

# Icing in Aircraft Fuel Lines



Federal Aviation  
Administration



Stainless Steel



Aluminum

Presented to: Rutgers University

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Rutgers Advisors: Professor Rossmann, Professor Diez

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# Introduction

- **This thesis is to partially fulfill the requirements for a M.S. degree in mechanical and aerospace engineering at Rutgers University**
- **The purpose is to understand ice accumulation in jet fuel such as that which caused flight accidents.**



# Background

- **A330 engine rollback (2009)**
- **Boeing 777 accident (2008)** <sup>[2]</sup>
  - Blockage of the FOHE from ice.
- **Boeing 777 engine rollback (2008)** <sup>[2]</sup>
- **B52 accident (1958)** <sup>[3]</sup>
  - Fuel pump screen clogged with ice.
  - Over 200 previous “cause unknown” accidents later attributed to fuel icing.
  - Fuel Heaters and Icing Inhibitors were introduced

# Objective

- **Perform experiments to better understand the collection of ice in fuel pipes.**
  - Material Dependence
    - How does the type of material effect ice accumulation?
    - How does the roughness of pipe material effect ice accumulation?
  - Temperature Effects
    - Is there a preferred temperature for ice accumulation?
  - Effects of Flow Rate and Flow Structure
    - How does turbulence such as from a defined region of recirculation effect ice accumulation?
    - What is the effect of a Reynolds Number variation on ice accumulation?
  - Heat Transfer Effects
    - If there is a greater heat transfer from the fuel pipe, will ice accumulation be greater?

# Experimental Setup (Altitude Chamber)

- Temperature Potential: -51.1C
- Pressure Potential: 2.73psi (40,000ft)
- Humidity Control
- Current fuel storage within the chamber: 115 gal.



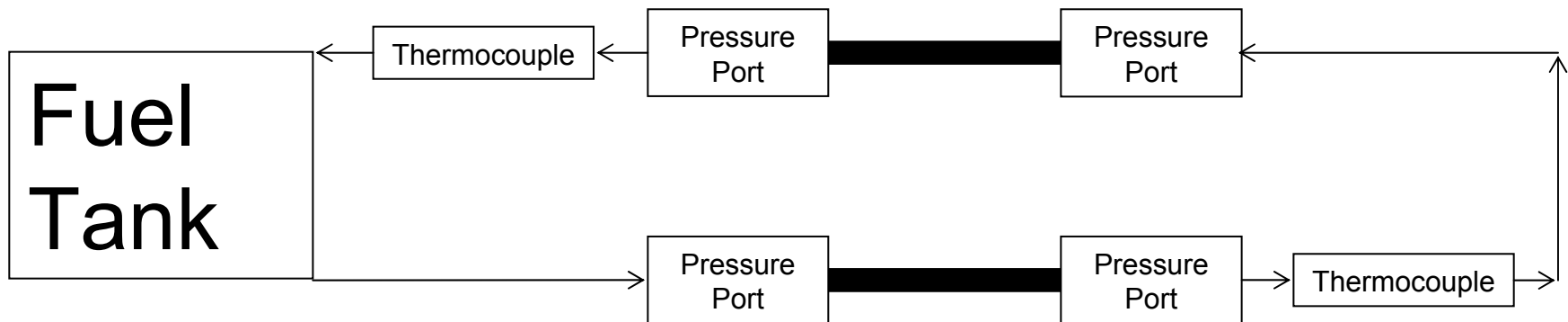
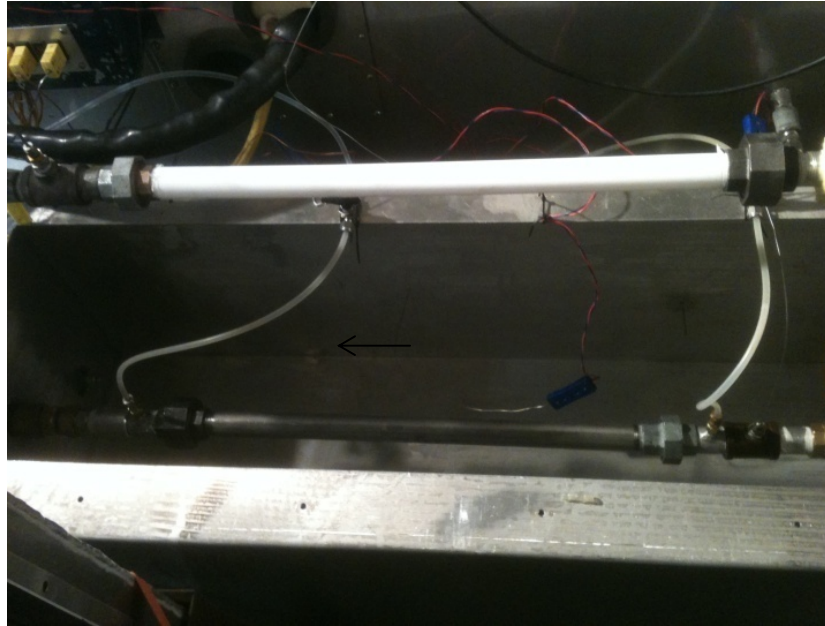
Altitude Chamber

