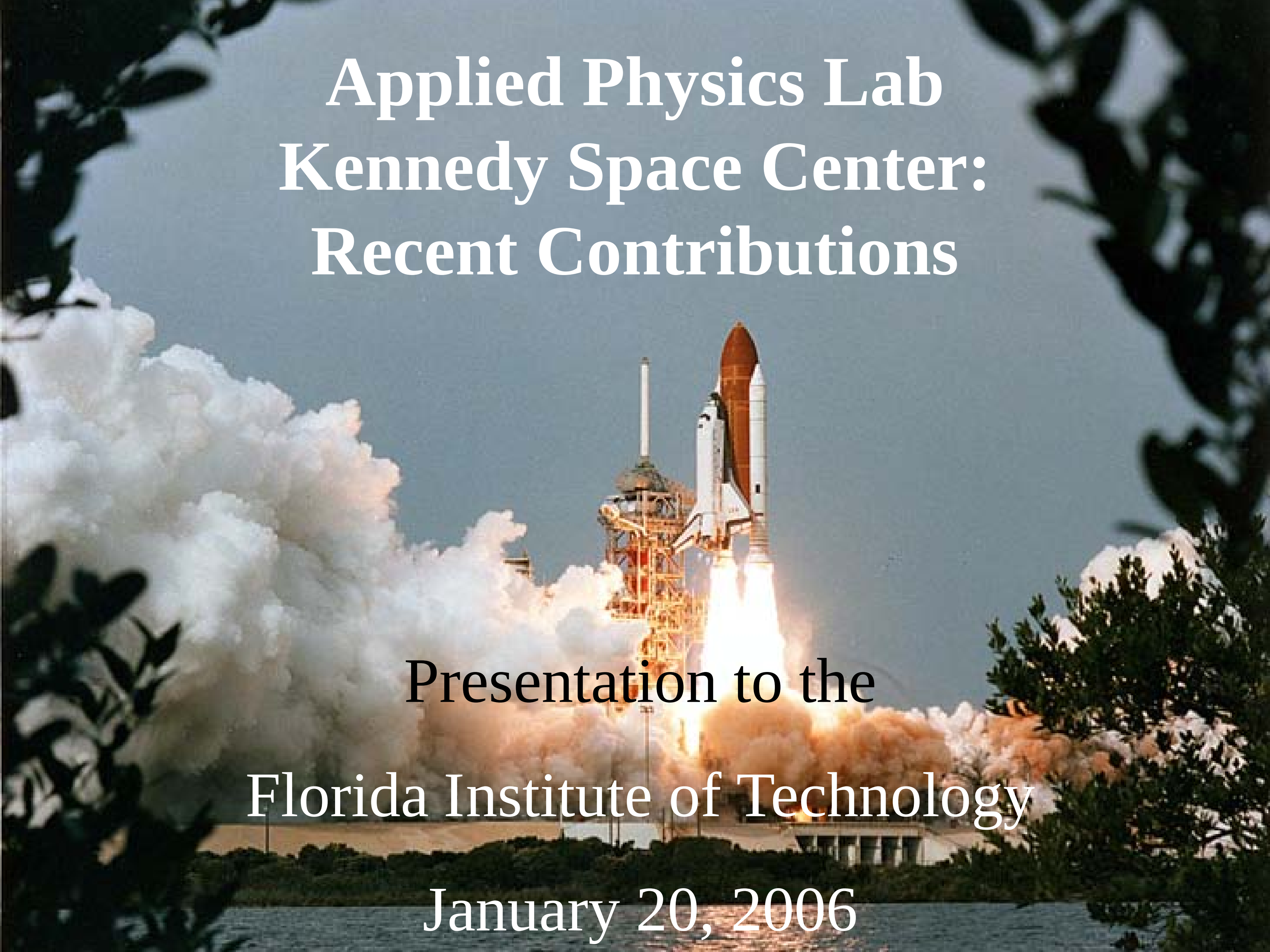
Applied Physics Lab Kennedy Space Center: Recent Contributions



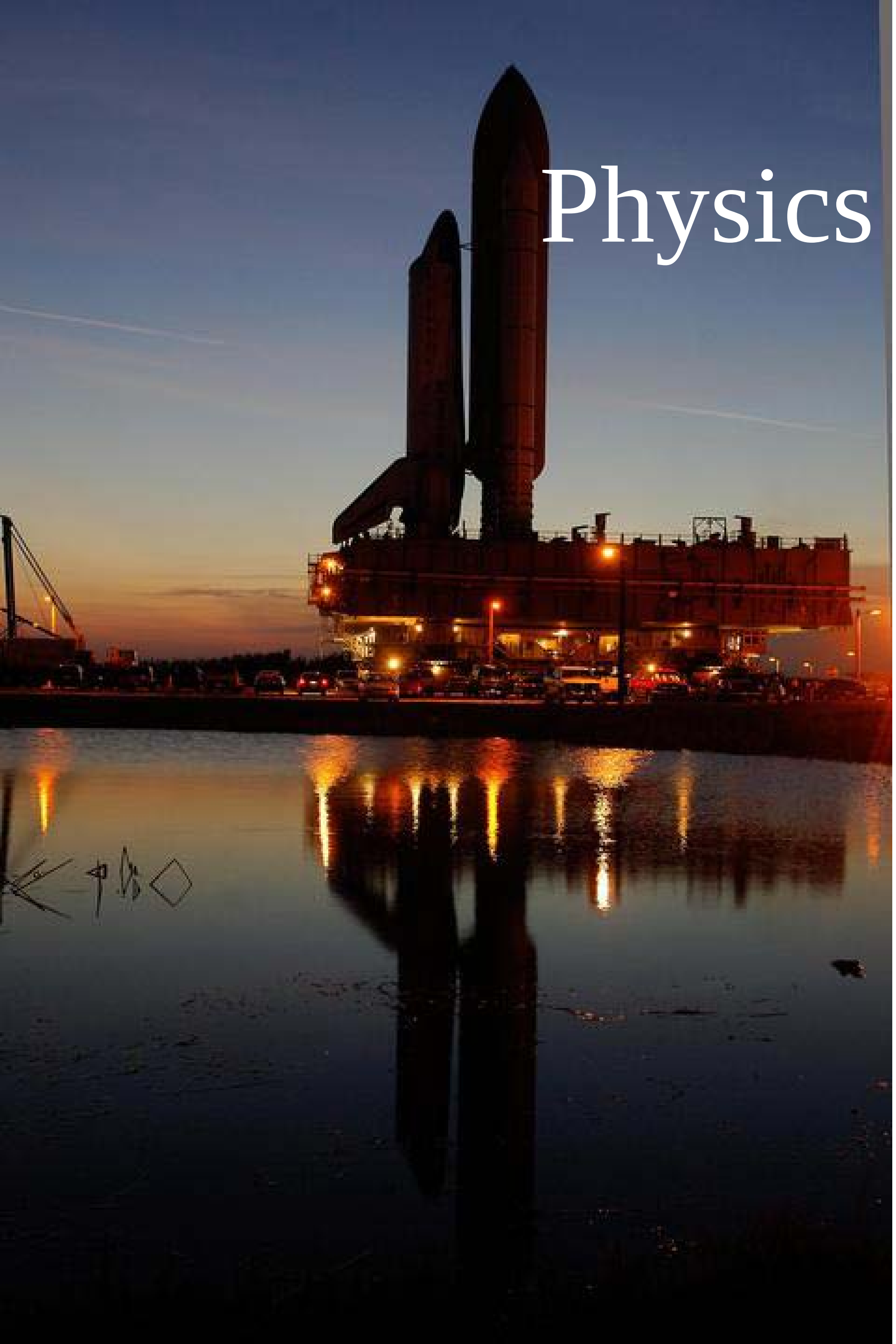
Presentation to the

Florida Institute of Technology

January 20, 2006

Agenda

- Introduction of Staff
- Mission of the Applied Physics Lab
- Historical Activities
  - Columbia Accident Investigation
  - STS-114 Return to Flight Activities
  - Shuttle “Proof of Concept” Tools
- Exploration
  - Rocket Blast and Cratering
  - Electrostatic Shielding Project
- Transition to Crew Exploration Vehicle and Lunar Exploration



Physics Lab Staff

- Robert Youngquist, PhD
- Phil Metzger, PhD
- Mark Nurge
- Doug Willard
- Tom Moss
- Curtis Ihlefield
- Teresa Lawhorn
- Stanley Starr
- Critical support by Artic Slope Research Corp.

Mission of the Applied Physics Lab

- Develop and deliver novel sensors and devices to support KSC mission operations.
- Analyze operational issues and recommend or deliver practical solutions.
- Apply physics to the resolution of long term space flight issues that affect space port operation on Earth or on other planets.

Columbia Investigation

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

ET Foam Debris Analysis:

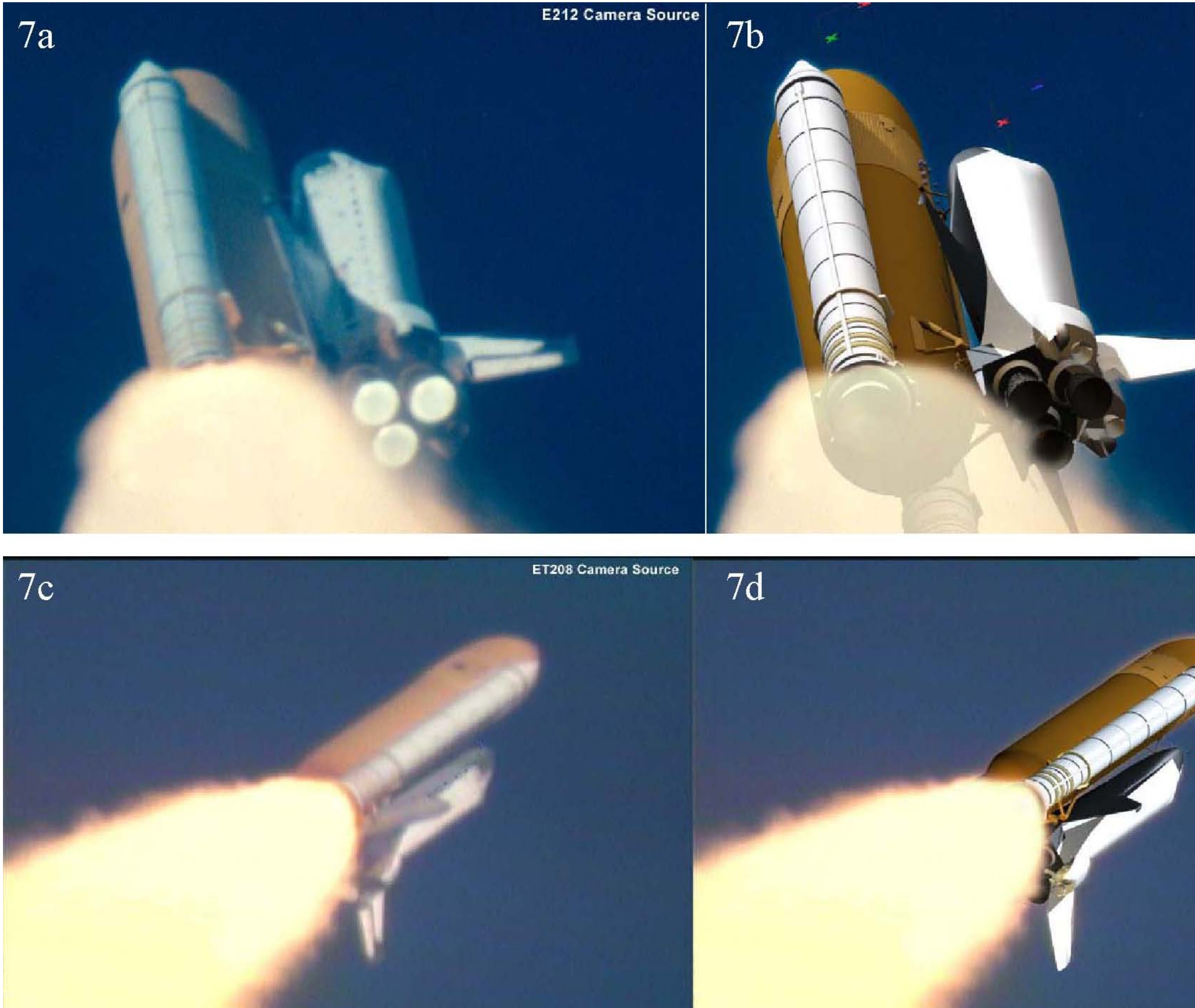
On Saturday, February 1, 2003, The Space Shuttle Orbiter Columbia was lost during re-entry.

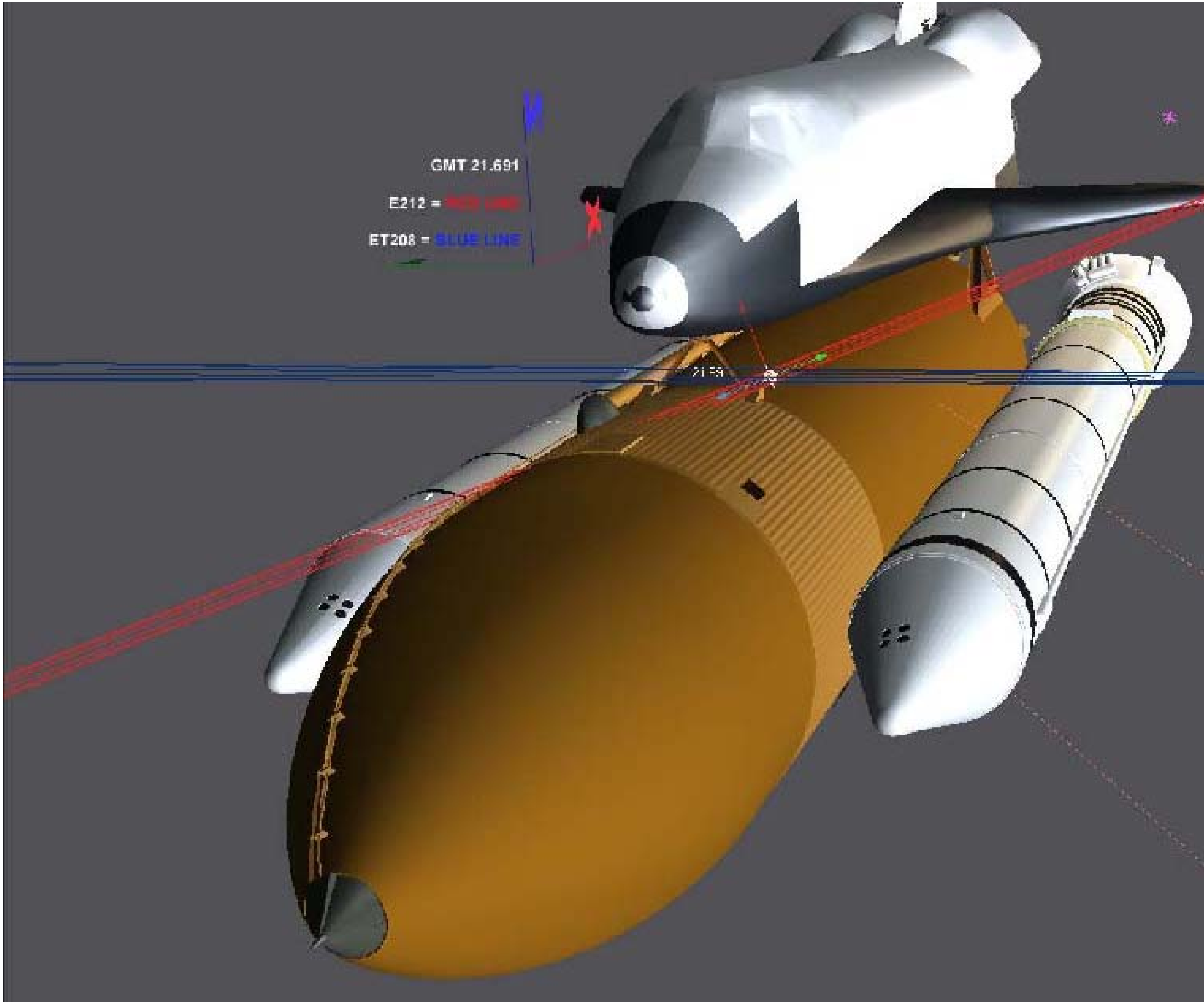
The film at left shows the loss of the left bipod foam ramp at 81.7 seconds MET and subsequent impact to the vehicle.

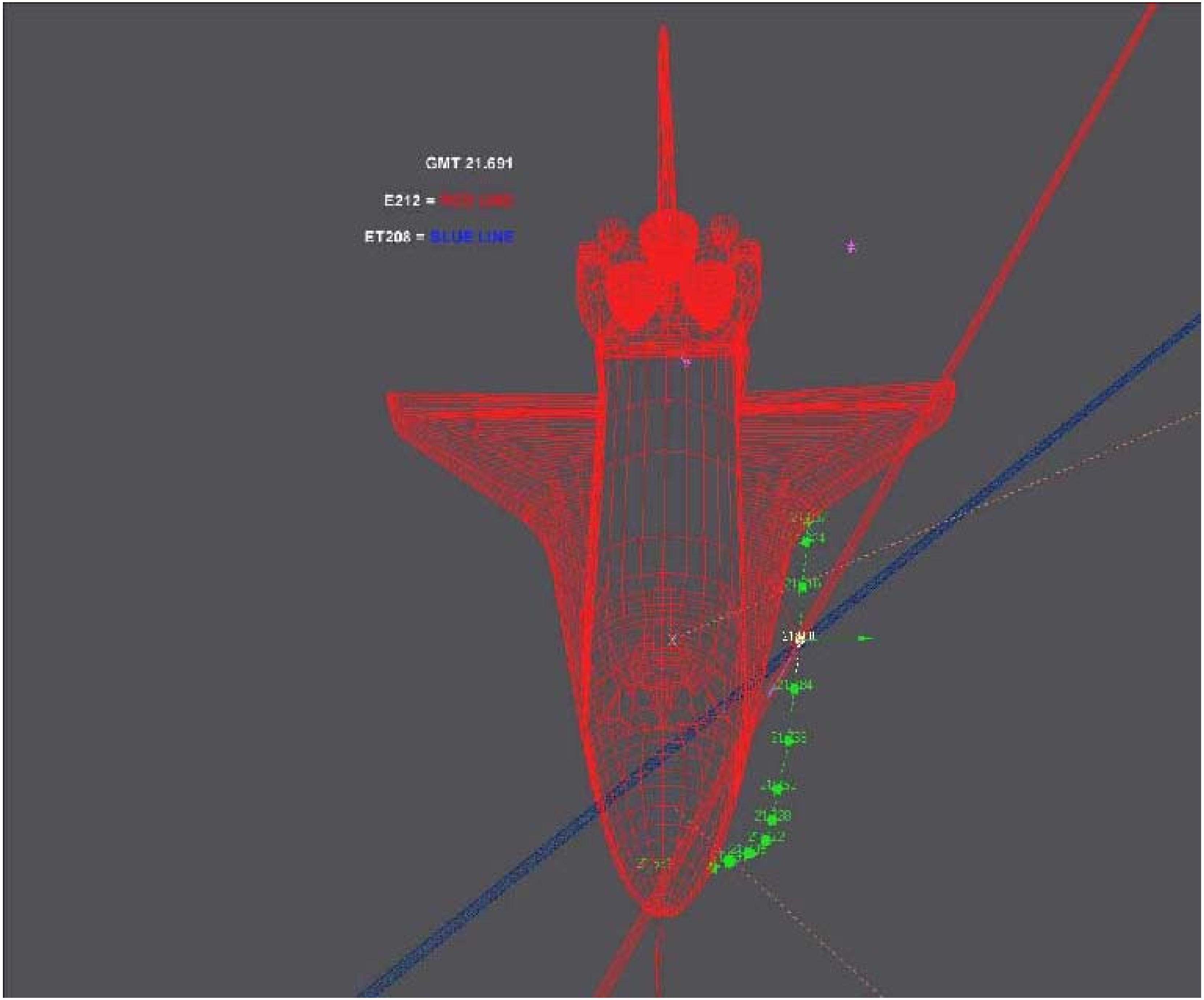
This work was primarily performed by John Lane ASRC.

