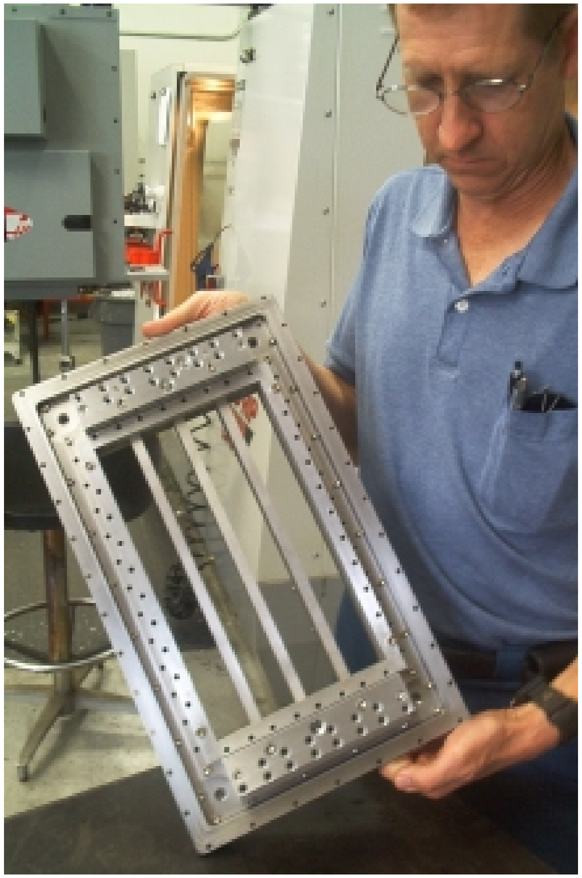
**Air/Water Mist Flow**
**[0% Saturation]**
(15m/s Air, 10% Water $T_{in}$=20 °C,
1 atm, $r_p$=30μm)

foils
(Titanium,
δ=0.025 mm)