# Experimental Setup (test sections)

- **Test sections**

- Each test pipe was fitted with ports for differential pressure measurement.
- Each pipe had a type T thermocouple port downstream of the test area.
- Each test pipe was easily removable for visual observation and ice quantity measurement.

# Experimental Setup (test sections)



# Experimental Setup (Fuel Preparation)

- Jet A-1 fuel was saturated at about 21.5 Celsius with approximately 25mL of free water in a tray at the bottom of the fuel tank.
- The fuel was filtered for particles and water prior to each test.

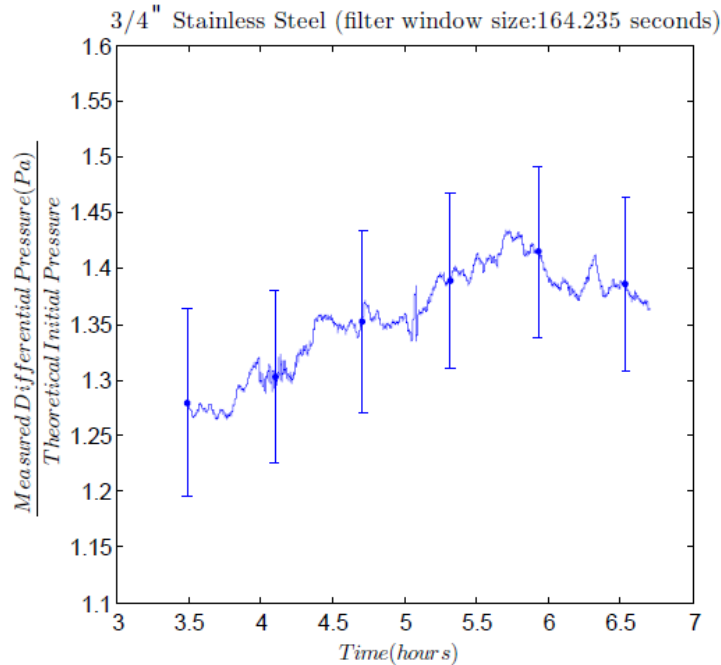




# Experimental Setup (Data Processing)

- In later quantitative tests, pressure was normalized by a theoretical pressure drop that would exist without any ice accumulation.
- Heat transfer was determined by a heat conduction analysis.
  - The fuel temperature in the test pipe represented the inner pipe wall temperature.
  - A thermocouple was “zip-tied” onto the outside of the pipe to determine the outside wall temperature.

# Typical Test Results



Reynolds Number:.....2031.3346  
Test Temperature:.....-9.3119 °C [-6.38 -13.14]  
Initial Temperature:.....21.405 °C[22.905 18.905]  
Test Duration:.....2.4714 hrs  
Flow is diverted prior to: -9.3119 °C  
Pressure Increase:.....0.0063987  $\frac{Pa}{m \cdot sec}$  [0.0064308 0.0063667]  
 $H_2O$  collected from pipe: 0.25 mL [0.25097 0.24903]