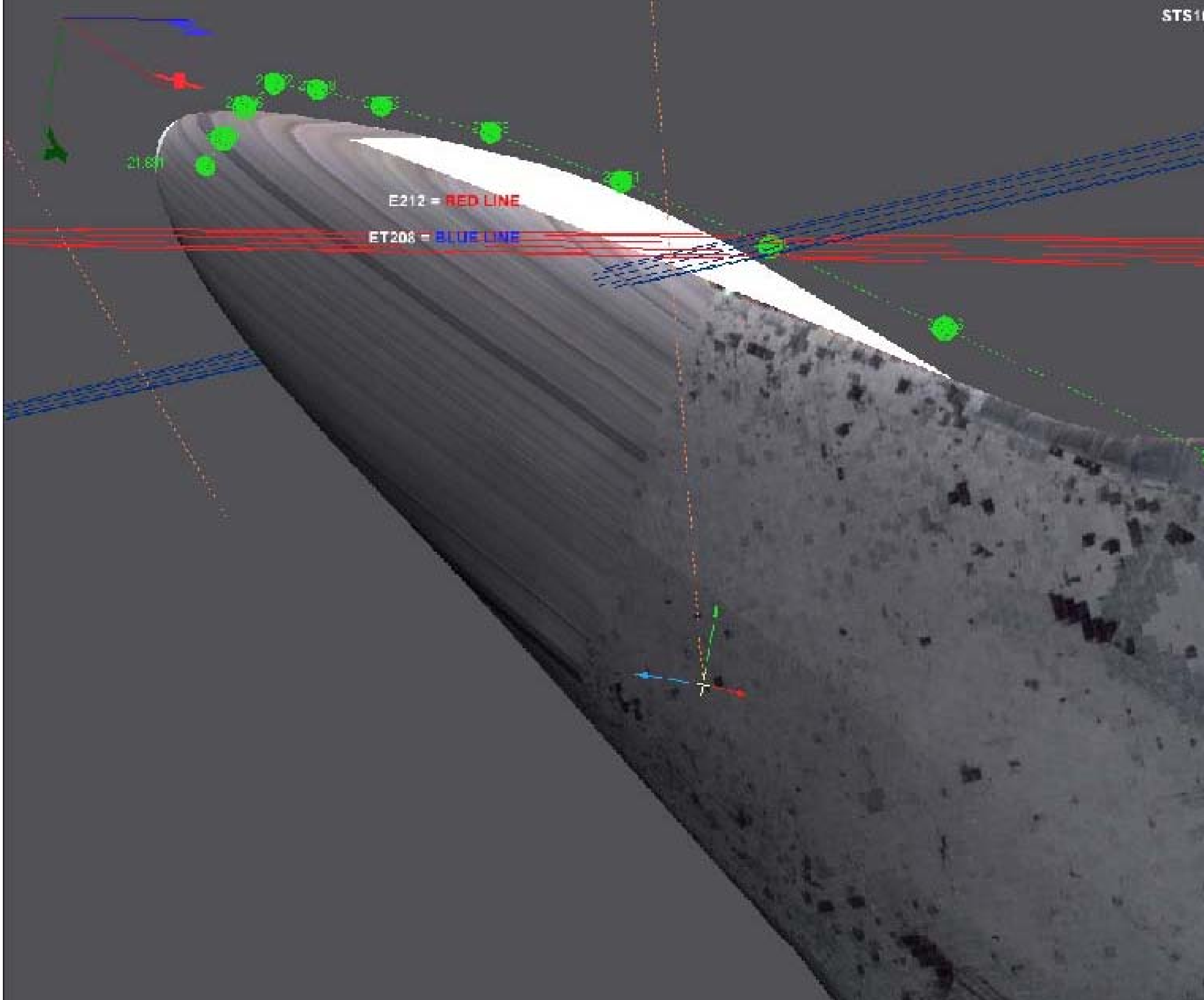
Analysis of Debris Impact

- Analysis of the debris impact velocity and location requires:
  - Scaling: Identification of the size and orientation of the vehicle in the images.
  - Identification of the location of the object's cg within that frame (assumed to be inertial).
- Scaling performed by matching images to a Lightwave 3D graphics model.
- Object identified by analyzing the difference of a background image and the 11 frames in which it appears.
- Object location defined along two intersecting rays (as 2D coordinates in planes normal to the camera to Shuttle vectors).
- Smoothed size, position and velocity solutions compared with wing images "painted" onto 3D model.


7a
E212 Camera Source
7b
7c
ET208 Camera Source
7d

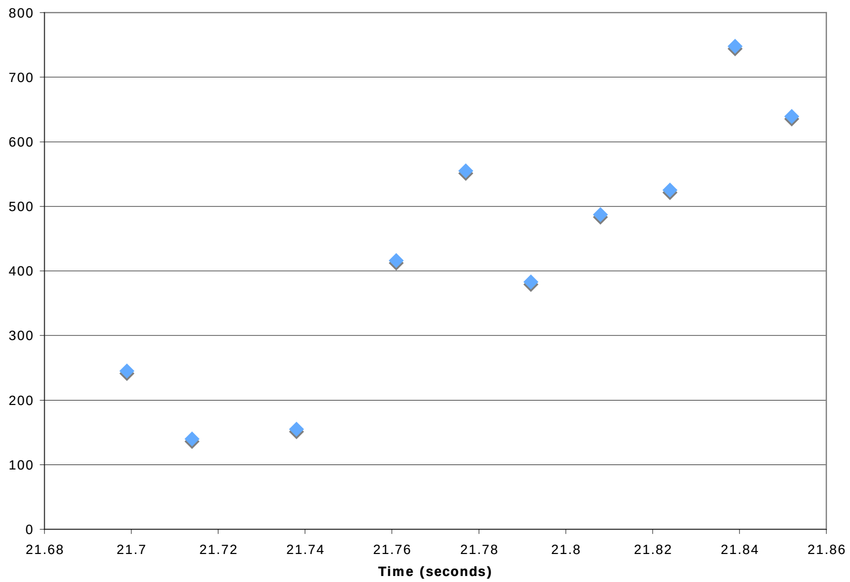

GMT 21.691
E212 =
ET208 = BLUE LINE


GMT 21.691
E212 =
ET208 = BLUE LINE



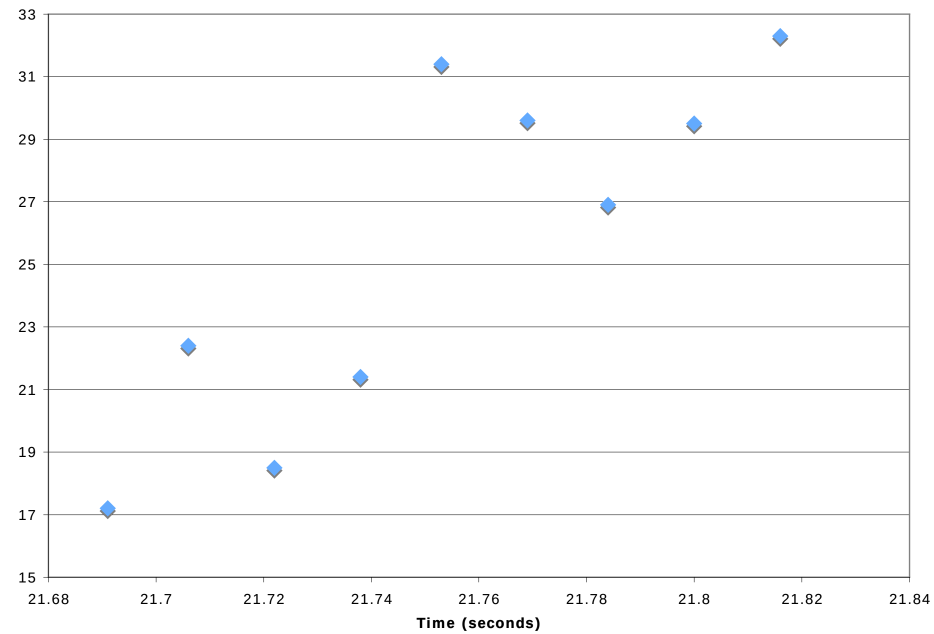
STS107
E212 = RED LINE
ET208 = BLUE LINE

Debris Impact Results



Size Estimates

Velocity estimates



Debris size, velocity and estimated location of impact utilized in Columbia Accident Investigation Board Report.

Columbia Debris Characterization Using Re-entry Imaging

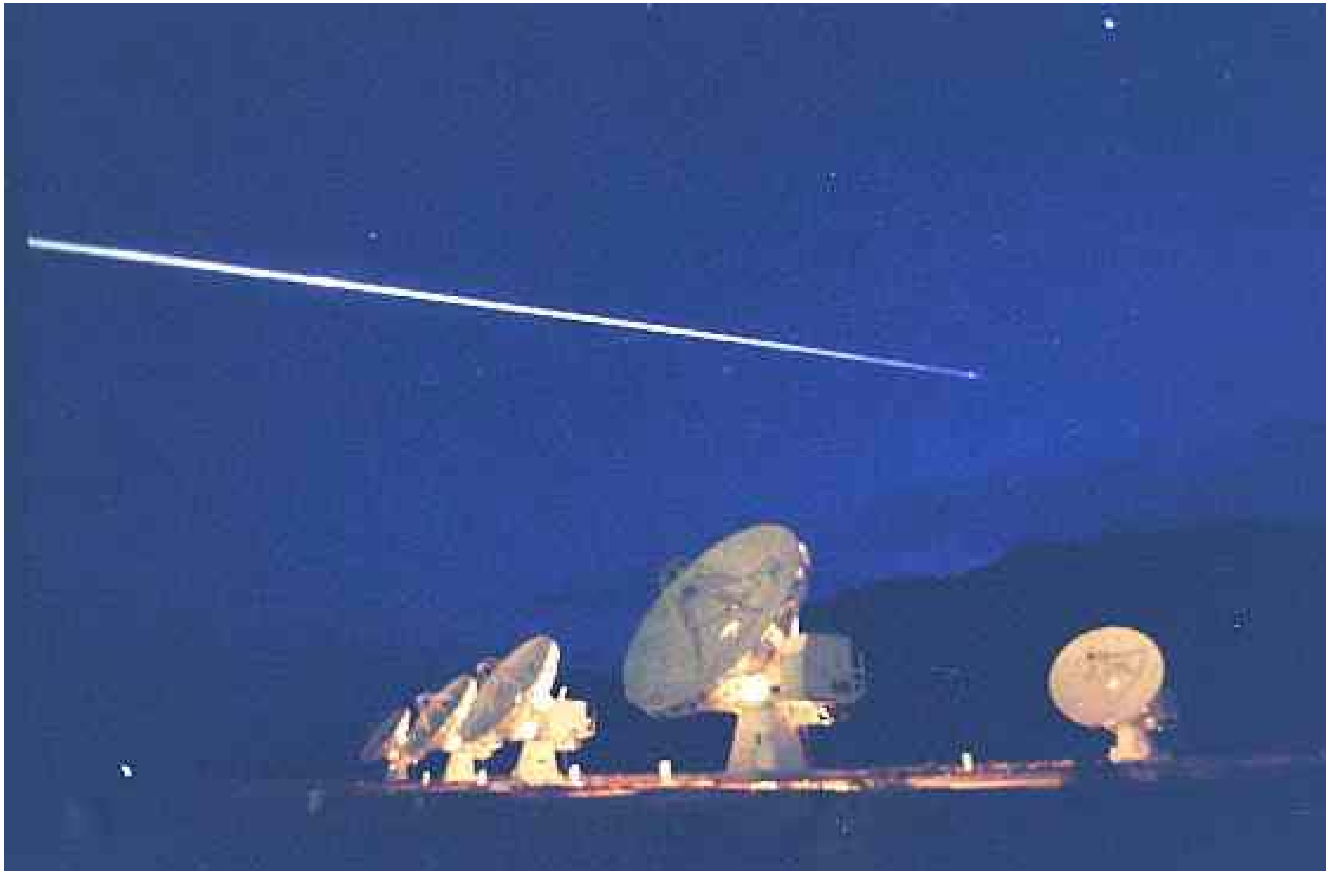
Luminosity Working Group:

David Bretz-JSC
Gregory Byrne-JSC
Bill Cooke-MSFC
Cindy Evans-JSC
Doug Holland-JSC
Kira Jorgensen-JSC
Joseph Olejniczak-AMES
George Raiche-AMES
Julie Robinson-JSC
Nicole Stott-JSC
Rob Suggs-MSFC
Wes Swift-MSFC
Robert Youngquist-KSC

Re-entry Video Sparks, Nevada

QuickTime™ and a
decompressor
are needed to see this picture.

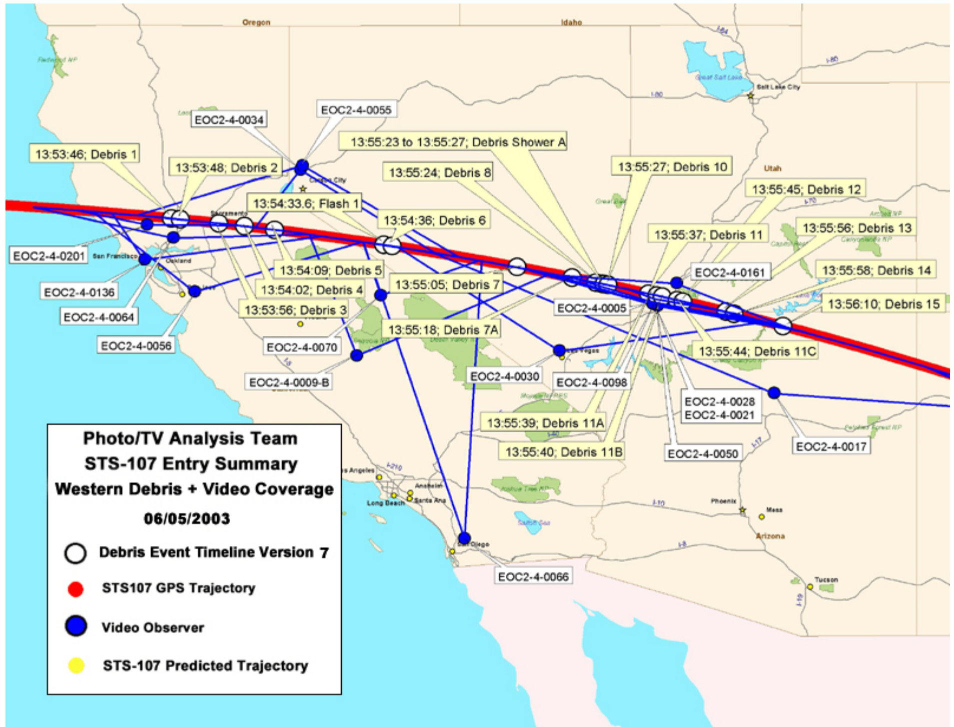
Columbia Debris Characterization Using Re-entry Imaging



More than 140 videos and hundreds of still images were sent to NASA documenting the Columbia's re-entry over the western U.S.

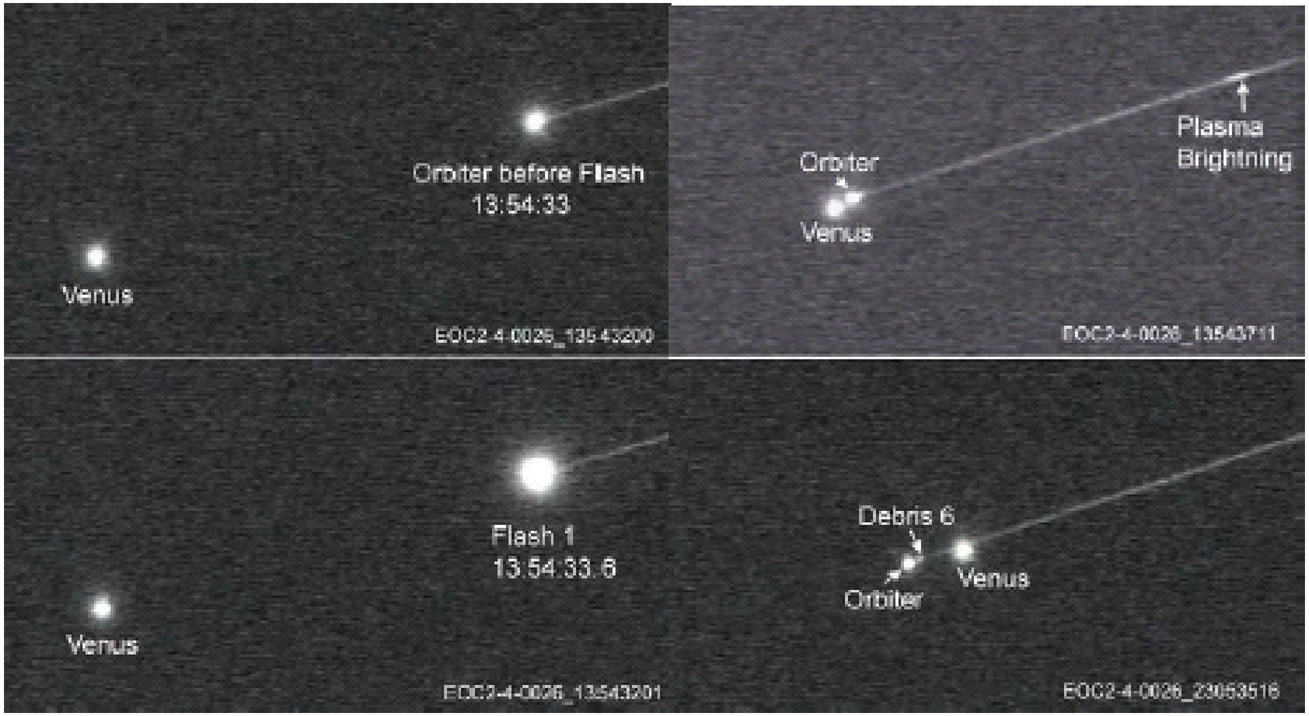
Picture from Owens Valley, Ca.