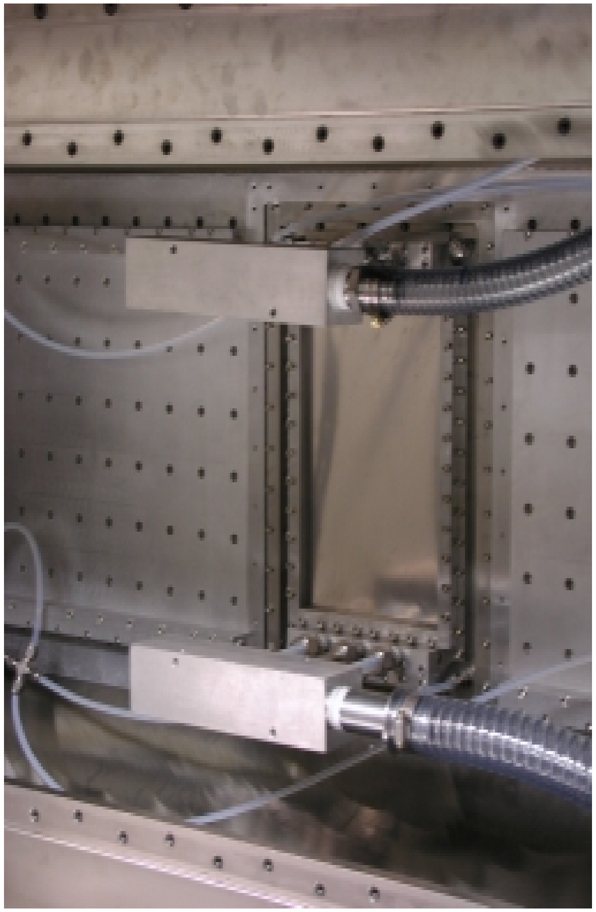



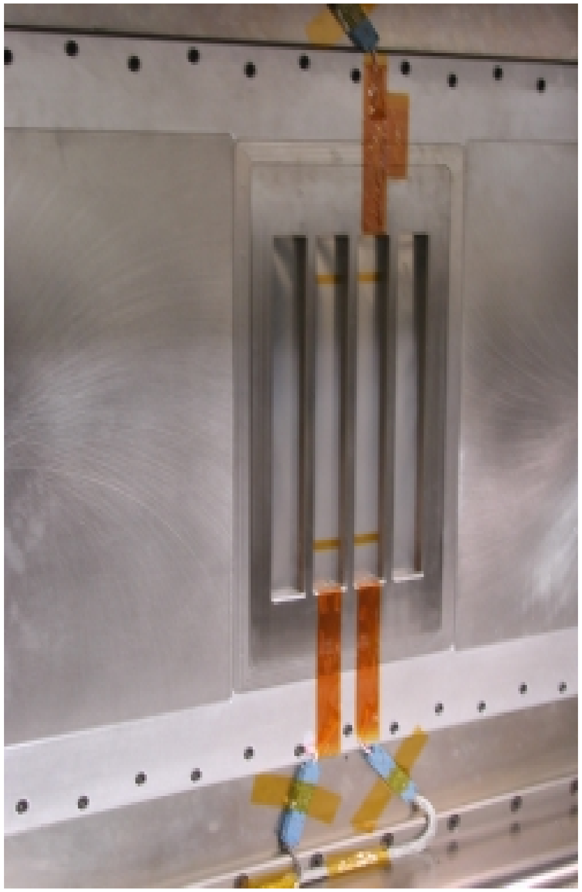
# Georgia Tech Mist-Cooled Hibachi Test Module



- Four Channels (three ribs), 1.3 x 3.4 cm cross section, 28 cm long
- Two foils; initial tests with 2-mil thick titanium
- Custom-designed gas atomizing nozzles for optimal droplet size
- Water-cooled support ribs on vacuum side
- Module mounted in cooled blank anode plate