Note: The figures displayed here do not necessarily correspond to a single test

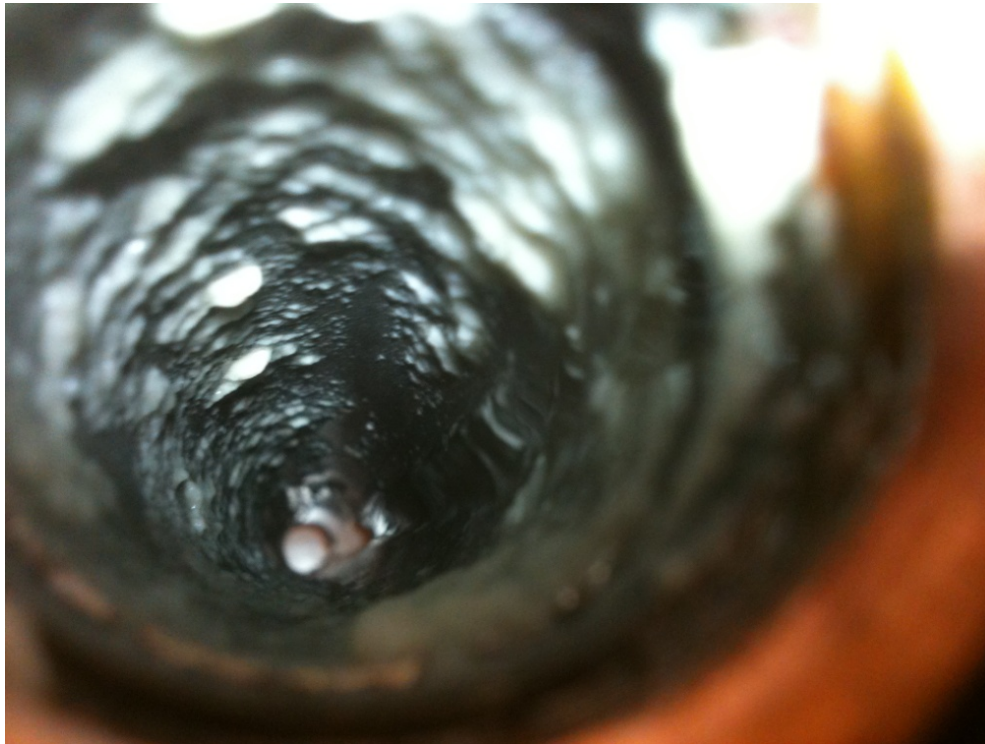


# Initial conditions variation

- **Initial conditions in the test pipe**
  - Fuel flowed through the test pipe as the fuel cooled to the test temperature.
  - Air was present in the test pipe as the fuel cooled to the test temperature.
  - Stationary fuel was present in the test pipe as the fuel cooled to the test temperature. (in this case there was a small air gap in the pipe also.)
  - Air was present in the test pipe except for a defined region which was sprayed with water

# Results of initial conditions variation

- Fuel flow through the test pipe as the fuel cooled to the test temperature.



# Results of initial conditions variation

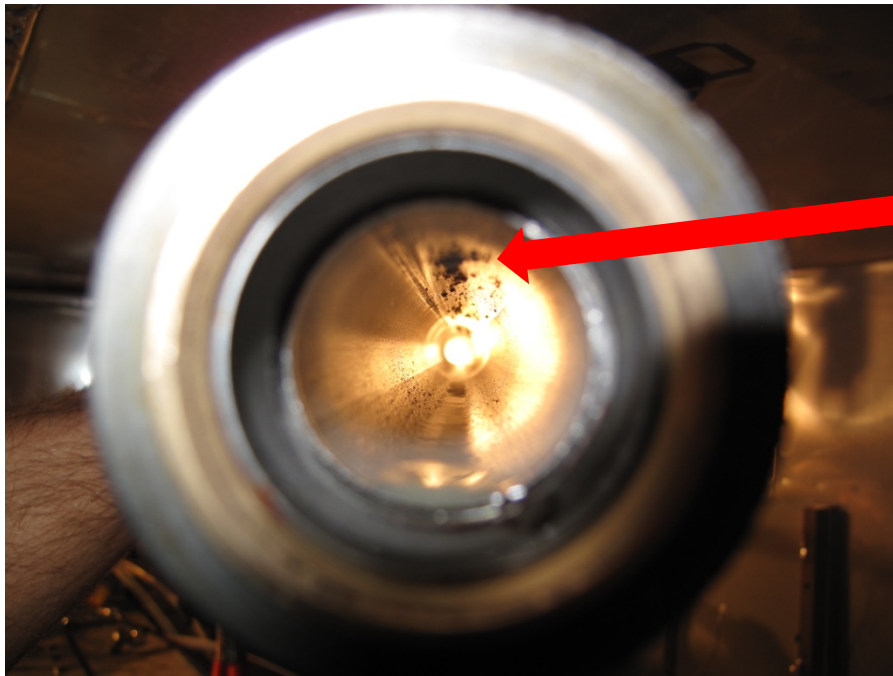
- Air in the test pipe as the fuel cooled to the test temperature.



A noticeable amount of ice but less than the previous condition.

# Results of initial conditions variation

- Stationary fuel in the test pipe as the fuel cooled to the test temperature. (in this case there was a small air gap in the pipe also.)