Columbia Debris Characterization Using Re-entry Imaging



NASA personnel catalogued, reviewed, and prioritized these images and soon realized that there were more than a dozen “debris events” captured in the videos. As part of the Columbia investigation a team was assembled with the task of characterizing this debris, using the video recordings, in any way possible. Of key importance was the size, mass, and composition of each debris event in order to understand the breakup of Columbia.

Columbia Debris Characterization Using Re-entry Imaging



Debris event 6. Images from Sparks, Nevada looking southeast.

So what information is available from one of these videos?

1. In some cases the brightness of the Orbiter, plasma trail, and debris can be found.
2. If field of view is known, then the relative position of the debris can be calculated.
3. In some limited cases color information is available.

Columbia Debris Characterization Using Re-entry Imaging

As objects decelerate in the upper atmosphere, most of their lost kinetic energy goes into the atmosphere—not into the object—and a small portion of this energy is radiated as visible light.

In general, the amount of light generated is a complicated function of the object's mass, velocity, shape, composition, none of which we know for the pieces of debris.   But a starting assumption can be considered:

For a given location and speed, the amount of light generated by an object is proportional to the amount of energy it is giving up to the atmosphere.

This assumption has limitations and issues, but it is a reasonable first try.

Columbia Debris Characterization Using Re-entry Imaging

So, we obtain the following relation

$$\frac{P_{D\_optical}}{\frac{\partial}{\partial t}\left(\frac{1}{2}m_D\vec{v}_D^{\,2}\right)} = \frac{P_{O\_optical}}{\frac{\partial}{\partial t}\left(\frac{1}{2}m_O\vec{v}_O^{\,2}\right)}$$

Where

P = optical power, m = mass, v is velocity, and the subscripts D and O refer to a given piece of debris and the Orbiter respectively.

If we assume 1) no ablation then mass is constant in time and 2) all velocities and decelerations, a, are co-linear and recall that the two velocities are equal, this reduces to

$$\frac{P_{D\_optical}}{(m_D a_D)} = \frac{P_{O\_optical}}{(m_O a_O)}$$

Columbia Debris Characterization Using Re-entry Imaging

Which allows us to solve for the debris mass yielding

$$m_D = m_O \left(\frac{P_{D\_optical}}{P_{O\_optical}} \right) \left(\frac{a_O}{a_D} \right)$$

Where we now need to determine

1) The mass of the Orbiter (provided 106,000 kg)

2) The Orbiter deceleration (provided by Trajectory team, 3.02 m/sec^2 for debris 6)

3) The debris deceleration at the time of separation, and

4) The ratio of the debris brightness to the Orbiter brightness at the time of separation (this is the primary challenge).

Columbia Debris Characterization Using Re-entry Imaging

Debris Deceleration at the Time of Separation-1

We need to know the debris deceleration at the time of separation. For debris 6 we do have good trajectory data (seen from Springville California) and so we can try to fit to this data.

Assume the usual formula for aerodynamic drag force

$$F_{drag} = A_{eff} \rho v_D^2$$

Where ρ is the density of the air and A_{eff} is an effective area for the debris. This then simplifies to a formula for the deceleration where

$$a_D = B v_D^2$$

where

$$B = \rho A_{eff} / m_D$$

Columbia Debris Characterization Using Re-entry Imaging

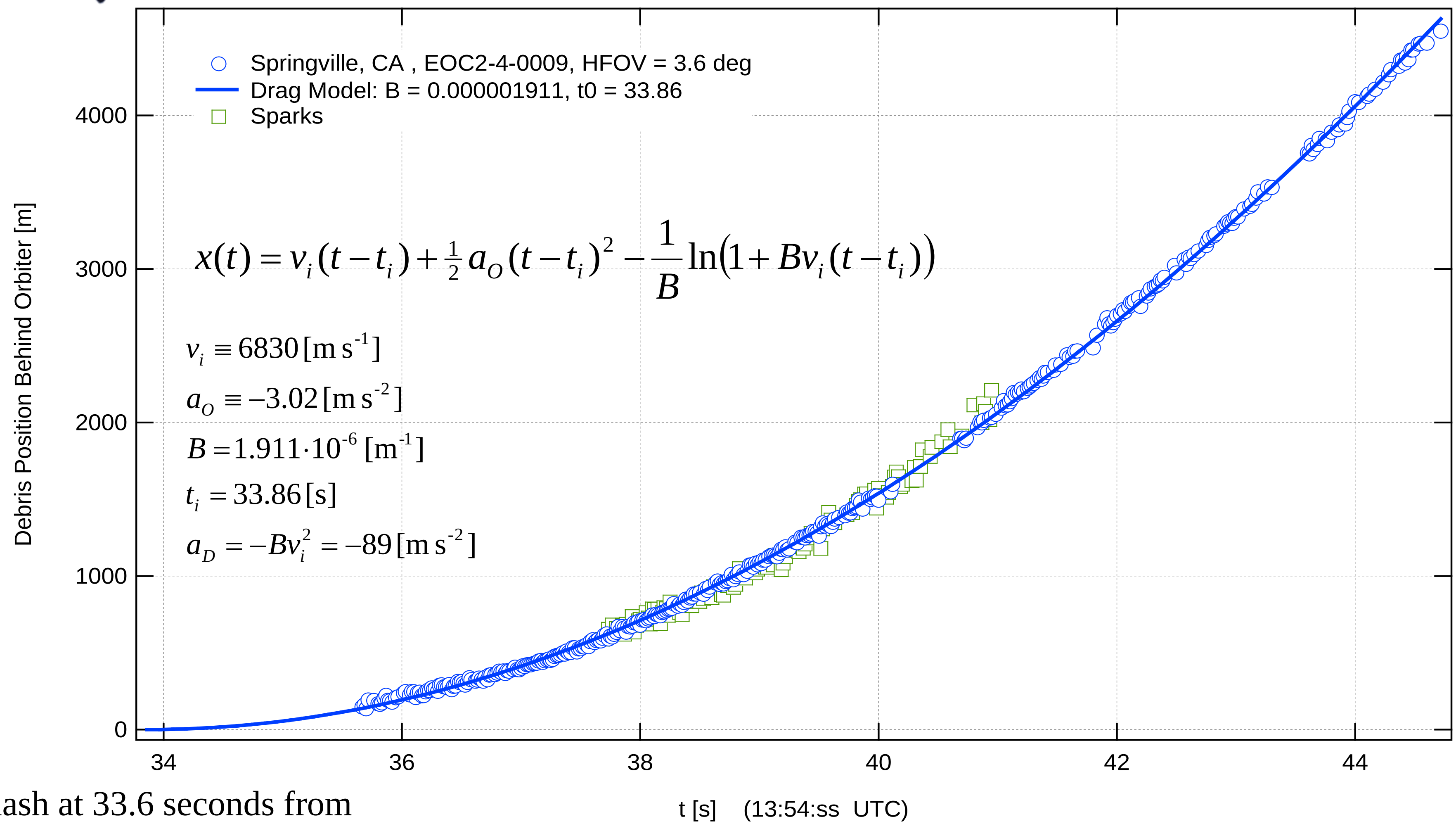
Debris Deceleration at the Time of Separation-2

This nonlinear differential equation can be solved in closed form and integrated to yield an equation for the distance, *x*, of the debris behind the Orbiter:

$$x = v_i(t - t_i) + (1/2)a_O(t - t_i)^2 - \log(1 + B(t - t_i)v_i)/B$$

Where v_i and t_i are the velocity and time when the debris separates from the Orbiter. We know the velocity of the Orbiter versus time, so the only free parameters in this equation are the separation time and B.

Columbia Debris Characterization Using Re-entry Imaging



Flash at 33.6 seconds from Sparks video.

Debris distance behind the Orbiter, theoretical fit versus observation.

Columbia Debris Characterization Using Re-entry Imaging

Debris Deceleration at the Time of Separation-4

Findings:

1) A surprisingly good fit of theory to observation.

2) The time of separation is found to be 13:54:33.9 GMT.

3) The Orbiter velocity at that time was 6830 m/sec.

4) The value for B is found to be $1.91 \times 10^{-6}\ m^{-1}$ yielding a

deceleration for debris 6 = 89 m/sec^2

5) Debris 6 separated from the Orbiter at the time of the Flash to within timing errors. This is suggestive that the Flash event is associated with the separation of this debris from the Orbiter. Come back to this later.

Replay Sparks mpeg describing the separation of the debris long ahead of its appearance, optical resolution is important to upcoming slides.

New slide showing optical power versus area. Neat relation!

<u>But we still need the brightness ratio of the debris to the Orbiter</u>

Brightness Ratio of Debris to Orbiter-1

The problem is:

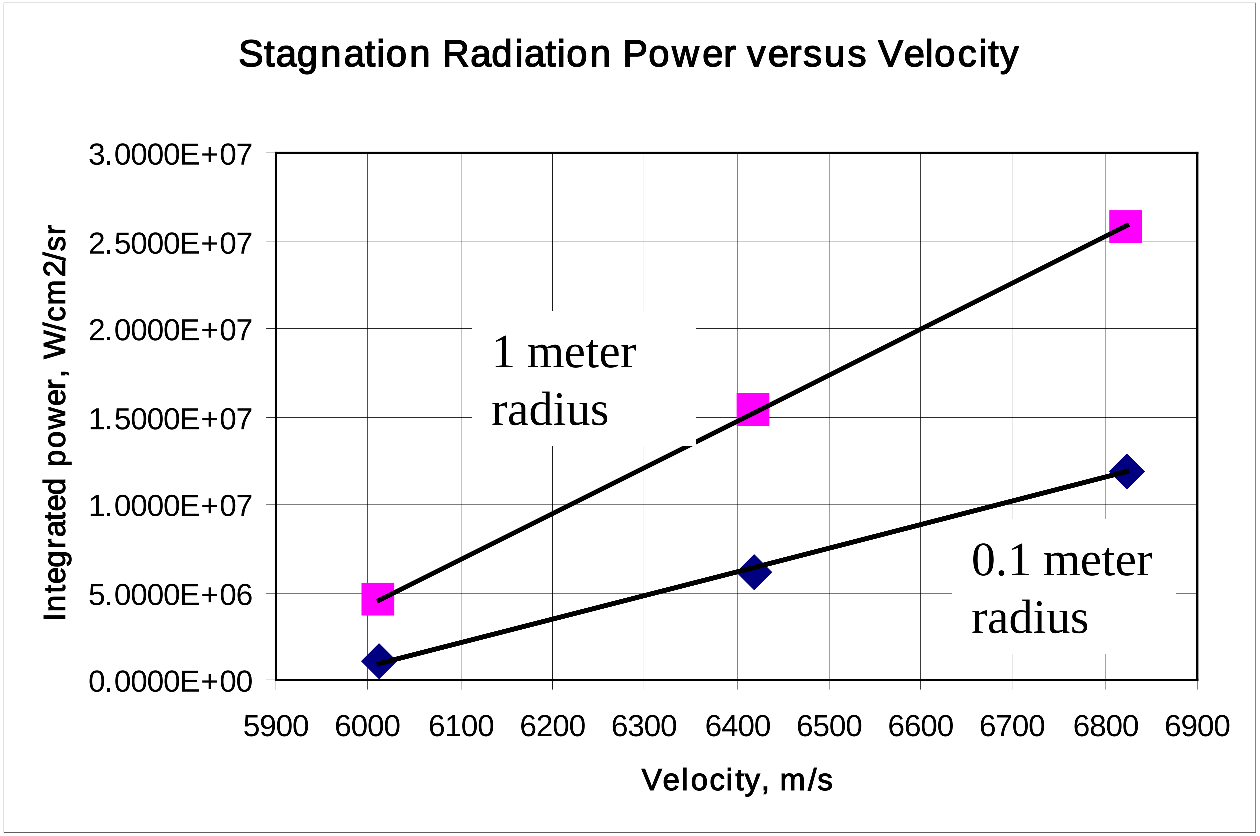
> We need to know the brightness of the debris relative to the Orbiter at a time when it is not resolvable from the Orbiter itself and when the Flash event is occurring.

This might seem to be an insurmountable problem, since we can only determine debris to Orbiter ratios when the two are optically resolvable, but the supercomputers at AMES came to the rescue.

Theoretical analysis (shown on the next page) showed that in this velocity regime that the radiated optical power was linearly proportional to the velocity. It also predicted that the debris would go dark at a speed of about 5850 m/sec. Both predictions matched the observations so we used a linear extrapolation of the data we had to obtain the brightness ratio at the time of separation.

Columbia Debris Characterization Using Re-entry Imaging

Brightness Ratio of Debris to Orbiter-2



Radiated Power for two spheres as a function of velocity demonstrating a linear relationship.

Columbia Debris Characterization Using Re-entry Imaging

Brightness Ratio of Debris to Orbiter-3

NASA purchased or borrowed many of the actual camcorders used to take the videos. These were taken to JSC where Neptec generated calibration tapes using a variable star system developed by MSFC, but while this was going on four other image processing methods were used to try and determine the needed brightness ratios.

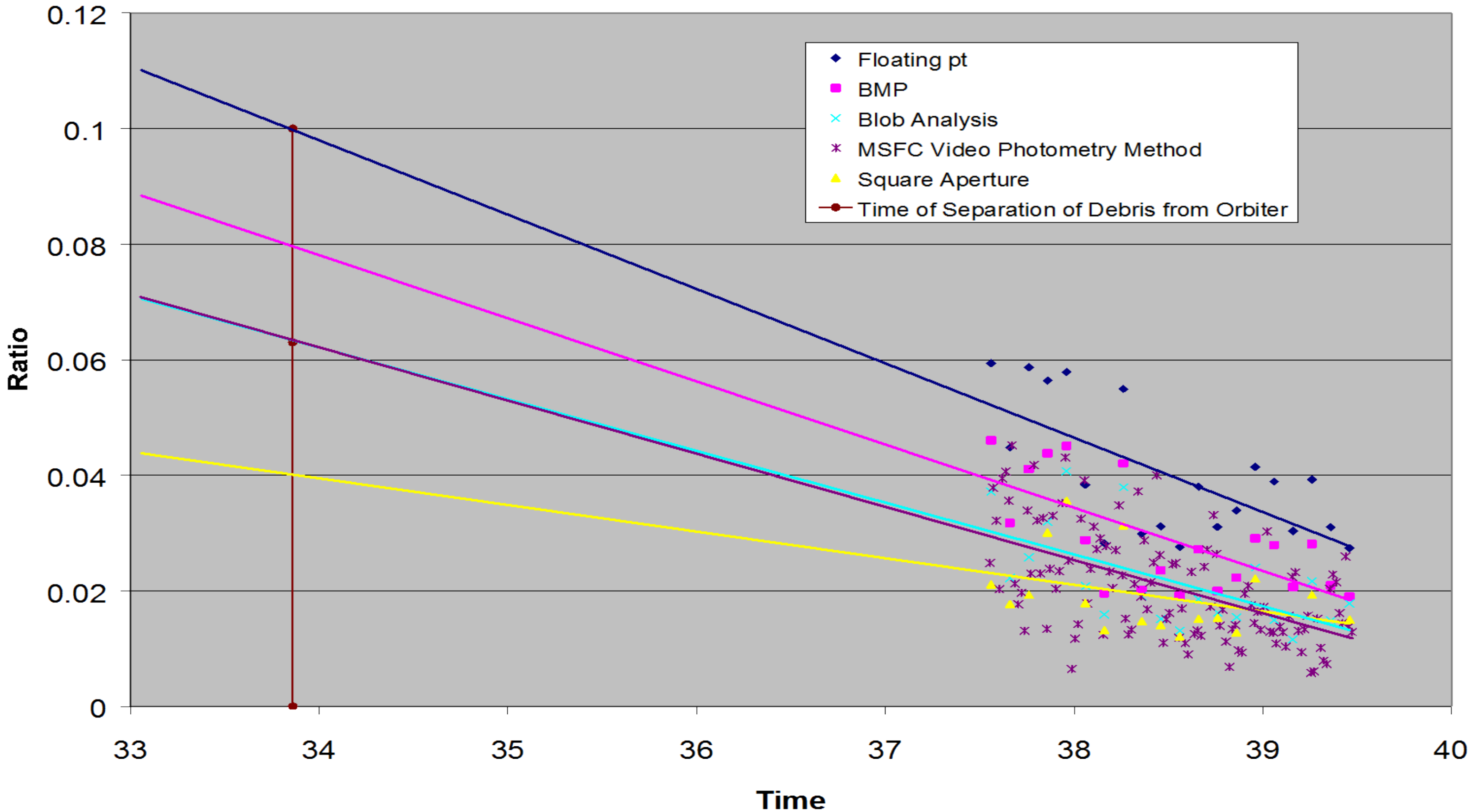
JSC developed "Blob" and a "Square Aperture" Analysis Techniques

MSFC developed a BitMap technique and a Floating Point Analysis technique.

MSFC also developed a Video Photometry Method that used the calibration tapes generated by Neptec.

Columbia Debris Characterization Using Re-entry Imaging

Brightness Ratio of Debris to Orbiter-4

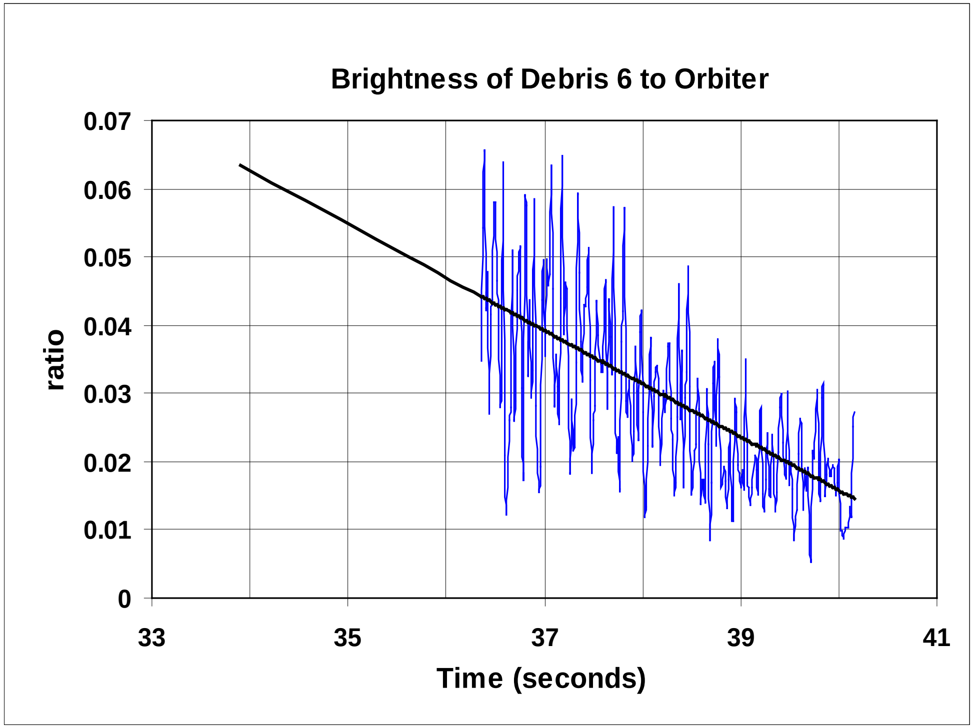


Comparison of five different image processing methods applied to the debris 6 Springville video and linearly back projecting to obtain a brightness ratio at time of separation. (assumes the Orbiter brightness is relatively constant).