# Georgia Tech Mist-Cooled Electra Hibachi Test Module

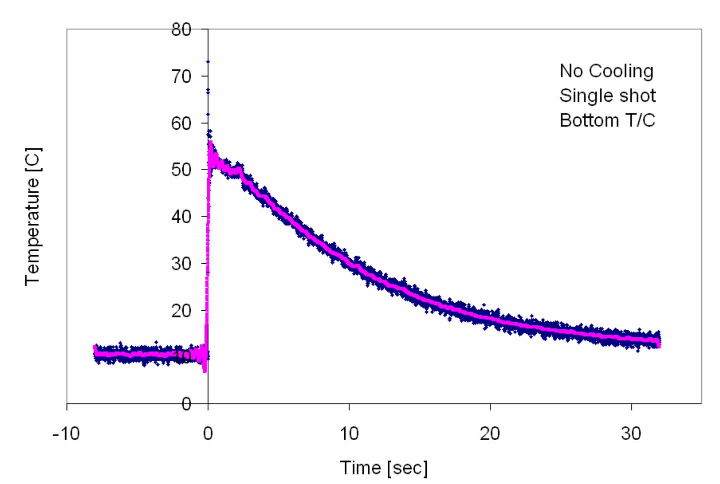


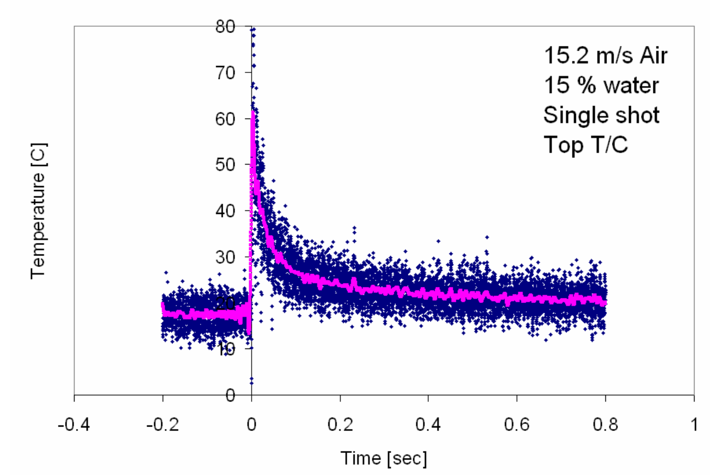


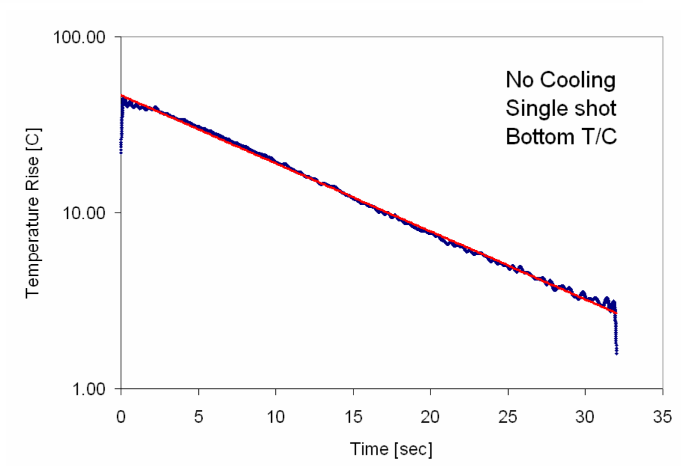
# On-Site Testing of Hibachi Test Module

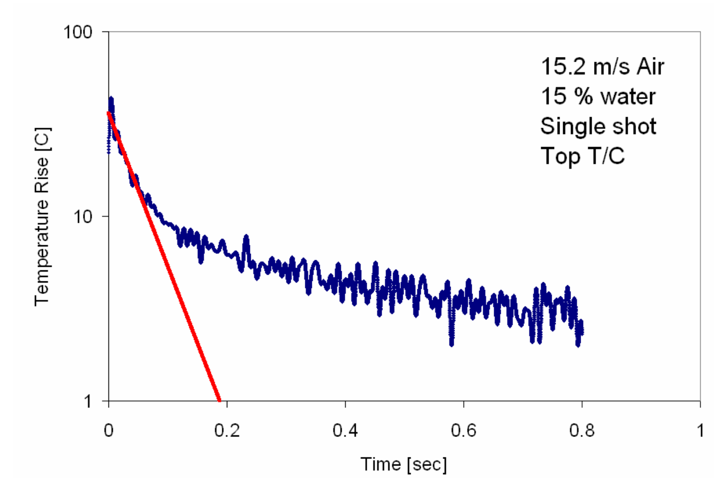
- **Instrumented Single-shot Experiments**
  - No active cooling
  - Low-velocity air between foils (2.5 m/s)
  - Moderate velocity air between foils (15.0 m/s)
  - Mist flow between foils (15.0 m/s air plus 5, 10, and 15% water mass fraction)
- **Instrumented Multiple-shot Experiments**
  - No active cooling (1 Hz for 10 sec; 5Hz for 2 sec)
  - Moderate velocity air (15.0 m/s, 5 Hz for 2, 4, and 6 sec)
  - Mist flow between foils (15.0 m/s air plus 5, 10, and 15% water ; 5 Hz for 6 sec)
  - Mist flow between foils (15.0 m/s air plus 15% water; 5 Hz for ~12 sec)
- **Un-instrumented Long-duration Experiments**
  - Mist flow between foils (15.0 m/s air plus 15% water; 5 Hz for ~1100, 1500, 1250, and 3000 pulses)