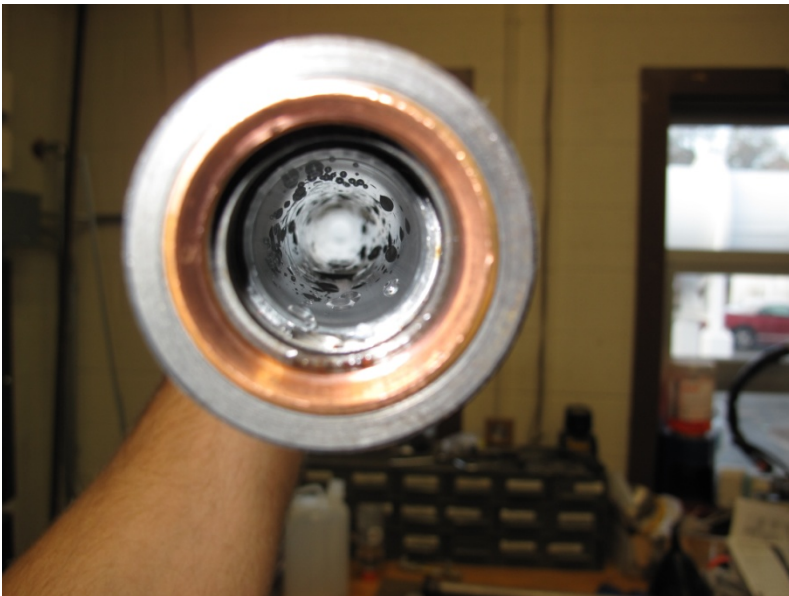


Ice along the top of the pipe where air was trapped



# Results of initial conditions variation

- Air in test pipe except for a defined region that was sprayed with water



Before



After

Note: A clear image of the other side of the pipe was not taken after the test where water was not sprayed but it had a lack of ice accumulation

# Conclusion for initial conditions variation

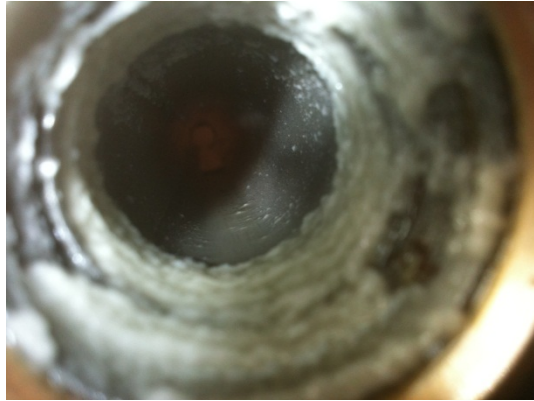
- The softer ice may stick to the pipe material but it stuck to hard ice substantially more.
- The case that fuel flowed continually through the flow loop as the fuel cooled was chosen for further quantitative tests.



# Pipe configuration Variation

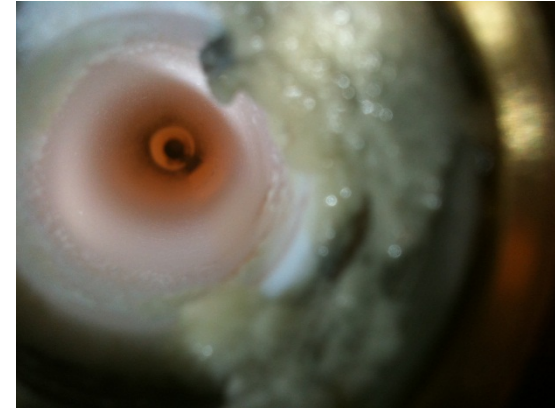
- **Material variation**
  - 6061 T6 Aluminum
  - 6061 Aluminum that has been scratched with 80 grit sand paper.
  - Type 304 Stainless Steel
  - PTFE Teflon
- **Geometry variation**
  - 2 ½ inch diameter pipe bends
  - 4 ½ inch diameter pipe bend
  - 50% area reduction step change
  - 50% area increase step change