Columbia Debris Characterization Using Re-entry Imaging

Brightness Ratio of Debris to Orbiter-5

The data is very random, but this is real and expected. Assuming an object broke away from the Orbiter we would expect it to be rapidly spinning, exposing different surface to the atmosphere and generating widely varying amounts of light. But even so, the averaged aerodynamic effect led to excellent agreement with trajectory analysis and we would expect similar averaging to yield a useful result for light generation.



So from the data we predict a debris to Orbiter optical power ratio of between 0.04 and 0.1 with the calibrated tape method yielding 0.063, between the two extremes.

Columbia Debris Characterization Using Re-entry Imaging

Debris 6 Mass = (106,000 kg) (3.02/89)(0.063)=226 kg (500 lbs)!

This number was received with disbelief, but no conflict with other data was known.

Consider the following Quote from the Columbia Accident Investigation Board (CAIB) (debris event 6 occurred at Entry Interface Time (EI) 601 seconds):

"At EI-602, the tendency of the Orbiter to roll to the left in response to a loss of lift on the left wing transitioned to a right-rolling tendency, now in response to increased lift on the left wing."

The loss of debris 6 was significant enough to substantially change the aerodynamics of the Orbiter left wing! But the structural engineers insisted that nothing of this mass could have come off of the left wing so we began to consider refinements to the model.

**Aside—assuming an atmospheric density, $\rho=7.3\text{x}10^{-5}\text{kg/m}^3$ an effective area for debris 6 can be found, $A_{eff}= B\ m_D/\ \rho = 6\ m^2$.

Columbia Debris Characterization Using Re-entry Imaging

Ablation

If we assume debris 6 is ablating, the above analysis must be modified. Not only is the mass now a function of time, but the ablated material generates additional light.

Small particles and molecules decelerate quickly giving up most of their kinetic energy to the atmosphere. If we assume that this kinetic power generates light in the same ratio as the Orbiter and debris (a very suspect assumption), then we can show a significant reduction in the debris mass.

First—redo the trajectory analysis with a time varying mass. A best fit for debris 6 shows a 2% reduction in mass per second.

Second—accounting for the extra light generated by the ablating material yields a reduced mass for debris 6 of

86.5 kg (190 lbs) , the value quoted in the CAIB.

(note that this result assumes the lower extrapolated brightness ratio, 0.04. A value of 140 kg or 310 lbs, is comparable to the earlier result. So ablation can yield a 40% mass reduction.)

Columbia Debris Characterization Using Re-entry Imaging

Other Thoughts on the Model

1) Perhaps the debris is far less aerodynamic than the Orbiter. An alternative model, assuming the debris is a non-ablating flat disk with maximum air resistance moving at constant velocity, predicts a minimal mass for debris 6 of 7.4 kg. This provides an absolute lower bound and refutes those who thought that debris 6 was a single tile.

2) Aerodynamic effects might be important. Comparison of a rough piece of debris to the "aerodynamic" Orbiter may alter the predictions, but without any information on the debris shape or composition it is difficult to know how to modify the model.

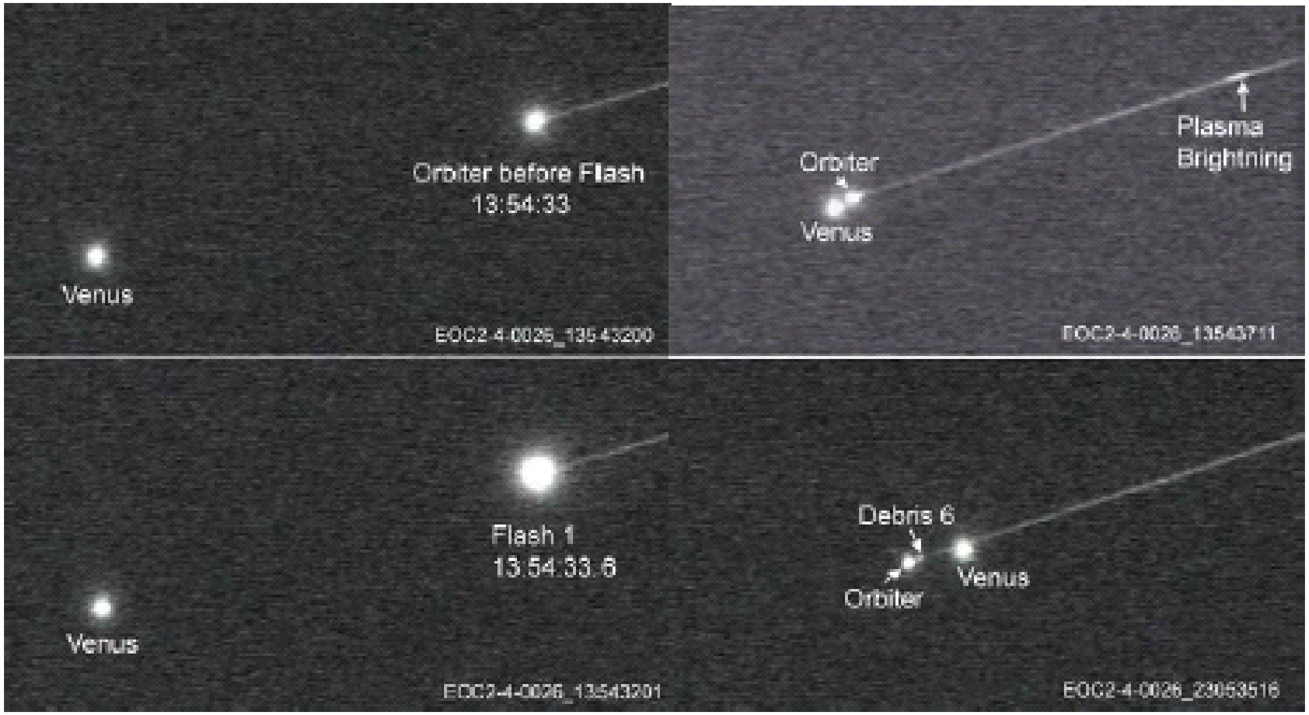
3) Blackbody radiation, while not significant for the Orbiter, may be significant for the debris, especially for small pieces of debris with larger area to mass ratios.

4) Viewpoint might be important. Observers watched the Orbiter and debris from very different locations and possibly light blockage by the structures could affect the results.

5) Material ablation might alter the generation of light in the atmosphere.

Columbia Debris Characterization Using Re-entry Imaging

So What is the Flash ?

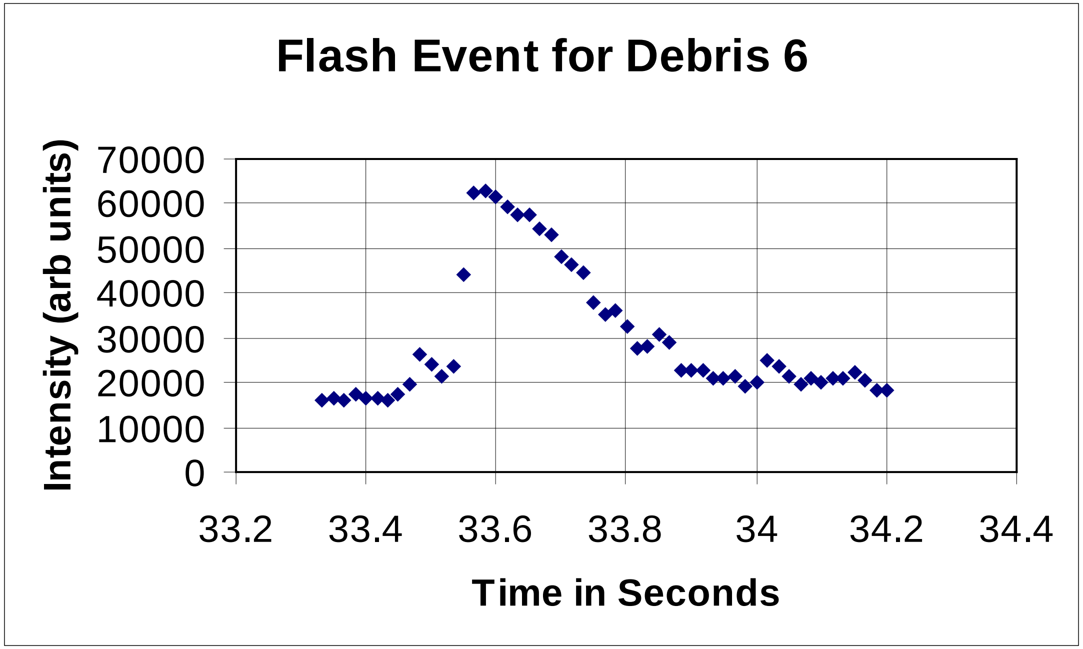


For a brief time the Orbiter becomes three times brighter and then leaves behind a brightened plasma trail. The brightened plasma trail indicates that the Flash is an atmospheric interaction similar to the Orbiter's interaction with the atmosphere.

This Flash is not unique. Flashes can be seen occurring at the separation time for several other debris events.

Columbia Debris Characterization Using Re-entry Imaging

So what is the Flash ?



This is an intensity plot of the Orbiter during the Flash event. The Orbiter gets very bright in about 0.1 seconds and then drops back down to a slightly higher level during the subsequent 0.3 seconds.

Columbia Debris Characterization Using Re-entry Imaging

So what is the Flash ?

Hypothesis: The Flash event is caused by the release of many small particles into the atmosphere when debris 6 separated from the Orbiter.

Argument:

1) Small particles will decelerate rapidly, giving up their kinetic energy to the atmosphere and thus generating light.

2) The subsequent atmospheric luminosity will be greater, i.e. there will be a brightening of the “plasma” trail.

3) If debris 6 is a large piece of the left wing it would be expected that thermal protection material would be shed when it broke away.

4) Both blankets (on the top) and tile (on the bottom) would produce a cloud of small particles. But blanket material is already shredded and is the more likely candidate.

Columbia Debris Characterization Using Re-entry Imaging

So What is the Flash ?

Two different attempts were made to estimate the amount of mass associated with the Flash event.

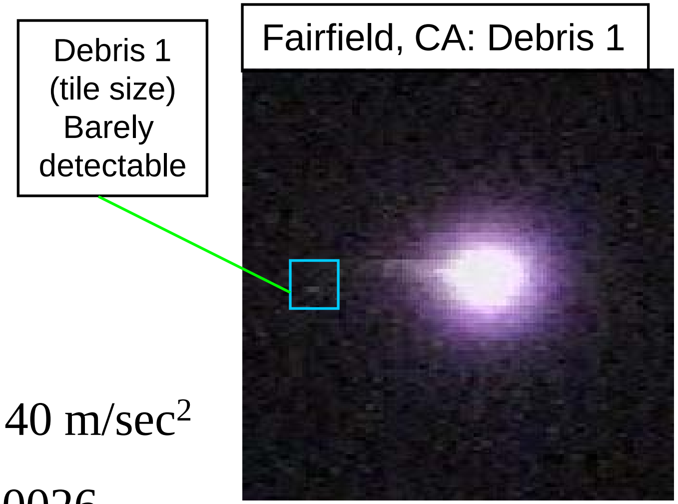
Attempt 1: Assume that the particles generate the same light per kinetic energy as does the Orbiter (a questionable assumption, but one which allows straightforward analysis). In this case the total mass ejected is about 75 kg.

Attempt 2: Determine the number of 2 mm radius ablating spheres (density 1gm/cc) that would need to be ejected to match the light curve. After modeling the number is 1.3 million, resulting in a predicted mass of 42.5 kg.

Both numbers are reasonable. Thermal blanket weighs about 5 kg/m^2 so this corresponds to between 8 and 15 square meters of material suddenly shed by the Orbiter, a number not inconsistent with the effective area calculated earlier.

Columbia Debris Characterization Using Re-entry Imaging

Debris Events-Number 1



Need mpeg for Debris event 1

Results:

Short duration yields a deceleration of 280 m/sec^2 +/- 40 m/sec^2

Image analysis indicates a brightness ratio of 0.0016-.0026.

<u>So the nonablative mass is between 1 and 3 kg.</u>

Ablative trajectory fits indicate possible ablation as high as 27% per second yielding

<u>an ablative mass of 0.2 kg.</u>

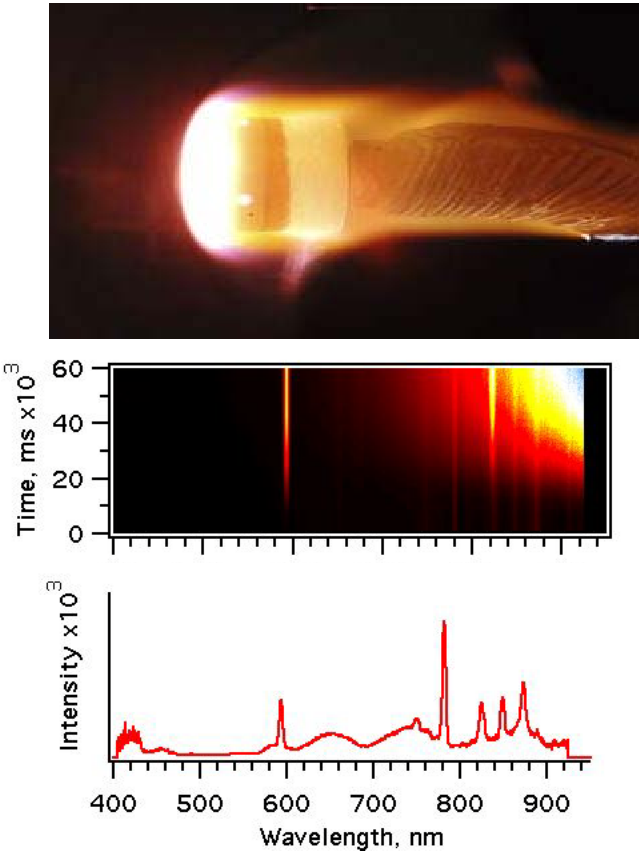
A lower limit for the mass using a non-ablating disk is 0.057 kg.

This is a small object, near the minimum detectable limit using the camcorder images.

Columbia Debris Characterization Using Re-entry Imaging

In an effort to resolve a number of open questions arc-jet testing was performed at AMES.

Test samples were exposed to an environment similar to that of the Orbiter at the time of debris 6. Items such as RCC (coated and uncoated), various tiles, blanket, aluminum (with and without primer), and a reference copper block were tested and the subsequent spectral emission versus time was measured.



NASA-ARC arc jet test of RCC (top), with spectral analysis of surface (center) and bow shock (bottom) emission, in support of Columbia debris image analysis

Columbia Debris Characterization Using Re-entry Imaging

Arcjet Testing Results and Conclusions

1. There does not appear to be a strong dependence of shock layer radiation on material composition. This helps to resolve the earlier concern about brightness versus composition.

2. No material indicated an obvious “flash” phenomenon. However, when uncoated RCC was inserted into the flow, its initial delamination was accompanied by a flash.

3. In these tests, the strongest (dominant) source of optical radiation is black/graybody radiation from the hot model surface. The shock layer radiation is generally weak in comparison. In flight (for an intact orbiter), shock layers would be thicker, and material temperatures would be substantially lower. Even so, blackbody radiation may be a substantial source of radiation in some cases.

4. The coated RCC surface radiated strongly at approximately 590 nm, a feature suggestive of the presence of atomic sodium, but this spectral effect was not seen in the Columbia images.

5. Aluminum did not burn, as suggested by some, nor ablate. It formed a skin, possibly Al_2O_3, and melted within this, sagging into a liquid.

Columbia Debris Characterization Using Re-entry Imaging

Conclusions

A simplistic model applied to amateur videos yielded a surprisingly consistent model predicting not only the size and possible area of debris, but supplying insight into the flash events.

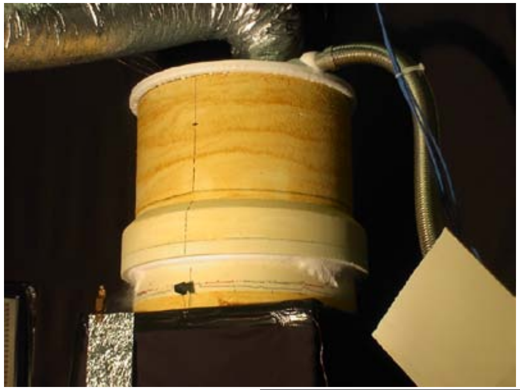
But what about Future Flights?

NASA needs imagery of nominal re-entries for comparison.

NASA needs theoretical analysis of debris light generation during re-entry.

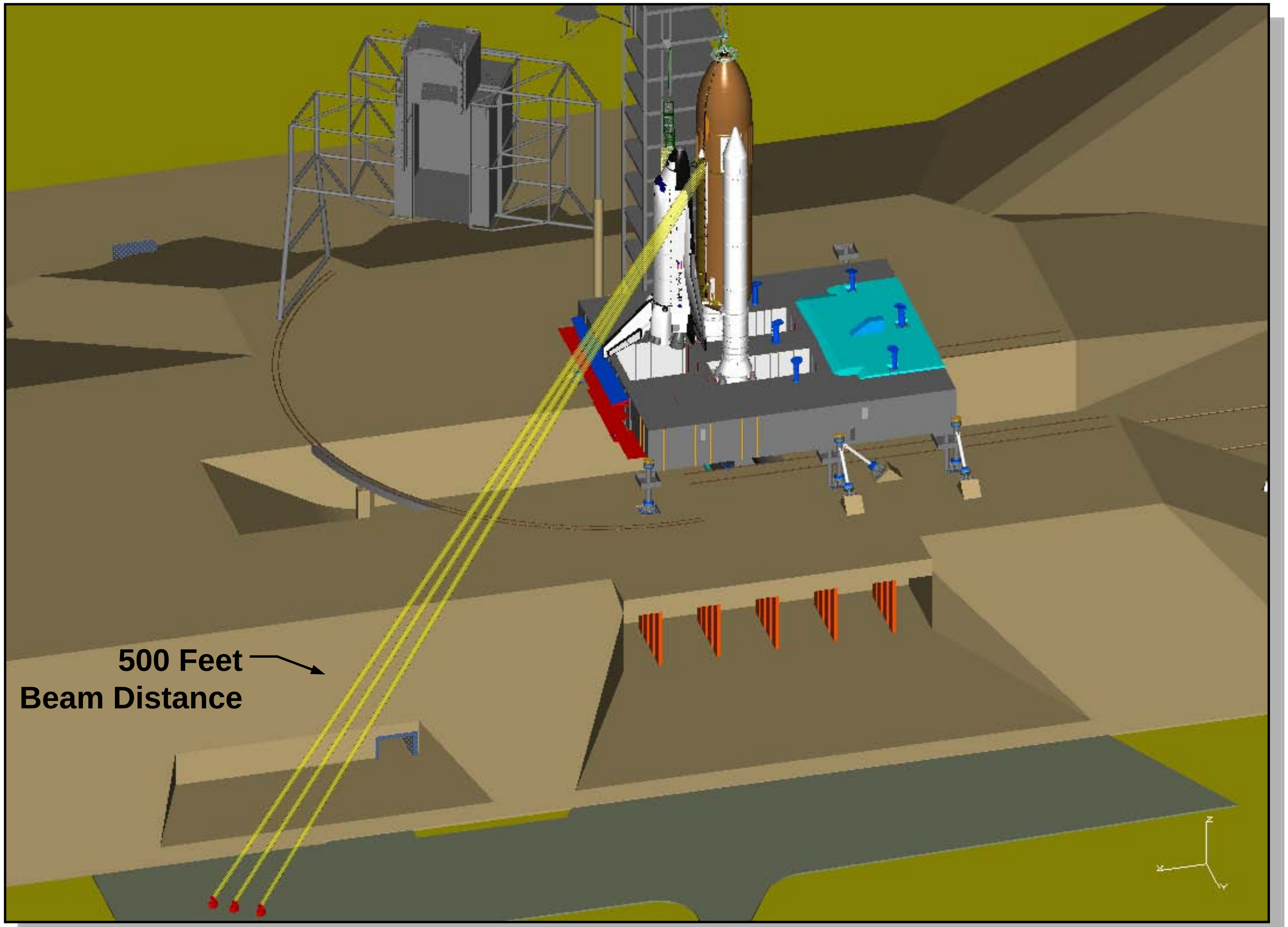
NASA needs to understand re-entry debris signatures and to determine how to best monitor for this under a variety of conditions.