# Single-Shot Experiments

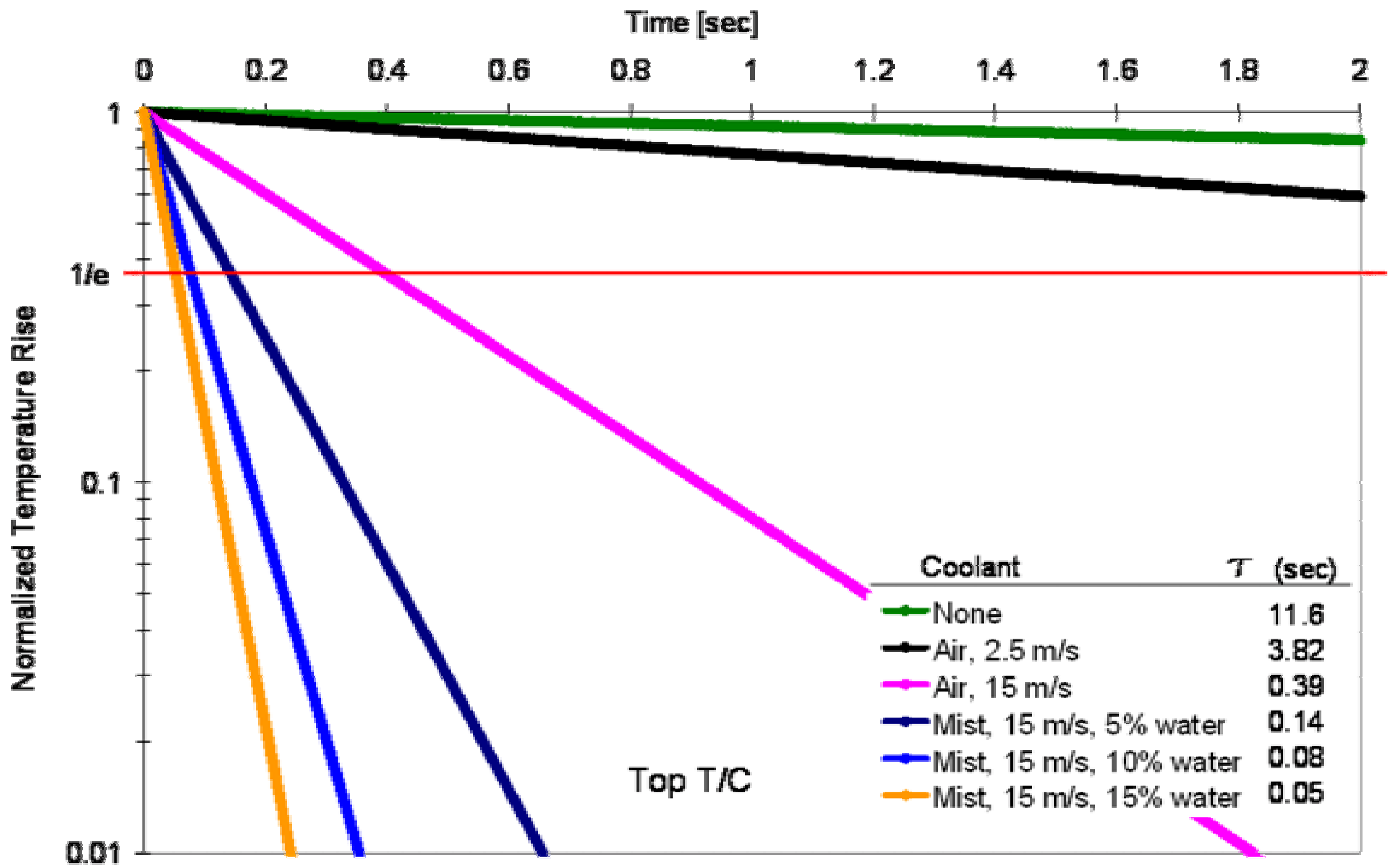


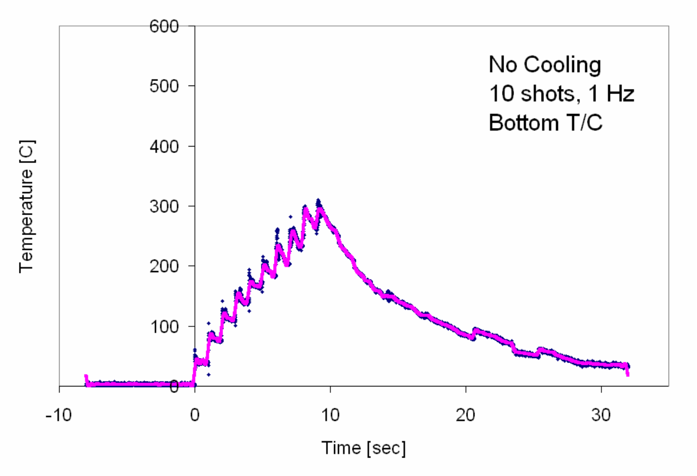



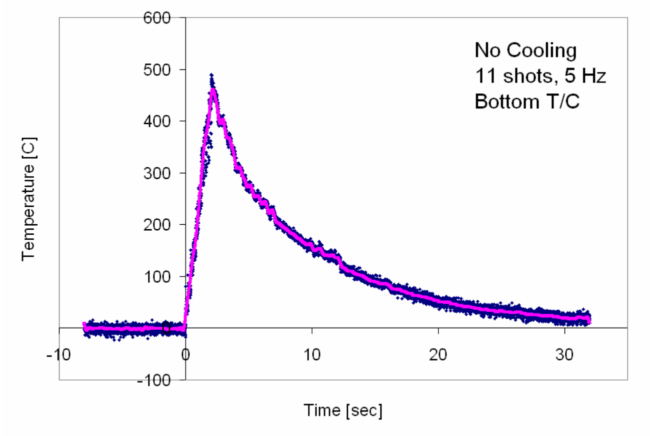



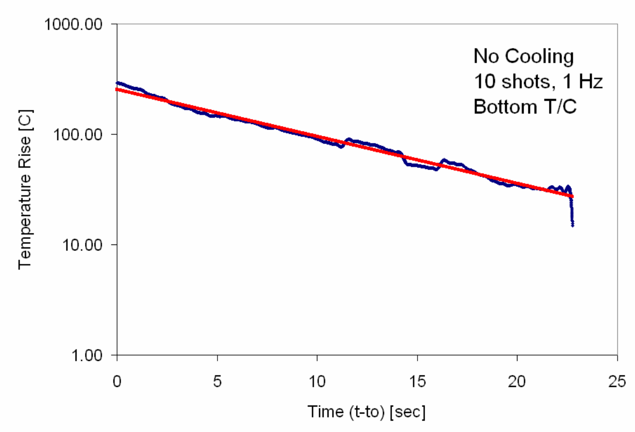
# Foil Cooling Time Constant

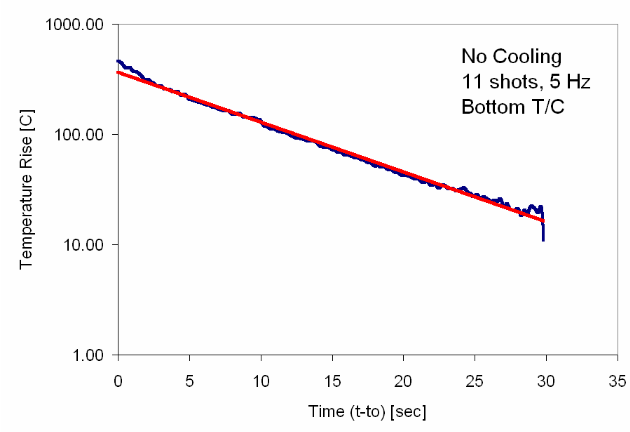


# Multiple-Shot Experiments

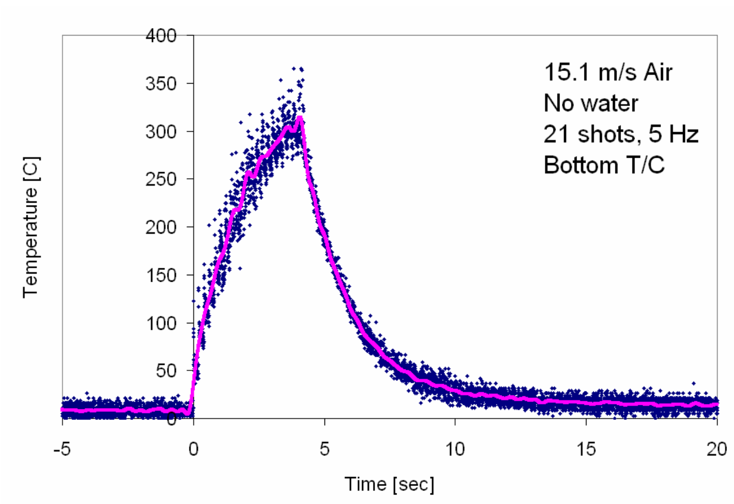


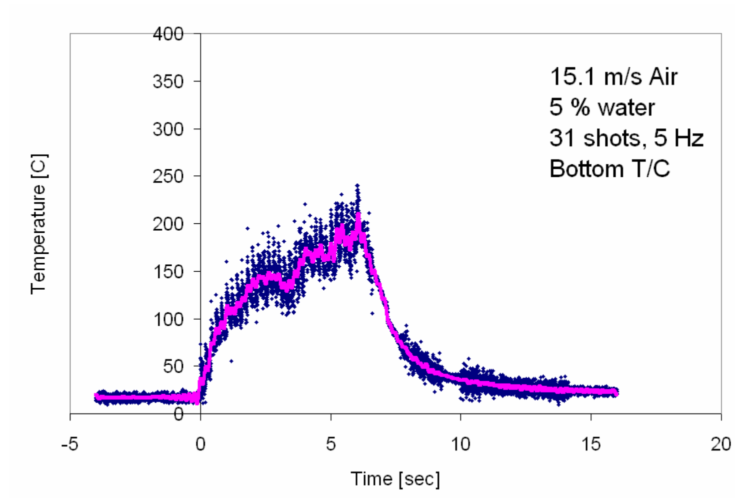



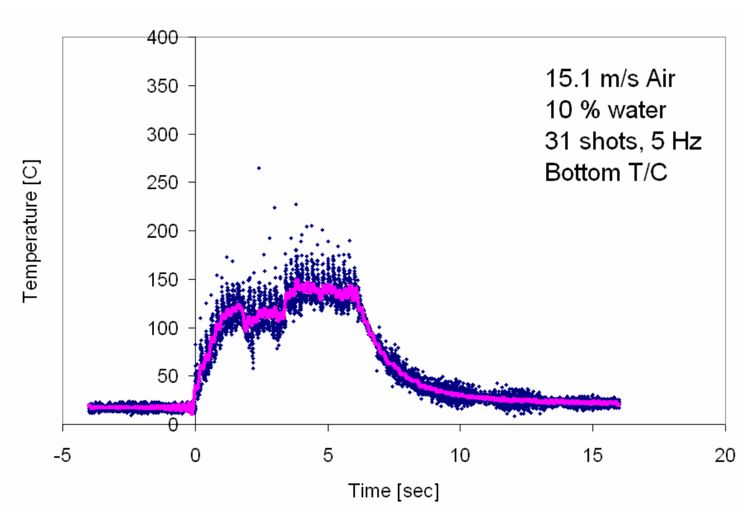



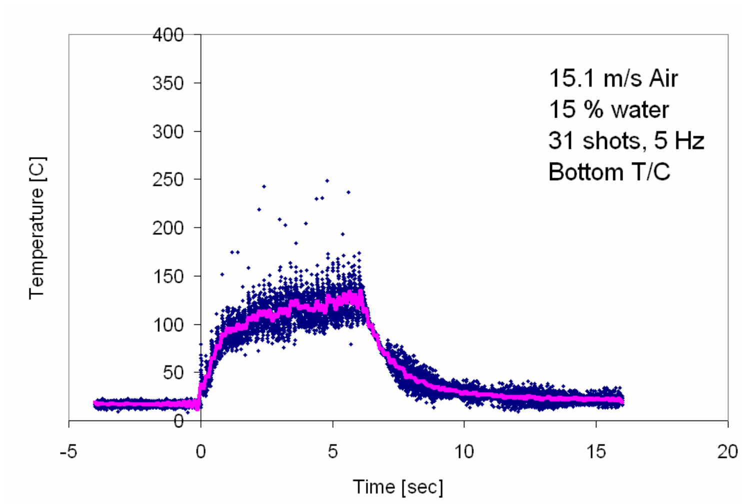



# Multiple-Shot Experiments

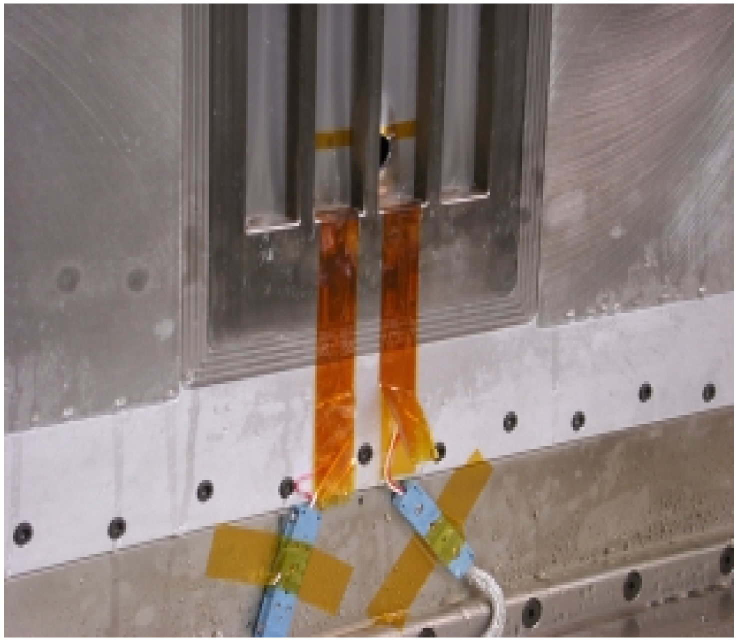


# Multiple-Shot Experiments



## Experiment #21

- **5 Hz, Mist Cooling with 15.0 m/s Air and 15% water mass fraction**
- **Cathode-side foil failed after ~12 sec**
- **Failure caused by arcing between broken thermocouple wire and foil**