# Results of pipe configuration variations (Materials)

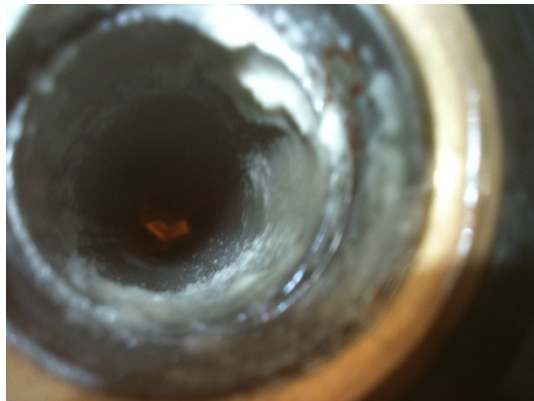


Stainless Steel

Re: 2023  
T: -9.5  
°C

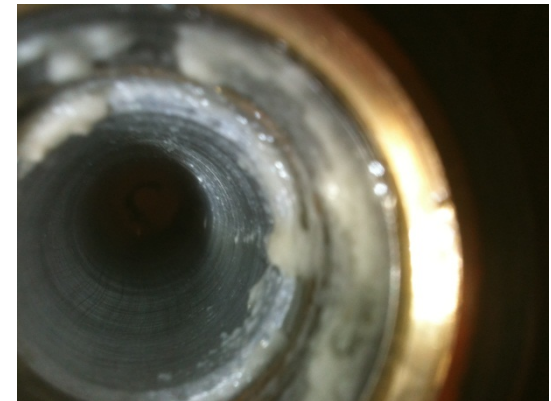


Teflon



Stainless Steel

Re: 5975  
T: -9.5 °C



Scratched Aluminum

# Results of pipe configuration variations (Geometry)



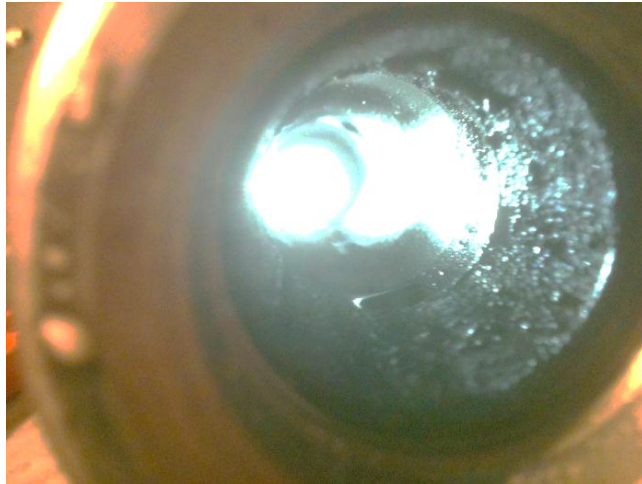
Downstream of  $\approx 4 \frac{1}{2}$  inch radius pipe bend.



Downstream of  $\approx 2 \frac{1}{2}$  inch radius pipe bend.

Note: These images illustrate what happened immediately downstream of the pipe bends but conditions farther downstream could be affected also. These bends were also tested in series and can therefore have synergistic effects with each other.

# Results of pipe configuration variations (Geometry)



Downstream of  $\approx 50\%$   
area reduction



Downstream of  $\approx 50\%$   
area increase

Note: These images illustrate what happened immediately downstream of the area change but conditions farther downstream could be effected also. These bends were also tested in series and can therefore have synergistic effects with each other.