STS-114 Return to Flight



- <u>IR Heat Projection</u> as a Method for Minimizing Condensation and Ice on the External Tank and ET Feedline LOX Bellows and Brackets.

IR Heat Projector System



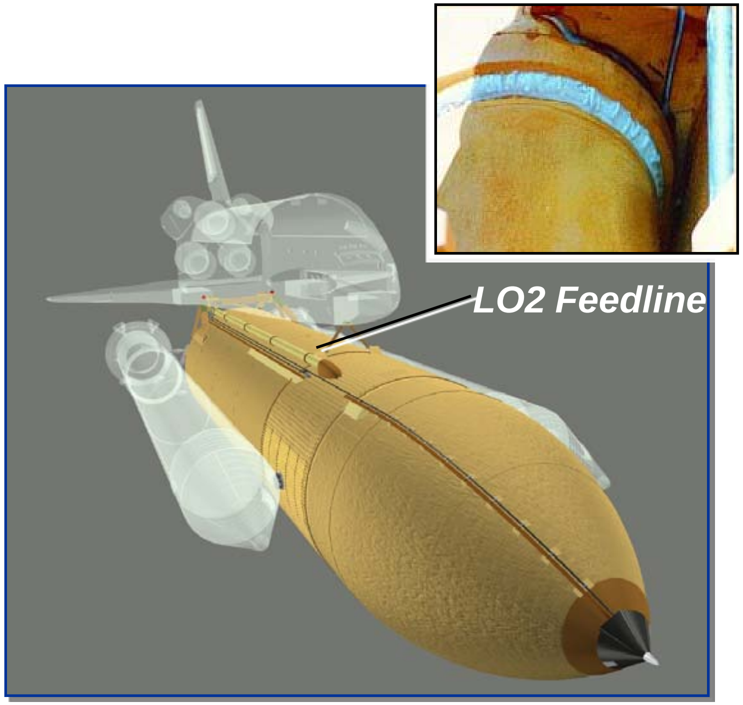
IR heat projectors minimizing condensation on the ET LOX feedline bellows area.

IR Heat Projector System

Background

The LOX Feedline Bellows and Brackets often develop high density ice and are located above the Orbiter's RCC panels on the leading edge of the wings.

This is a serious issue since this ice could break off during ascent and lead to serious Orbiter damage.



The bellows area is covered in foam, but not completely because the bellows must be free to move. Consequently, a small (roughly ½ ") strip of bare metal is exposed to the air around this 17inch diameter line and this is where the ice forms.

The Basic Idea

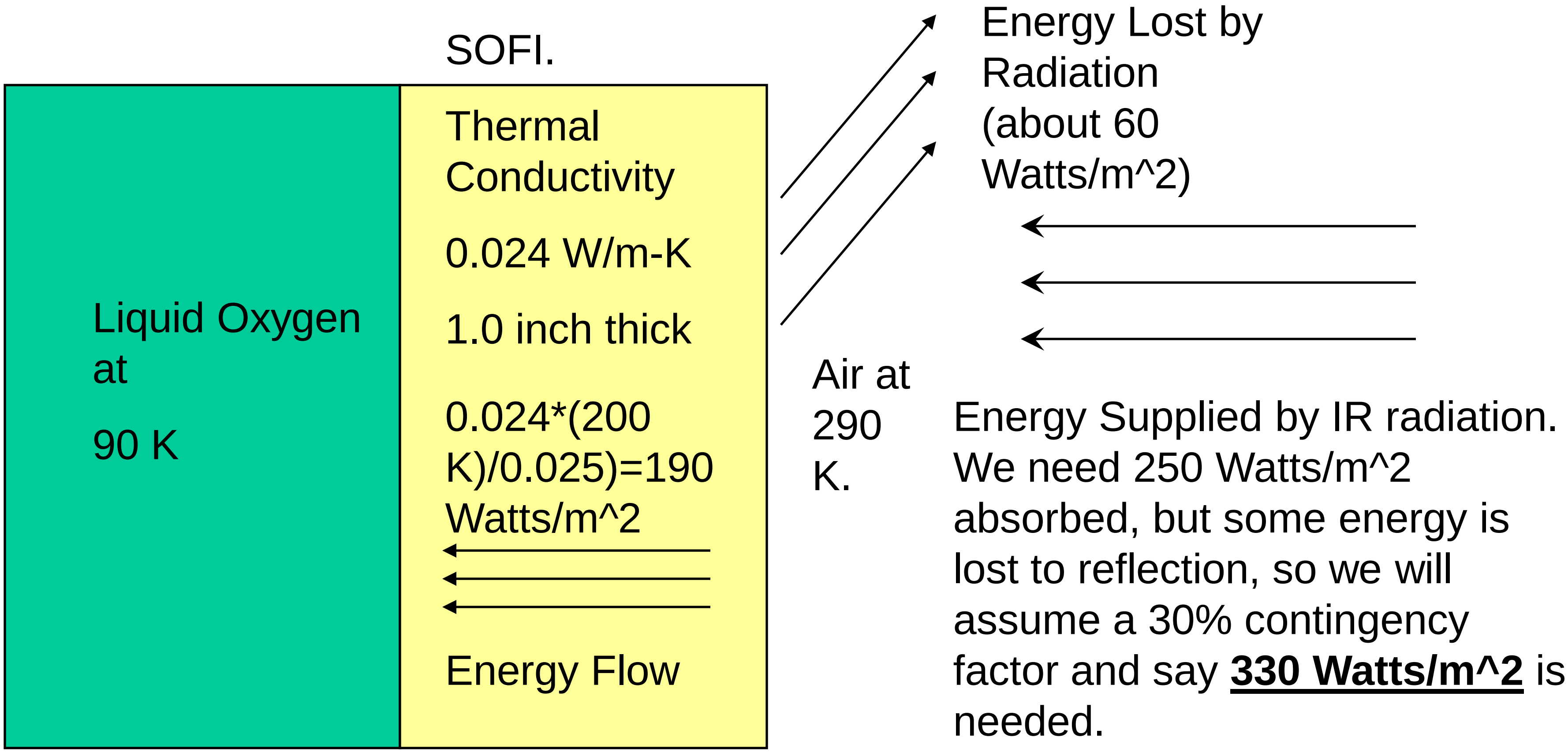
When air comes into contact with a cold surface, it is chilled. If this chilling brings the air below the dew or frost point, condensation in the form of water or frost will occur.

If this condensation runs down the External Tank and reaches the LOX bellows it will freeze into hard ice. So the goal is to prevent ice formation by preventing condensation, i.e. cut off the source of the water.

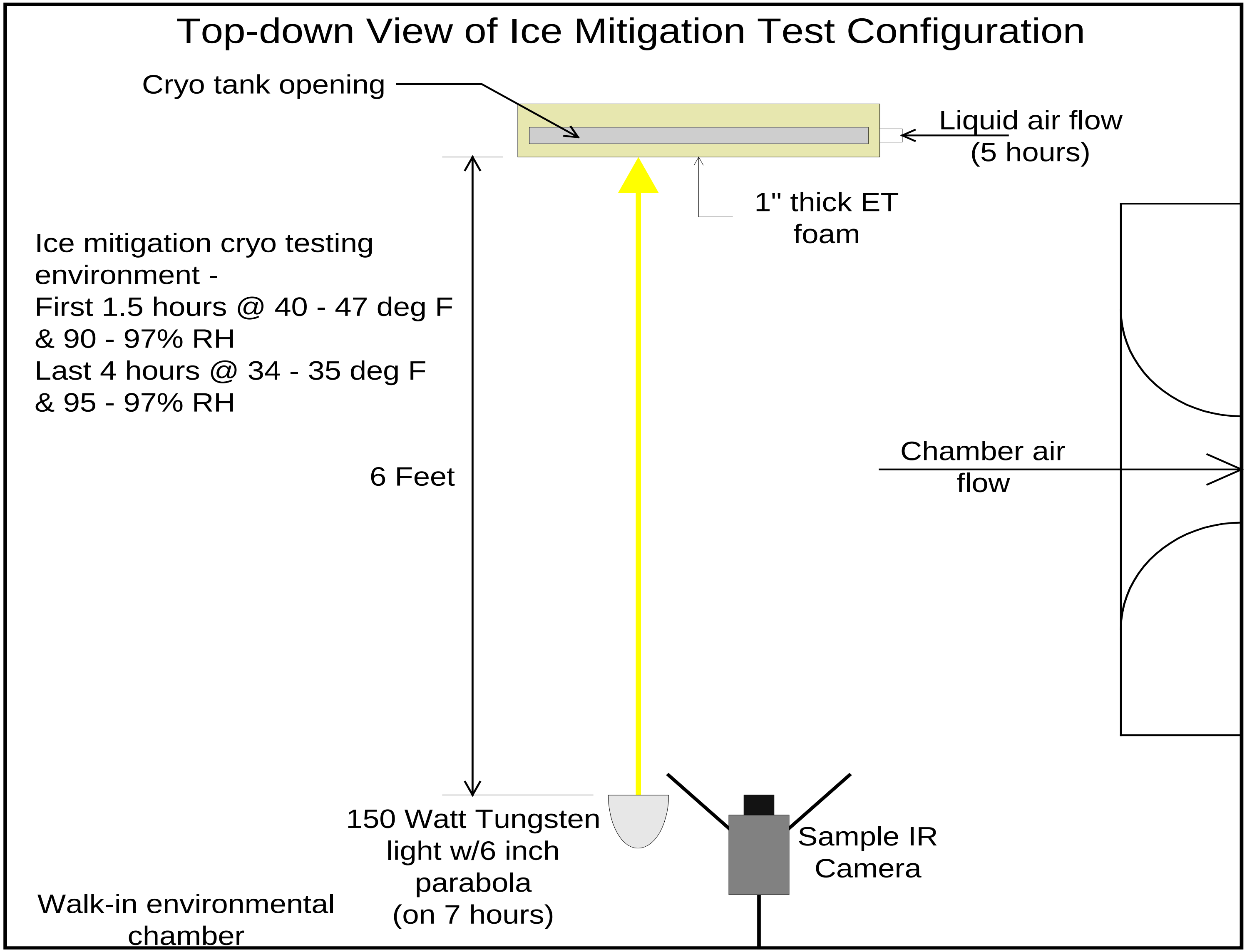
The basic idea is to project heat onto the area around the bellows to keep the foam at ambient (or higher) and thus prevent condensation from occurring.

What Energy Density do we need?

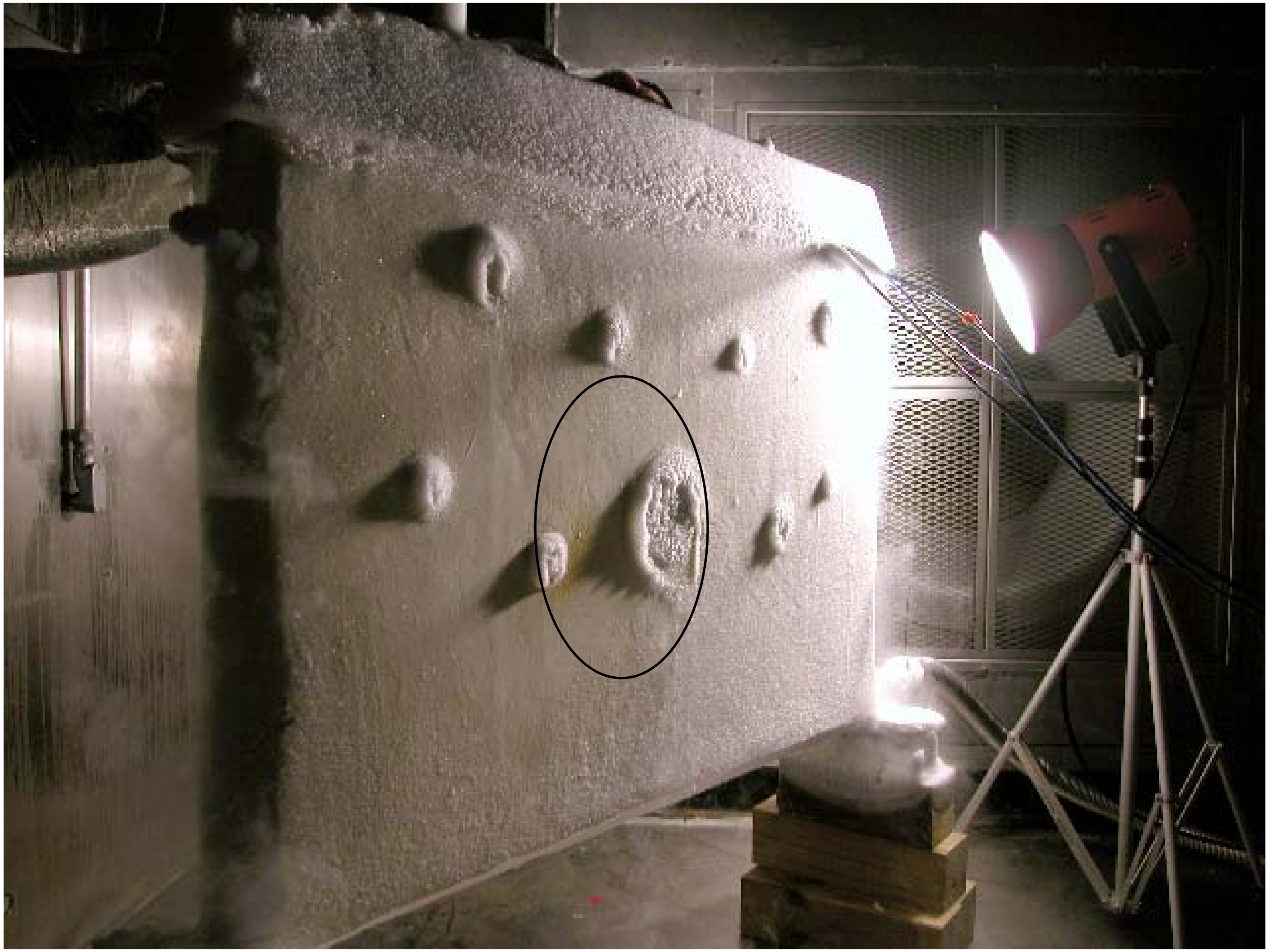
Our goal is to use radiation to hold the foam temperature at ambient to minimize condensation. We need to supply the same or higher energy to the foam than is pulled away by thermal conduction and emission (a detailed analysis has been performed).



Chamber Testing



Testing Results



Frost can be seen on the panel everywhere except in the circled area where the IR lamp radiation was projected.

Testing Tentative Conclusions

- Under the cases tested so far a radiated intensity of 250 Watts/m^2 +/- 50 Watts/m^2 prevents frost formation.
- Illumination of the frost on a stud has not resulted in hard ice formation. Only light frost has appeared on the studs.
- Even under maximum illumination (about 1.6 times solar, or 1600 Watts/m^2) for a period of nearly 20 hours we have not observed any change (degradation) in the foam.

Acreage Heating-How big a Spot?

We will assume that we need to keep a **16 foot** (5 meters) diameter spot dry.

This has been chosen for two reasons: 1) This is achievable with the technology we have and 2) it confines the light to a reasonably well defined area on the tank.

That's 2.5 meter radius with 330 Watts/m^2= 6500 Watts.

We need **6500 Watts** projected into this area from 500 feet away.

External Tank is 27.6 feet in diameter, 154 feet long.

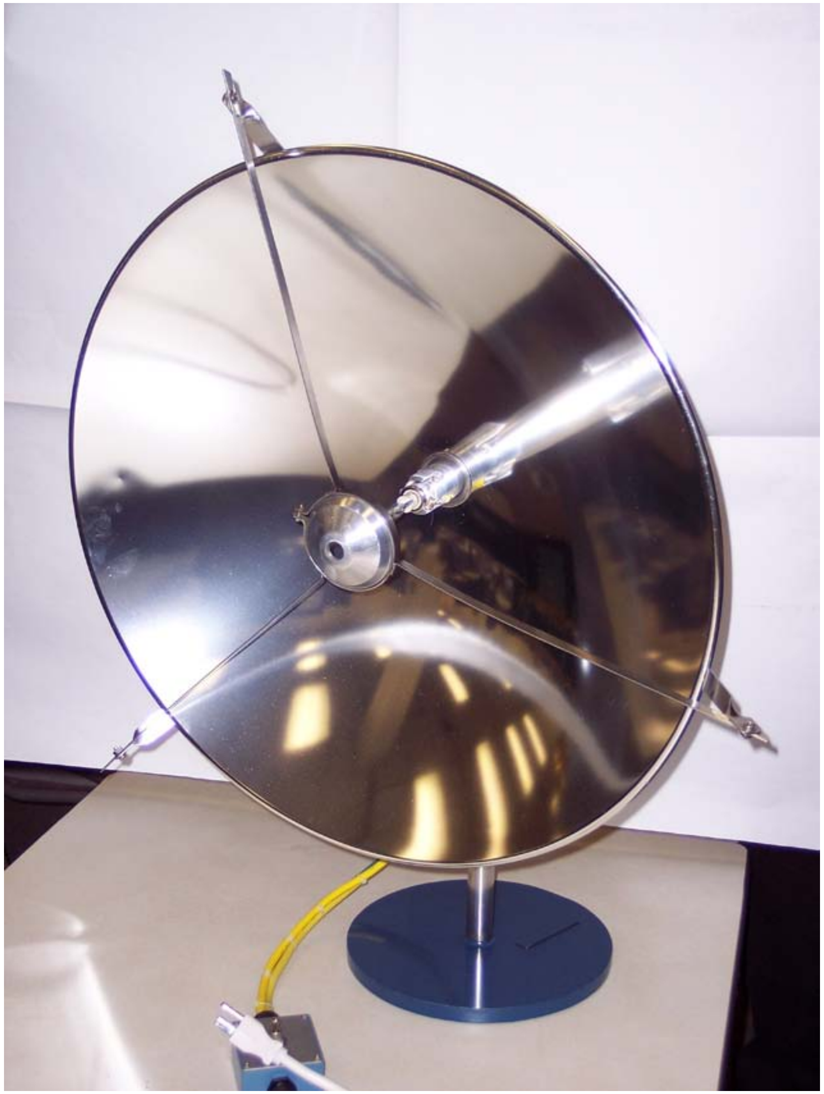
6500 Watts Into a 16 foot Diameter spot

So how do we do this?