- **Failure unrelated to mist cooling – Decision was made to proceed with un-instrumented long-duration, high rep rate, experiments**

# Un-instrumented Long-duration Experiments

- 5 Hz, Mist Cooling with 15.0 m/s Air and 15% water mass fraction
- Four experiments (A through D, with 1100, 1500, 1250, and 3000 pulses)
- Foils did not fail during any of the four sequences
- Experiments A, B & C: conducted sequentially; several minutes between runs; total of 3911 shots; arcing between ceramic cathode and middle rib caused discoloration of rib and foil (deposition of contaminants?); internal (cooled) foil surfaces remained in original pristine condition; tests stopped due to abnormal Electra performance.
- Experiment D: inadequate cooling of blank anode plate and interface with test module caused anode plate and test module frame to overheat resulting in O-ring seal failure; experiment terminated after 3000 pulses because of loss of vacuum; foils remained intact with no indication of overheating; internal (cooled) foil surfaces remained in original pristine condition.

# Summary

- **An experimental and numerical investigation has been conducted to examine the effectiveness of gas/liquid mist as a means of cooling the Electra hibachi structure**
  - Effect of various operating and design parameters on mist cooling effectiveness has been quantified
  - Data were used to validate a mechanistic model which can be used to predict the hibachi foils' response under prototypical pulsed operating conditions
  - A prototypical, mist-cooled, Electra hibachi test module has been constructed and tested under pulsed operating conditions

# Conclusions – The Path Forward

- **Air-Water Mist Cooling at moderate air velocities and water fractions can effectively cool the Electra hibachi under prototypical pulsed operating conditions**
  - Failures experienced to date were determined to be unrelated to the cooling system effectiveness
- **Future efforts will focus on:**
  - Design and construction of a “robust” anode plate and test module frame to allow long-term testing of the module (~ $10^5$ shots at 5 Hz) with different foil materials (including aluminum 5052)
  - Measurement of beam attenuation at different air velocities and water mass fractions to verify calculations and optimize operating conditions
  - Design of fluid delivery systems to meet the <2.5% power fraction constraint
  - Design and testing of a full-scale mist-cooled Electra hibachi