# Conclusions for Pipe Configuration Variations

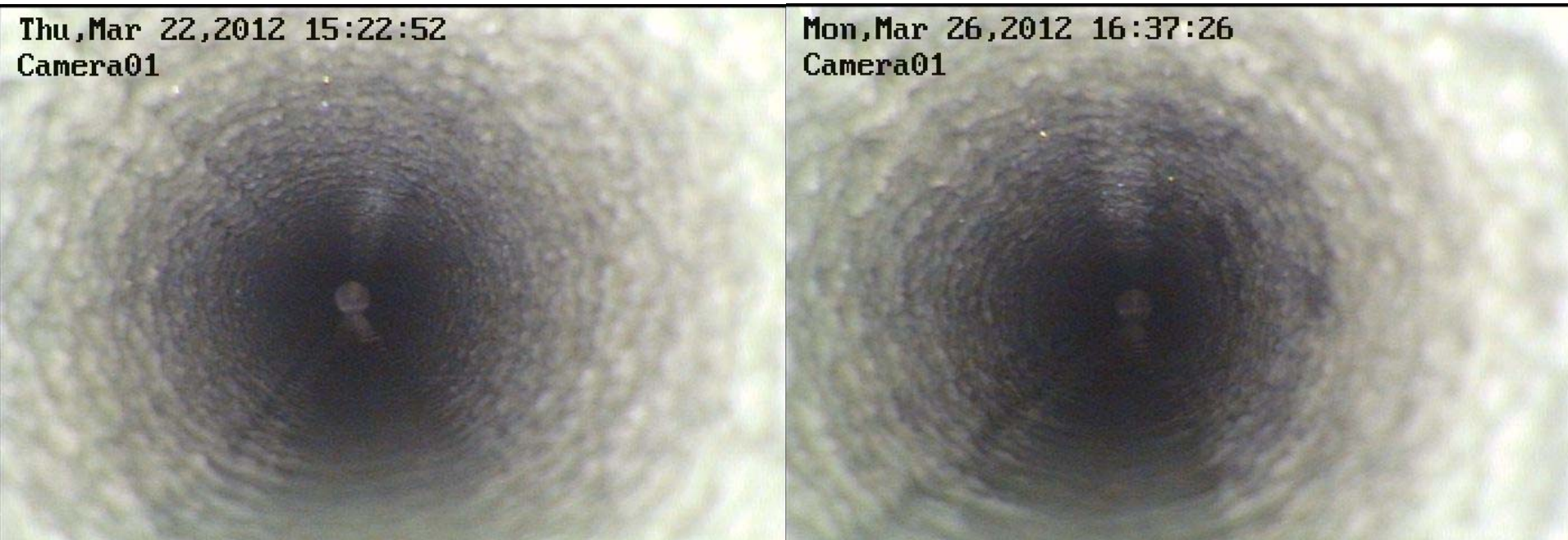
- Materials with a greater adhesion force to water will collect more water and will therefore have a greater potential to collect soft ice.
- Pipe geometry variations created a change in the flow structure but lacked a defined region of ice accumulation where an eddy might exist.

# Test Conditions Variation

- **Repeatability**
  - Repeatability tests were done at a Reynolds number of 8362 and temperature of -11 °C
- **Variation of Reynolds Number**
  - $\approx 3150$  to  $\approx 13000$
  - This Re regime covered the range that a commercial airliner may typically encounter.
- **Variation of Temperature**
  - $\approx -7$  °C to  $\approx -20$  °C
  - Boeing attributed -5 °C to -20 °C to be the temperature range that had sticky ice. [2]
- **Variation of Heat Transfer from the Pipe**
  - Insulated pipe or not insulated pipe
  - This variation was done because of what was unintentionally found in earlier tests.



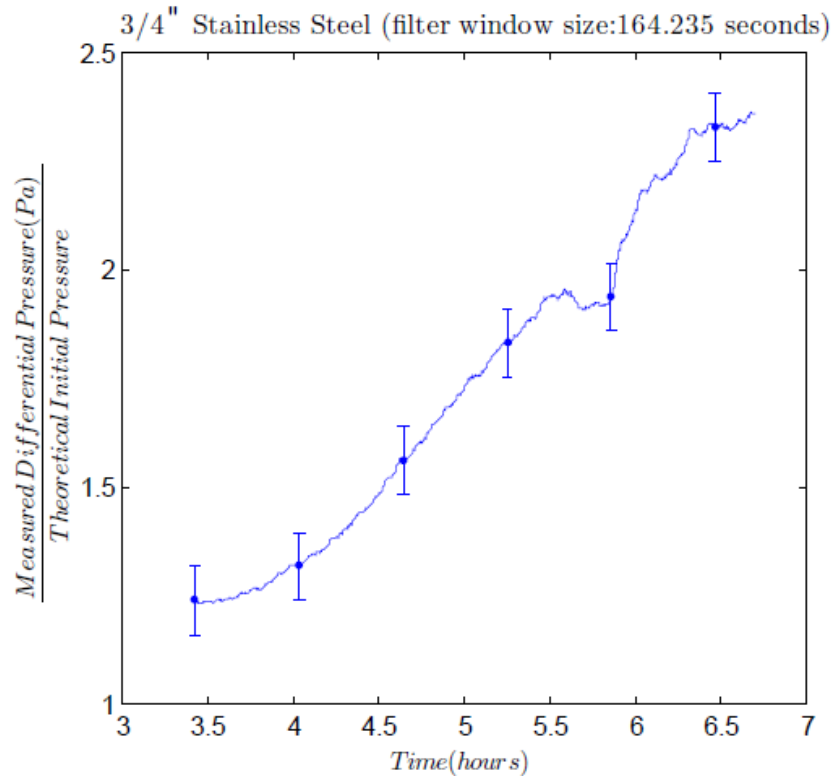
# Results of test condition variation (Repeatability)