We propose to place high wattage bulbs at the focal point of parabolic reflectors and beam the IR energy onto the External Tank.

We have parabolic design code that appears to be correct, so we are using it as a basis for predictions.

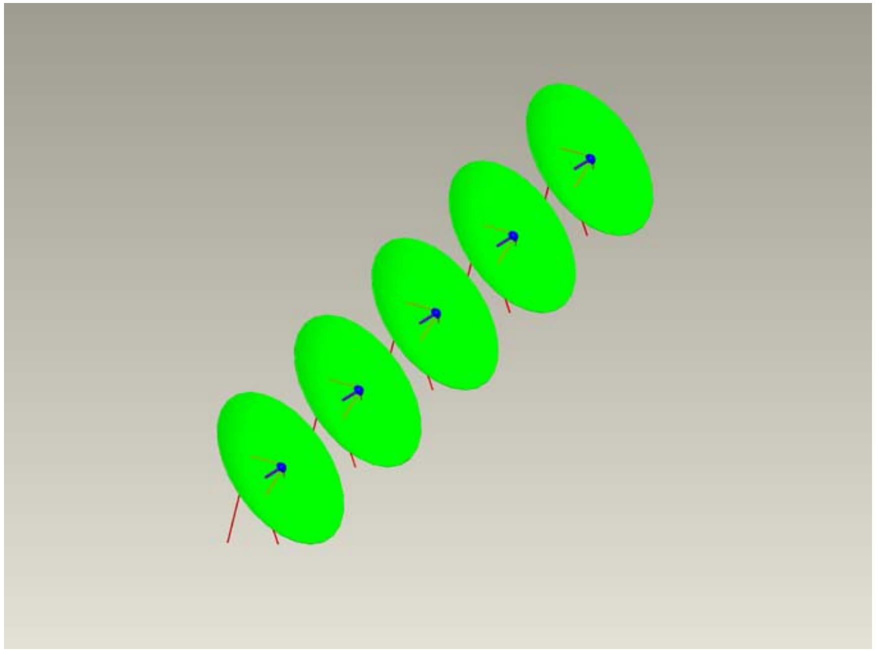
The picture to the right shows a 2-foot diameter prototype system with a 750 Watt bulb.



IR Heat Projector System

An array of parabolas will then be used to project the necessary total radiation onto the External Tank.

The number and size of these parabolas is still to be determined, but we have a decent estimate.



IR Heat Projector System

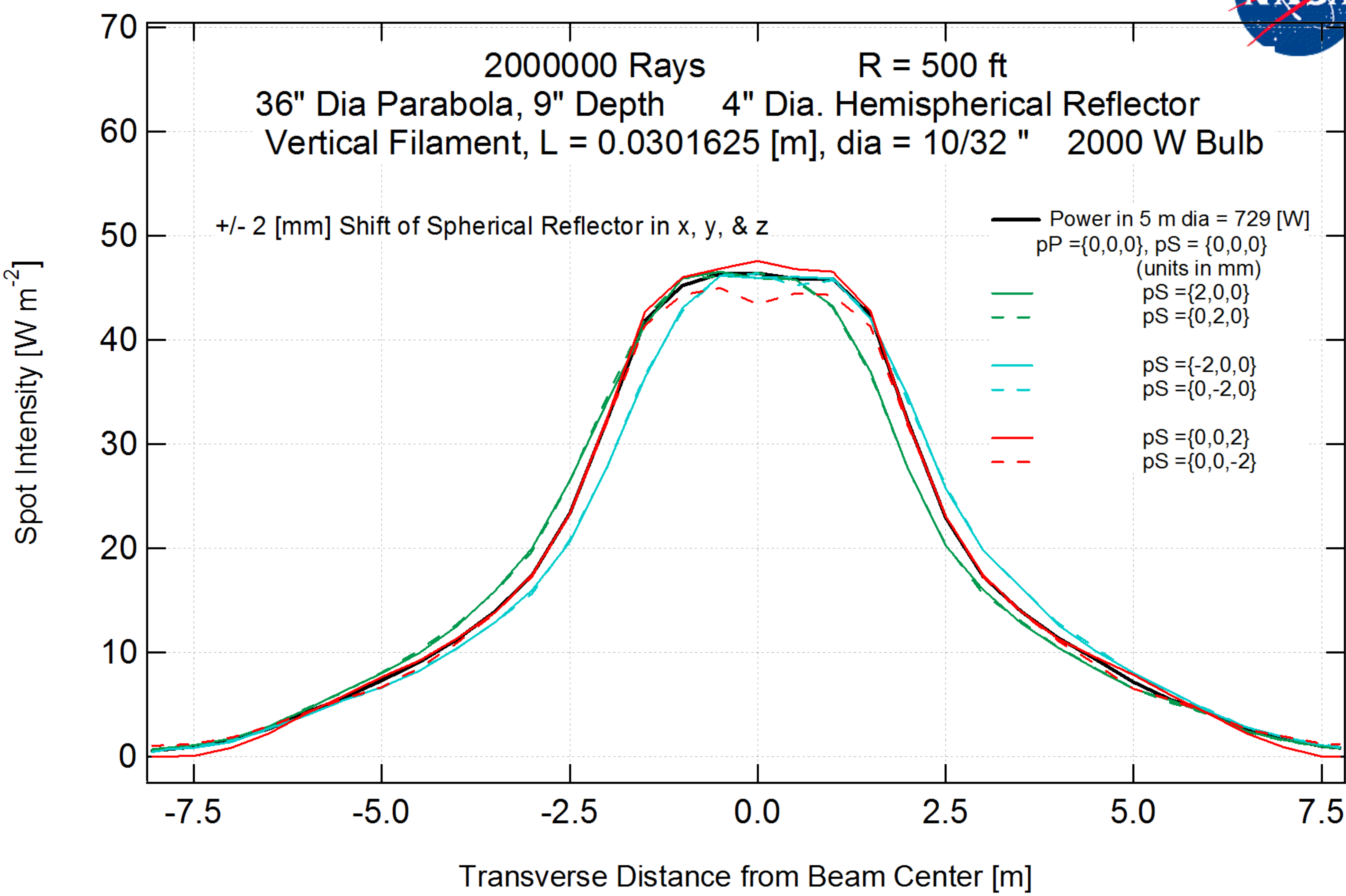
We are proposing to use three foot parabolas for the system.

These parabolas will be polished and mounted on a rugged adjustable alt-azimuth mount.

A three foot diameter parabola with a rough surface.

IR Heat Projector System

We are proposing to use 2000 Watt, 120 Volt bulbs. We have located these as well as the mating sockets. Sufficient quantities can be on hand within two weeks of ordering. The cost is about $100 each for the bulbs and $9 each for the sockets.



2000000 Rays
R = 500 ft
36" Dia Parabola, 9" Depth
4" Dia. Hemispherical Reflector
Vertical Filament, L = 0.0301625 [m], dia = 10/32 "
2000 W Bulb
+/- 2 [mm] Shift of Spherical Reflector in x, y, & z
Power in 5 m dia = 729 [W]
pP ={0,0,0}, pS = {0,0,0}
(units in mm)
pS ={2,0,0}
pS ={0,2,0}
pS ={-2,0,0}
pS ={0,-2,0}
pS ={0,0,2}
pS ={0,0,-2}
Spot Intensity [W m-2]
Transverse Distance from Beam Center [m]
70
60
50
40
30
20
10
0
-7.5
-5.0
-2.5
0.0
2.5
5.0
7.5

IR Heat Projector System

- System was successfully built and tested on schedule.
- System was not implemented due to decision to replace the ET after TT#1.
- New ET had heaters installed at LOX Feedline Bellows.
- System may be used in future to mitigate “ice balls” due to cracks in the foam.

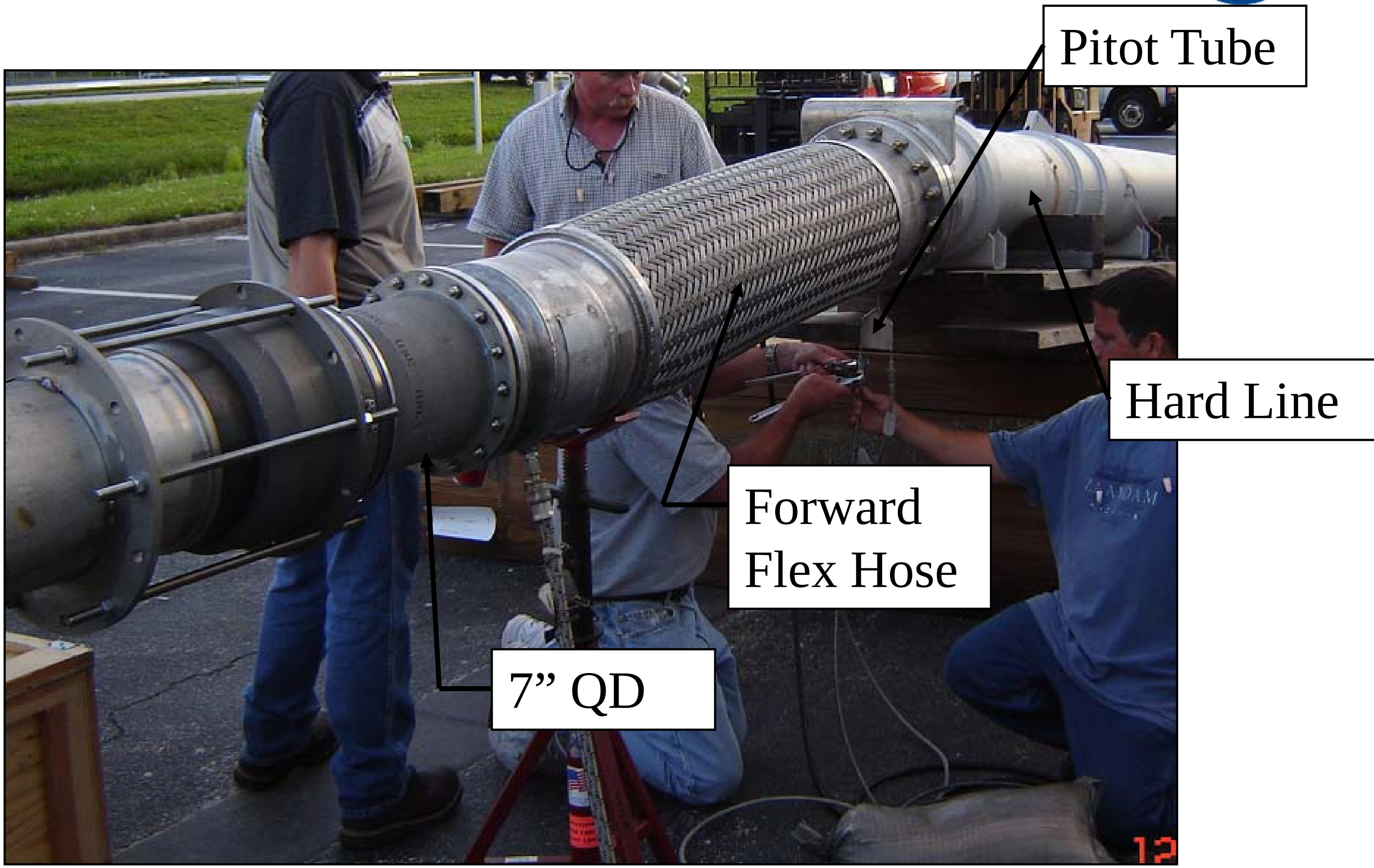
STS-114 Return to Flight

- Second tanking test was required due to unexplained high use of Helium during LH2 tank pre-pressurization.
- APL led a team that developed a Pitot tube instrument to measure possible LH2 vent valve leakage flow.

Pitot for TT#2

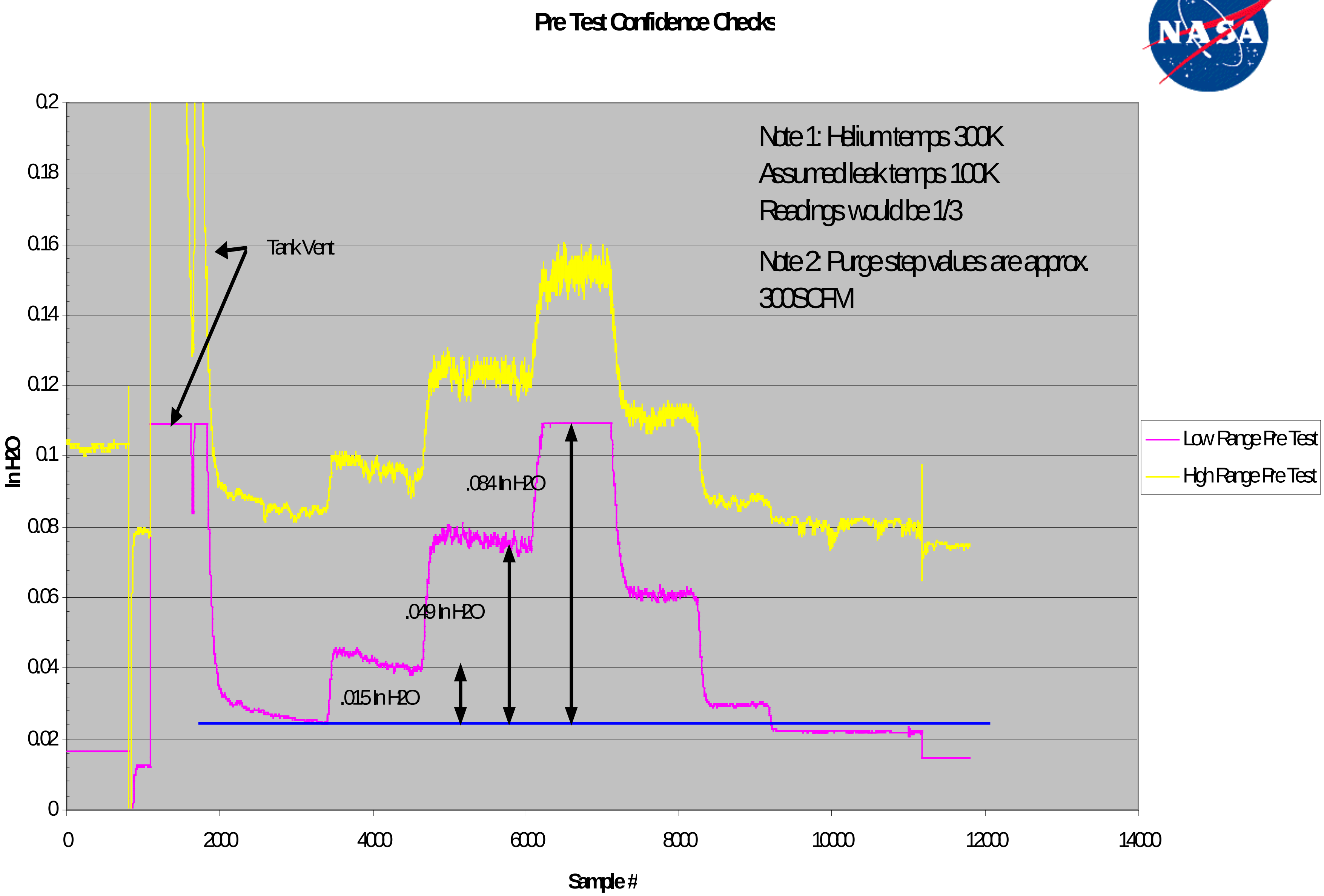
- Excessive He pre-press cycles were experienced during STS-114 tanking test #1 (4/14/05)
- Pitot measurement built and delivered in less than 4 days for TT#2: only measurement of possible vent valve leakage.
- Pitot results confirmed that the ET Vent valve did not leak to within limits of detection.