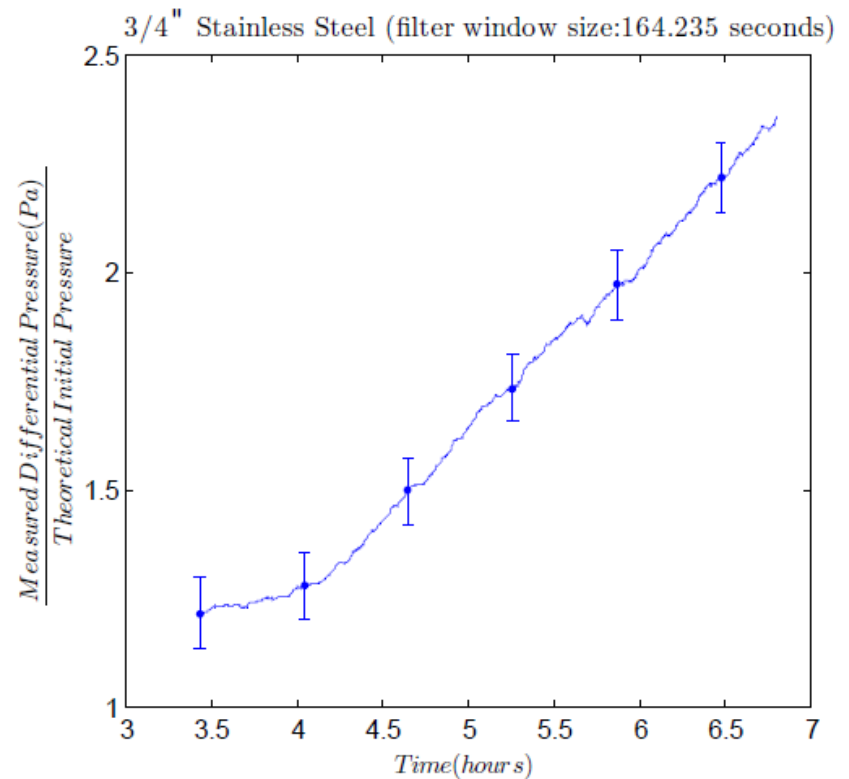
Test 1

Test 2

# Results of test condition variation (Repeatability)



Test 1



Test 2



# Results of test condition variation (Reynolds Number)



Re: 4000



Re: 8362



Re: 12922

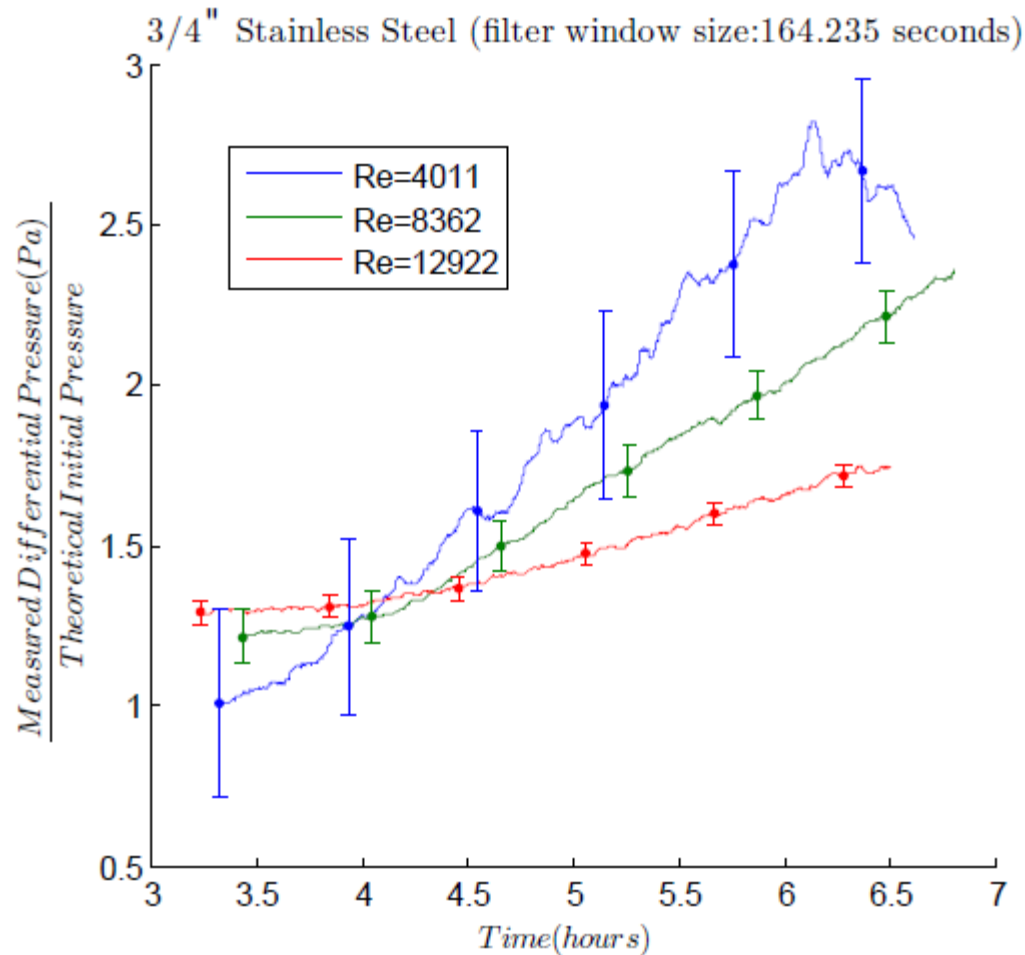
Thicker  
ice



Thinner  
ice