LETF Test Setup



Transducers and cabling
to GMS2

Pitot spool
piece installed
in Vent line



Helium purges flow through the empty LH2 tank and out vent line

ET He Purge Results

- Measurements tracked to changes in purge flow
- First step was 329 SCFM, measured 264 SCFM using Low Pitot (20% error)
- Second step 329 SCFM, measured 342 SCFM using Low Pitot, (4% error)
- Third step 258 SCFM, measured 233 using High Pitot, (10% error)
  - Low Pitot was at high range of 0.11 inch during peak purge
- Pitot system functioned properly after TT#2 drain

Tanking Test He Pre-press Cycles

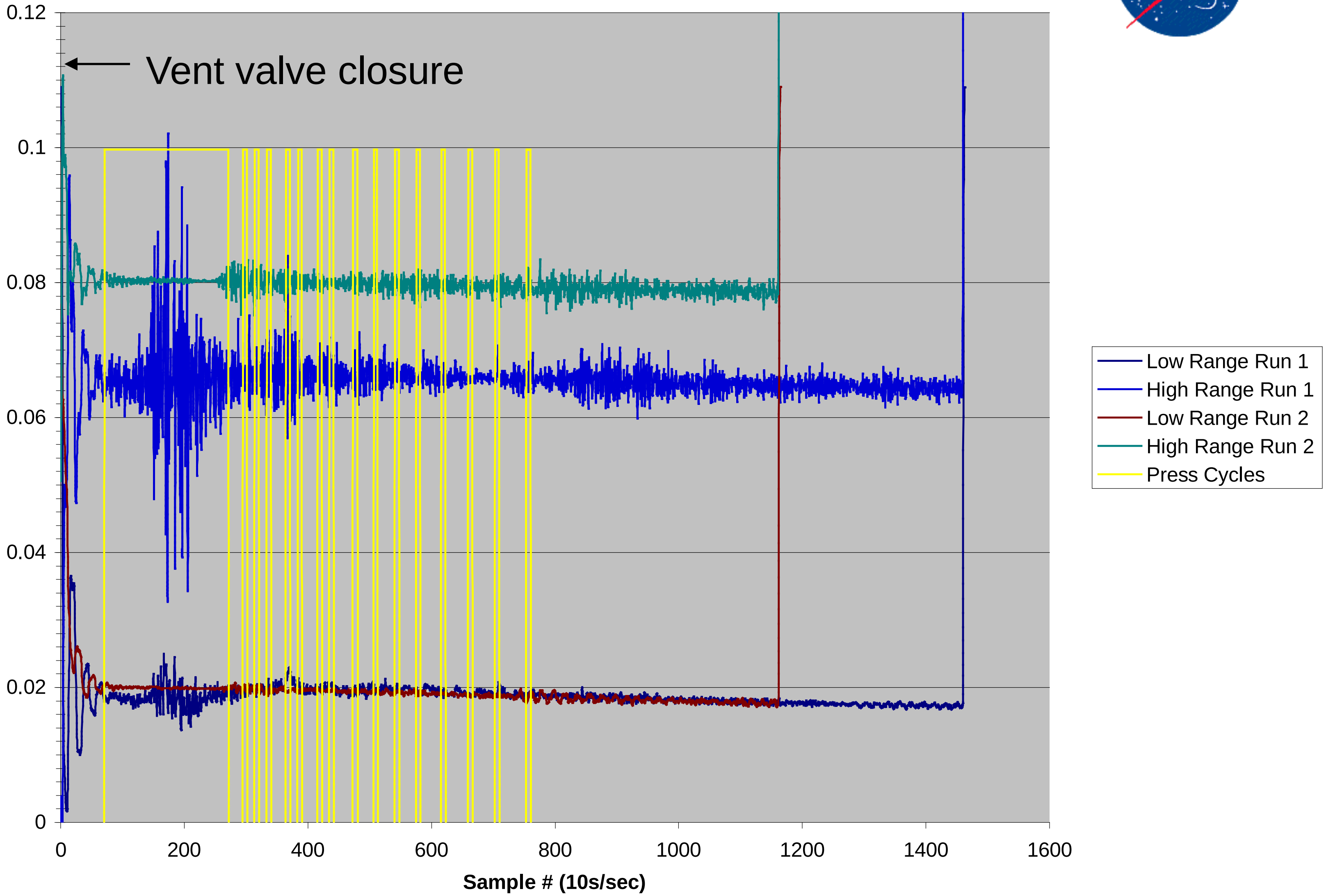


Image shows overlay of two Pre-press cycles TT#2: Noise amplitude higher on less sensitive measurement!

Flow Analysis of Pre-Press Cycles

- No ET Vent Valve leakage detected within limitations of instruments.
- Instrumentation performed as expected except some zero drift in high range Pitot
- Post ET vent closing oscillations caused by “organ pipe” resonance (expected behavior of flow stoppage)
- Unknown noise source during first Pre-press appears to be electronic noise.

TT#2 Pitot Summary

- Pitot system successfully ruled out Vent Valve leakage on ET120 during two pre-press cycles of TT#2.
- System designed built and flow tested in 4 days.

Water Detection in and Removal from Shuttle Tiles

In March of 2001 Atlantis landed in California and was exposed to severe rain.

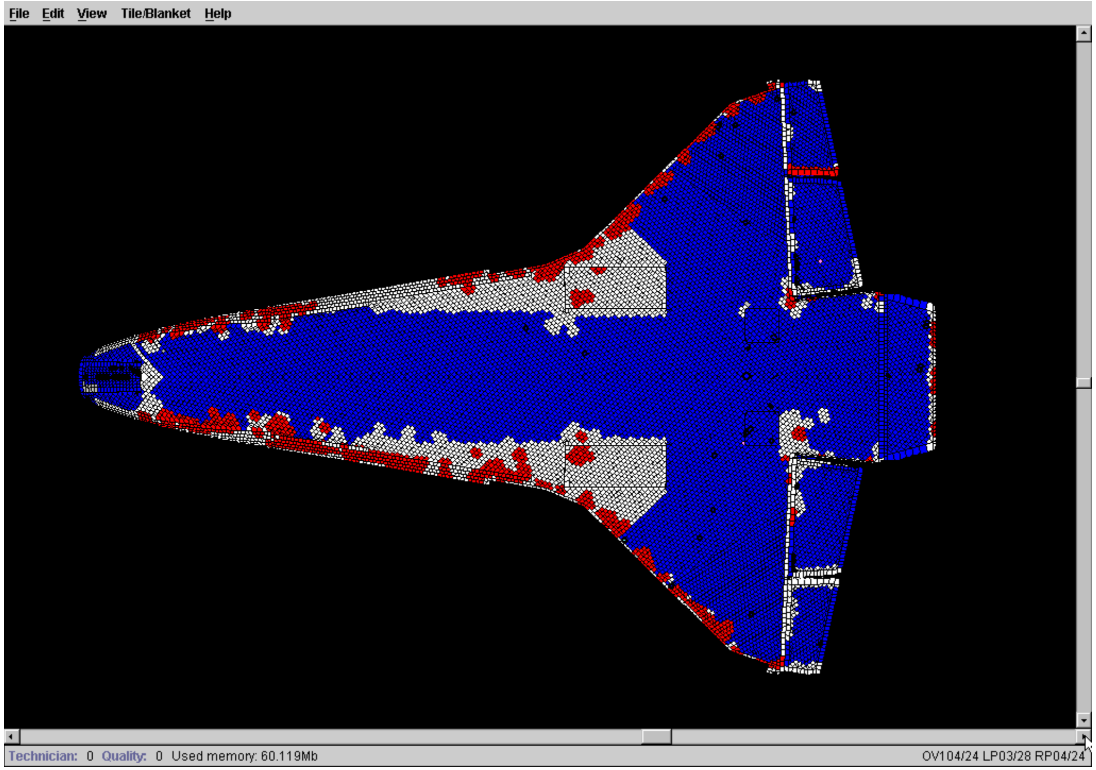
This resulted in excessive absorption of water by the Orbiter tiles.

Atlantis returning to KSC in March of 2001 after landing in California.

Water Detection in and Removal from Shuttle Tiles

Wet tiles were found by using an infrared camera to locate cold regions due to the evaporation of water.

The water was then removed by boiling it out, tile-by-tile, using heat lamps.



The blue areas indicate wet tiles on the underbelly of Atlantis.

Water Detection in and Removal from Shuttle Tiles

After four months of drying Atlantis still had wet tiles, resulting in a delay of launch.

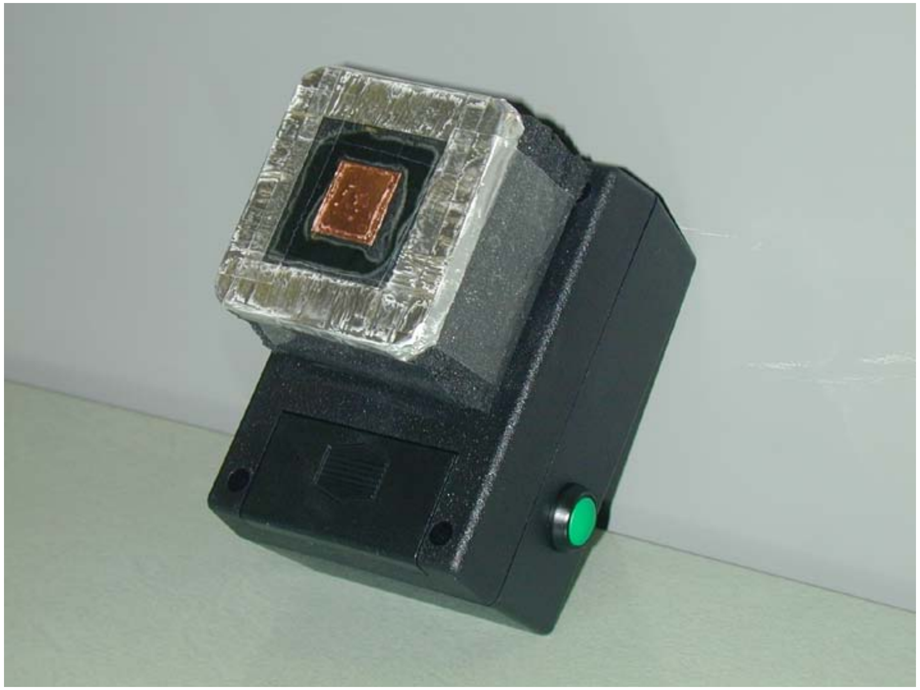
New techniques for detecting and removing water from the Shuttle tiles were needed.

Heat lamps being used to dry tiles on Atlantis.

Water Detection in Shuttle Tiles

Water has a dielectric constant of 70-80 as compared with 4 for glass and nearly 1 for tile material.

So a simple capacitive sensor was fabricated and given to Shuttle engineers to try out.



Concept version of capacitance based water detector for Shuttle tiles showing the detection electrode.

Water Detection in Shuttle Tiles

First field version provided:

Long battery life,

An extended sensor,

Automatic shutoff,

A stable reference with calibration on start-up,

Two levels of sensitivity for thick or thin tiles,

Field version of the capacitive tile water sensor.

Water Detection in Shuttle Tiles

The field prototype also provides:

A LED indication of water,

An LCD display indication of capacitance level,

and

An audio alarm indicating water.

Back of field prototype sensor.

Water Detection in Shuttle Tiles

Almost Final Shop Aid

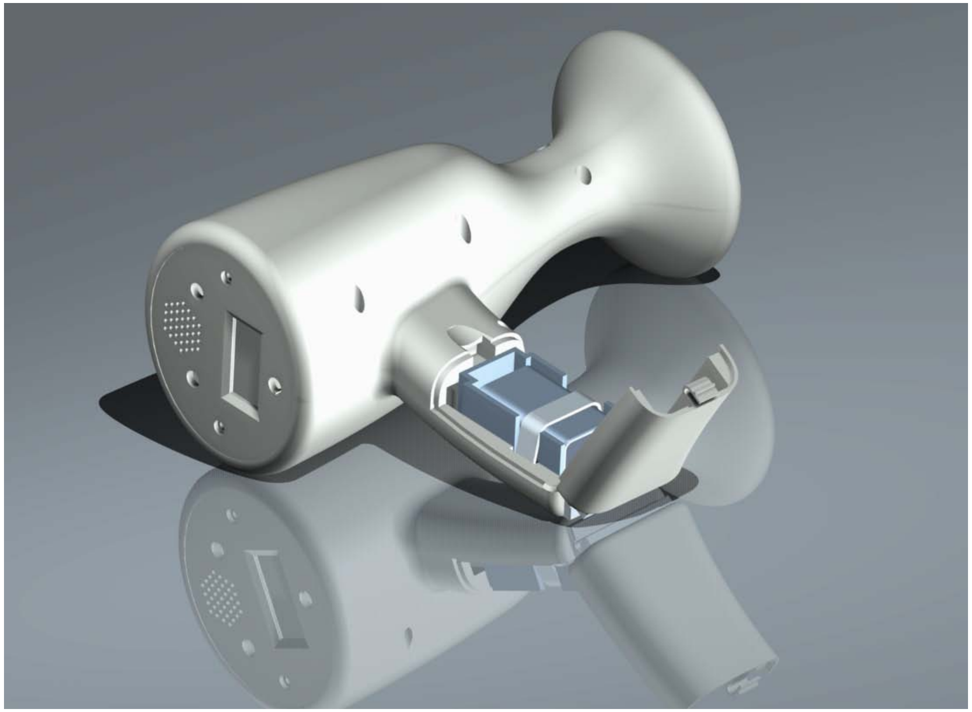
Rounded, rapid prototyping grown housing.

Stabler operation.

Louder Alarm

Easier battery Access

Hazard proofed.



Pro E rendered image of the almost final shop aid.

Water Detection in Shuttle Tiles

Final Shop Aid

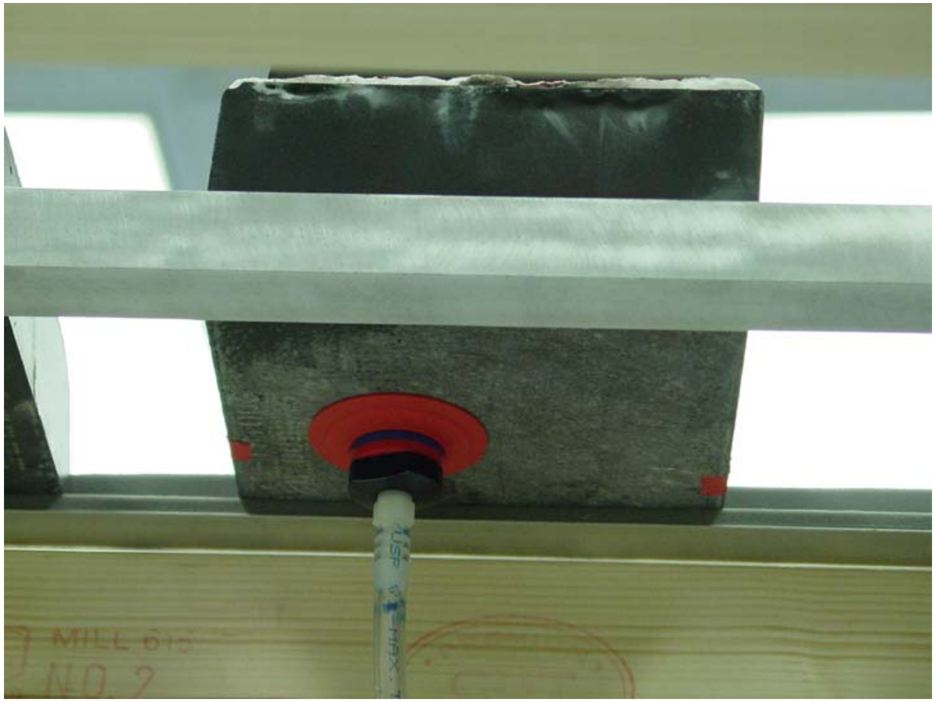
ABS Plastic

Smaller Handle

Four of these are now shop aids and have been delivered to Shuttle personnel.

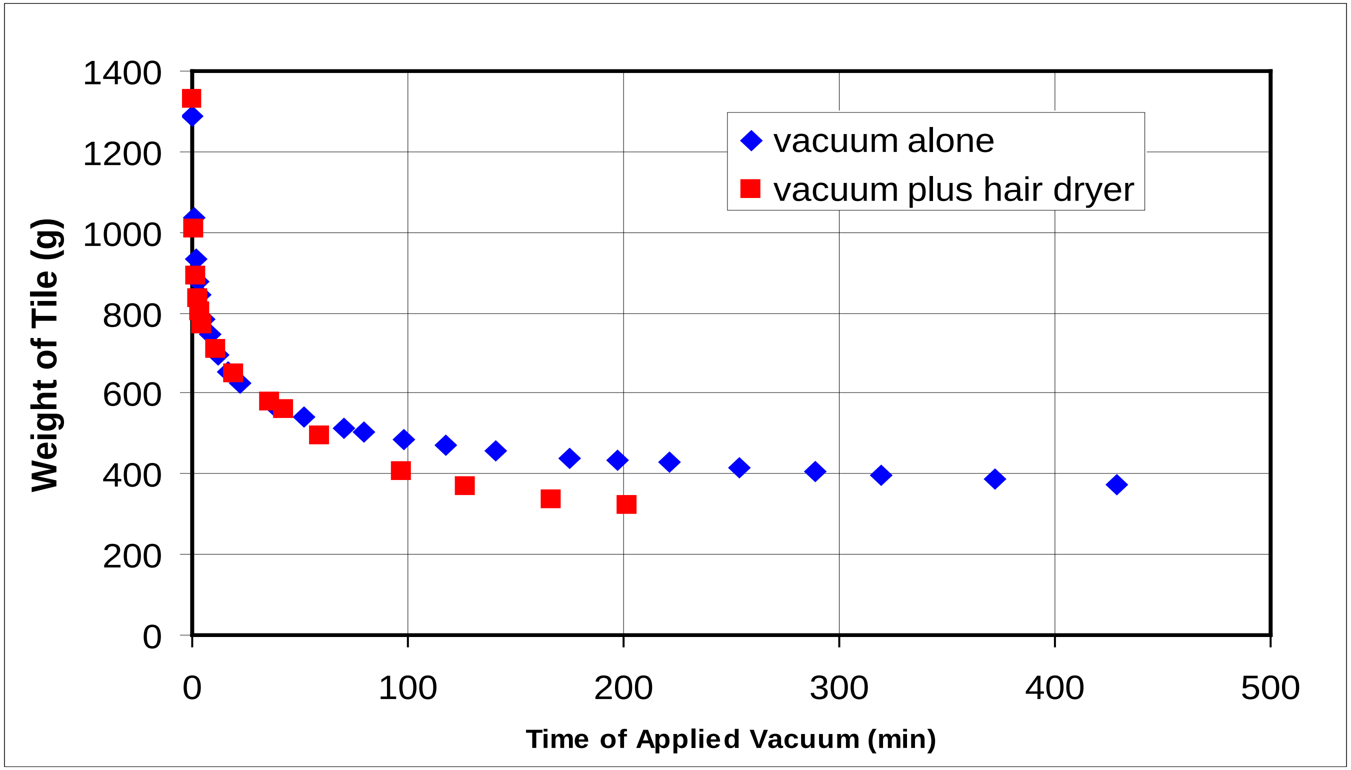
Water Removal From Shuttle Tiles

After many trials it was realized that the water in a tile could be removed through the single small water proofing hole located near the center of each tile.



A suction cup attached to a tile.

Water Removal From Shuttle Tiles



A plot of tile weight versus time while being vacuum dried (dry weight is about 235 grams). Heat improves the drying rate, but the majority of the water is removed in the first hour regardless of heating.

Water Removal From Shuttle Tiles

We then developed a field prototype, designed to pump water from 25 tiles at a time using the facility vacuum system within each of the Orbiter Processing Facilities.

Field system water separator attached to facility vacuum system.

Water Removal From Shuttle Tiles

As many as six of these tile drying systems could be used simultaneously, allowing 150 tiles to be dried every 2 hours.

The Shuttle tiles could be completely dried in weeks instead of months, minimizing the occurrence of another water based launch delay.

2003 demo in OPF 1 on ten wet tiles

Water Removal From Shuttle Tiles

So we constructed four units, placed them in storage, and began to work turnover issues.

In June of 2005 we received permission to deliver them and they were given shop aids status…just in time because

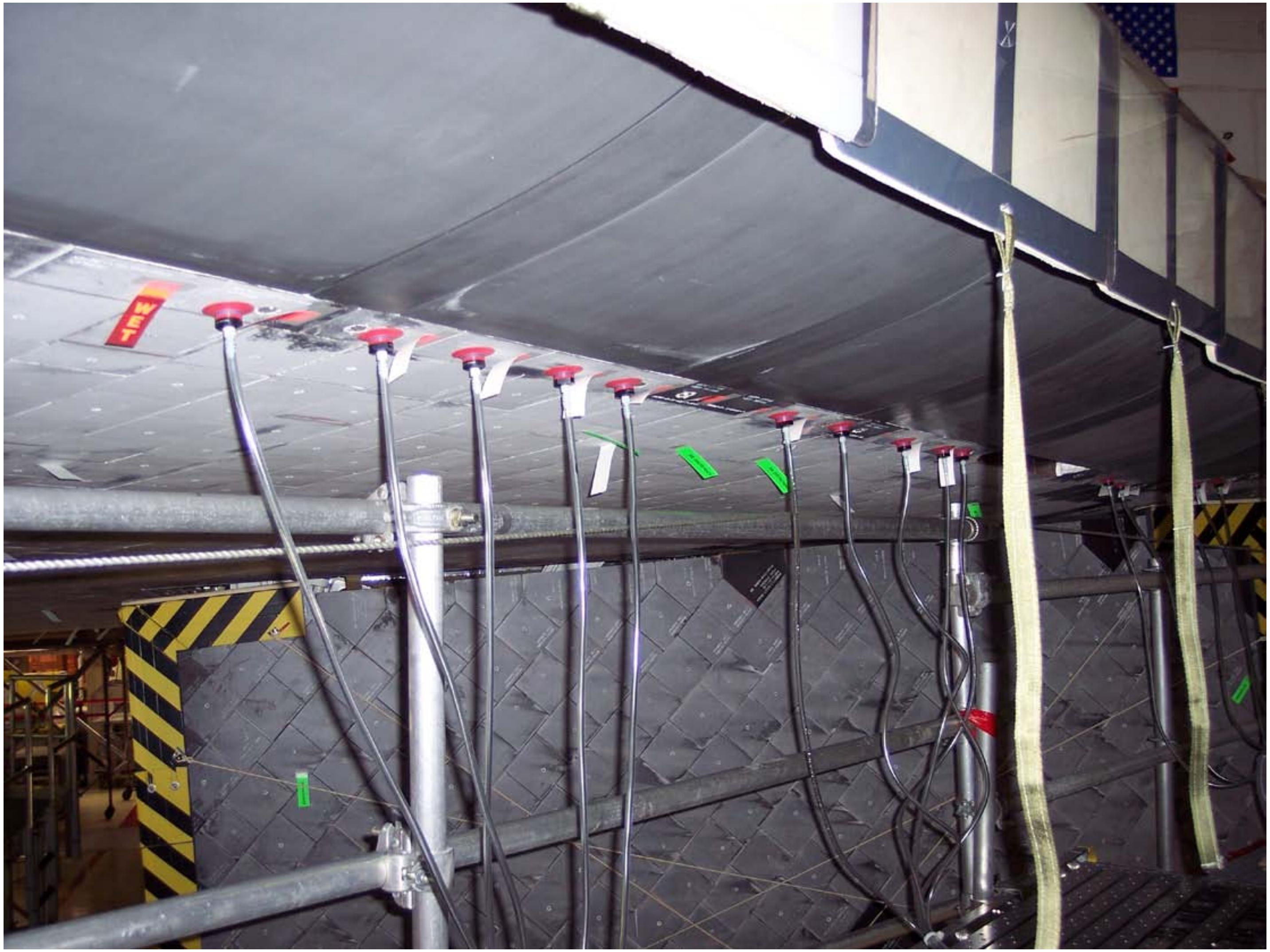
in August of 2005 Discovery landed in California and was hit by nearly 2 inches of rain.

Water Removal From Shuttle Tiles

The system on a platform in front of the right wing of Discovery.

Water Removal From Shuttle Tiles

15 Wet Shuttle Tiles being dried by the system in Sept. 2005.



50 tiles being dried on Discovery's left side. Sept. 2005

Water Removal From Shuttle Tiles

50 Tiles being dried.

Water Detection in Shuttle Tiles using Humidity Measurements

A final shop aid.

The unit to the right can be used to locate residual water, but pulling an air sample from an enclosure and measuring the humidity of this air.

Four of these were delivered as shop aids earlier in the year and are being used in the field to locate hidden water.

Water Detection and Removal From Shuttle Tiles

Acknowledgements:

Jan Surma, Timothy Hodge, and **Steve Parks** for work on the tile vacuum system and the humidity sensor.

Carlos Mata, Irving Bushnell, and Peter Vokrot for work on the capacitive water sensor,

Alyssa Daya for months of lab work on both units,

Stan Starr and **Phil Metzger** for theoretical modeling,

Charlie Stevenson, Chris Davis, and Mark Minich for programmatic issues, and

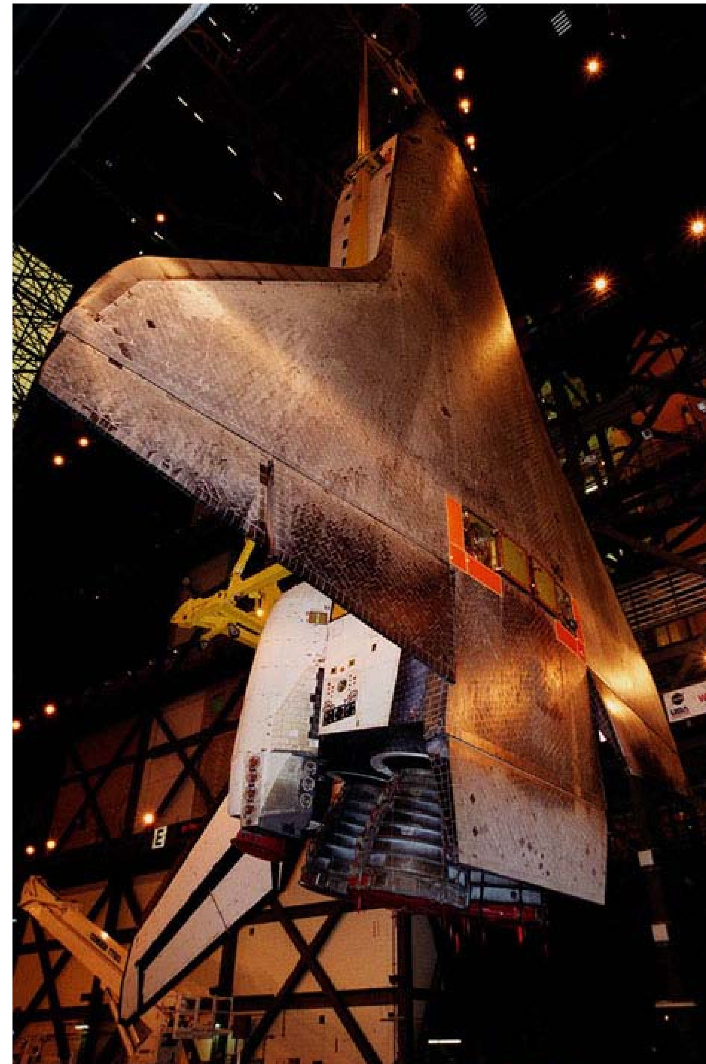
The **Members of the Shuttle Wet Tile Team**, especially **Katherine Laufenberg** and **Terrence White** for providing requirements and design suggestions.

Backup Slides

Water Detection in and Removal from Shuttle Tiles

The Space Shuttle Orbiters are protected from the heat of re-entry by more than 20,000 tiles.

These tiles are composed of nearly pure silica fibers that form a strong, yet extremely low thermal conductivity coating over the Orbiter.



Water Detection in and Removal from Shuttle Tiles

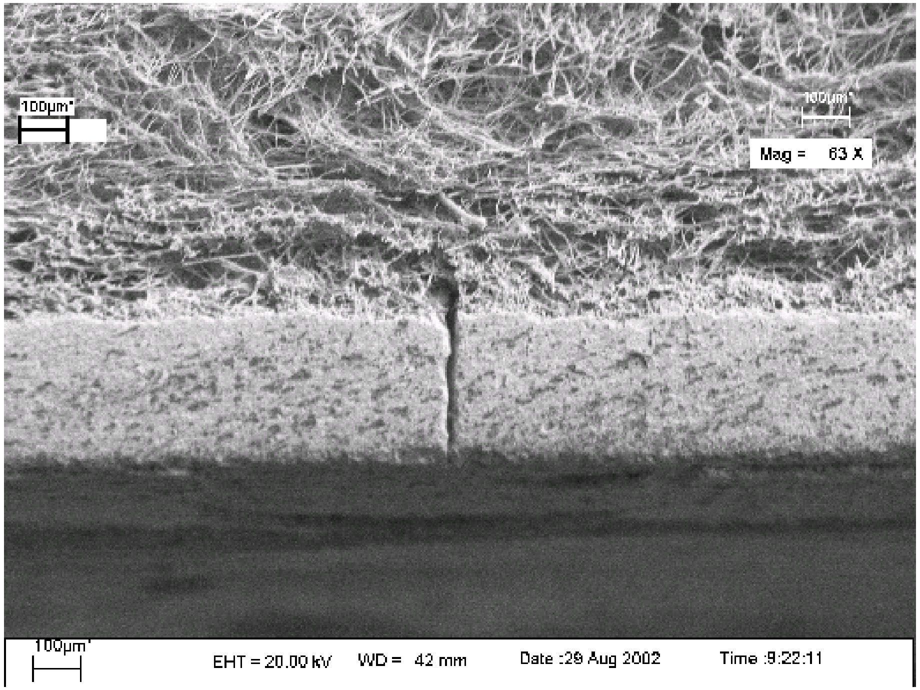
The tiles are only 7% glass by volume and are partially coated with a thin (0.01 inch) layer of black borosilicate glass to increase their emittance.

Typical acreage tiles are 6 inches by 6 inches by 2.5 inches in size.

Shuttle Landing Gear Cover Showing Tiles

Water Detection in and Removal from Shuttle Tiles

A typical acreage tile has about 40,000,000 meters of fiber (once around the earth) and a net glass surface area of 180 square meters.



This results in high thermal isolation, but also very strong water capillary effects.

An SEM photo showing tile fibers and a crack in the borosilicate glass coating layer.

Water Detection in and Removal from Shuttle Tiles

To prevent water intrusion, tiles are injected with a water-proofing compound through a small hole located on each tile.

This compound burns out on reentry and must be reapplied before the Orbiter can be exposed to the weather.

A few Orbiter acreage tiles showing markings, variations in color, and water proofing holes.

Water Detection in and Removal from Shuttle Tiles

An alternative/addition to the IR camera water detector should

- allow tile water to be detected regardless of the tile temperature.
- be easy to use on single tiles.
- be operator friendly.
- provide a clear signal that a tile is wet or dry.

Water Detection in Shuttle Tiles

Shuttle engineers accepted this new tool and requested that a field version be developed.

Capacitive water sensor being used on an uncoated tile sample.

Water Removal From Shuttle Tiles

But of more interest is a better method for removing water.

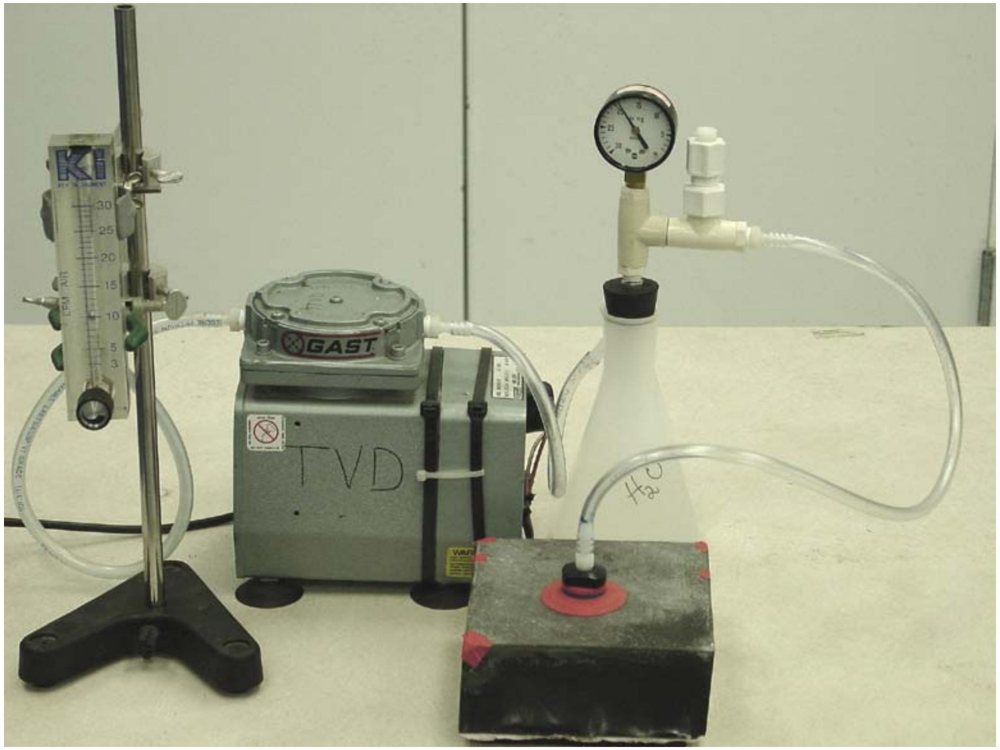
Boiling the water tile-by-tile is slow and produces steam.

A new method that removes the water more rapidly from a tile and that can be used on more tiles simultaneously would help to prevent future launch delays.

Water Removal From Shuttle Tiles

A low level vacuum (7-12 in Hg) was shown to withdraw the water from a tile in a few hours.

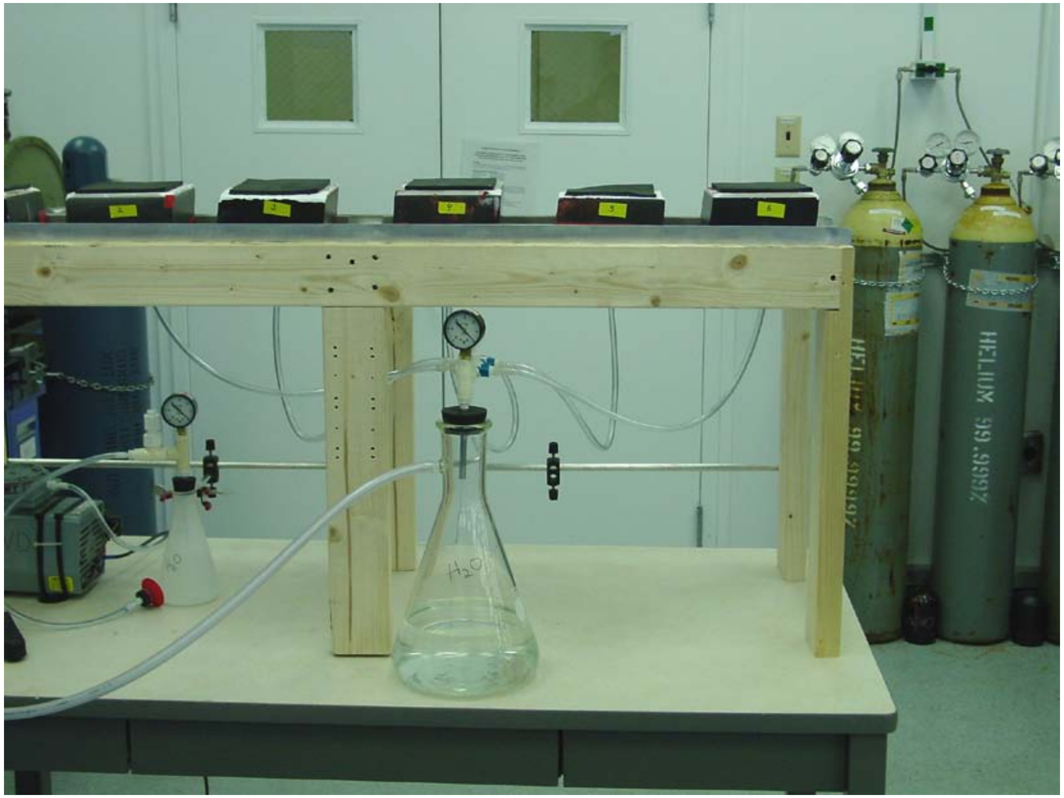
Tests were done to validate the safety of this process and no problems were found.



Early experimental system showing tile, suction cup, water separator, pump, and gages.

Water Removal From Shuttle Tiles

The results were so encouraging we moved on to a five tile system, demonstrating that a single vacuum system could dry multiple tiles simultaneously.

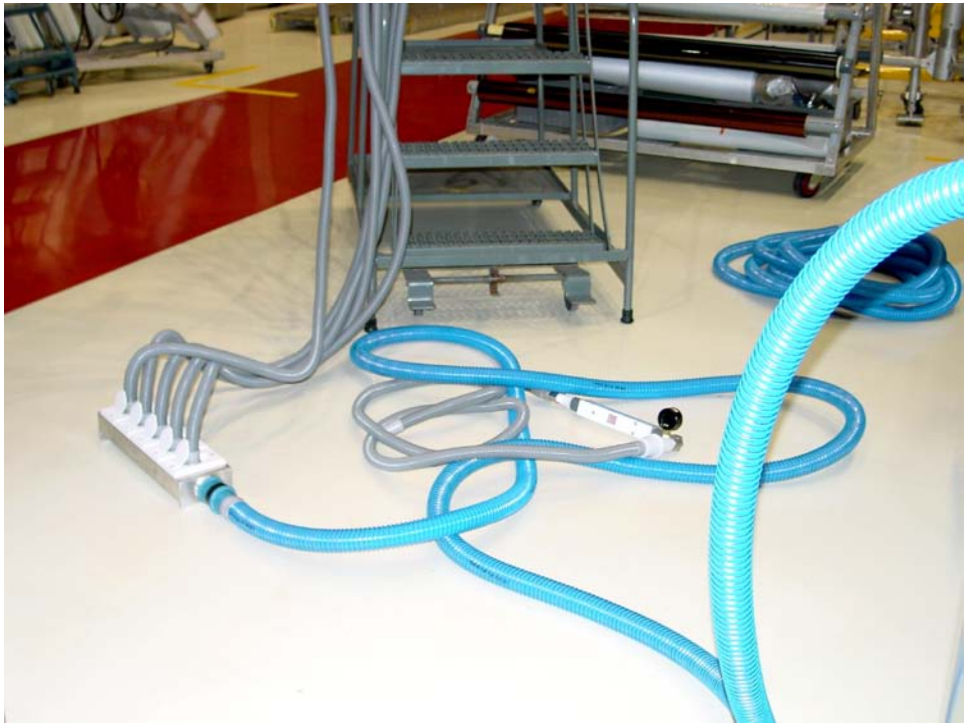


Five tile system with single water separator and manifold.

Water Removal From Shuttle Tiles

The water separator is located on the floor with a vacuum line reaching to a one to five manifold.

The five smaller lines then each break out into five ¼ inch Tygon lines with suction cups.



Primary vacuum line breaking out into five smaller lines at system manifold.

Water Removal From Shuttle Tiles

The resulting 25 lines can then be attached to 25 tiles, allowing parallel drying with a single system.

The existing facility system provides 7 in Hg at each tile allowing significant drying to occur over a two hour period.

Water Detection and Removal From Shuttle Tiles

Better Shuttle tile water detection and removal systems have been described.

These will minimize the potential for tile damage and launch delays and may find use, not only on the Shuttle, but on future thermal protection systems.