-11 °C

# Results of test condition variation (Reynolds Number)



# Results of test condition variation (Temperature)

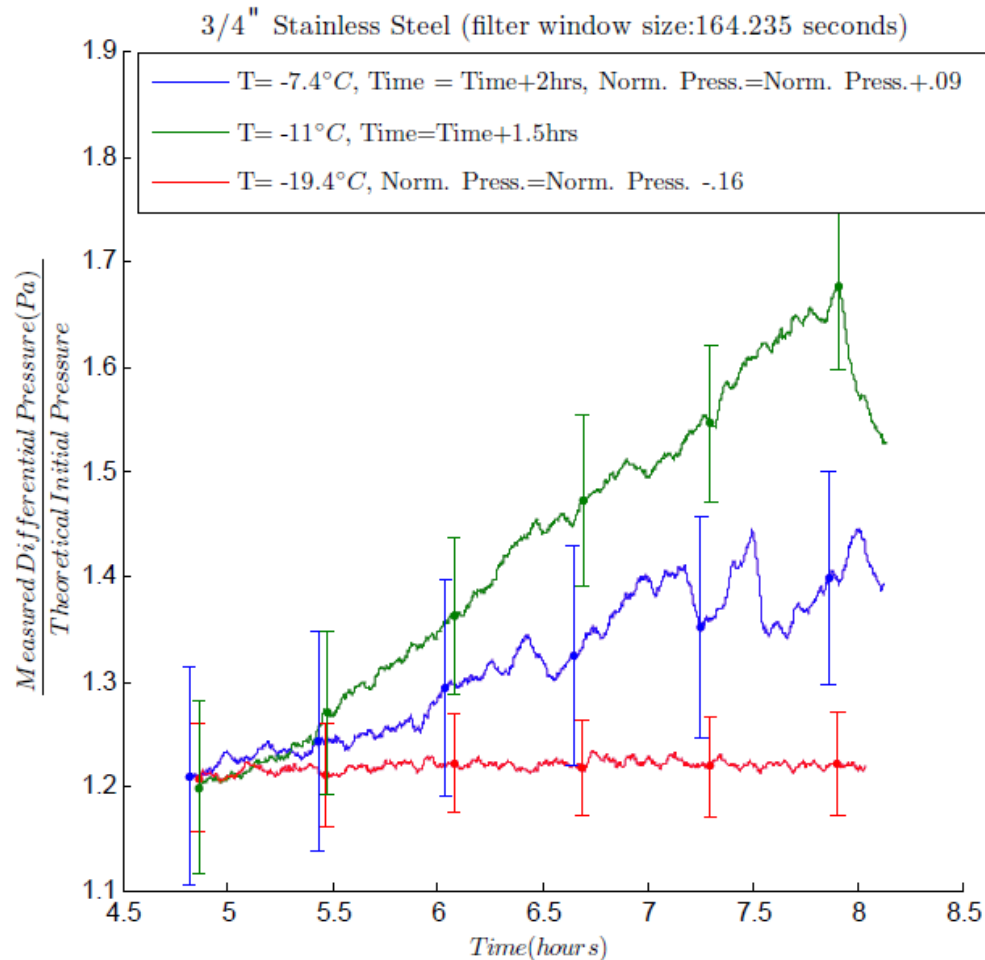


-7.4 °C

-11.24 °C

-19.35 °C

# Results of test condition variation (Temperature)





# Results of test condition variation (Heat Transfer)

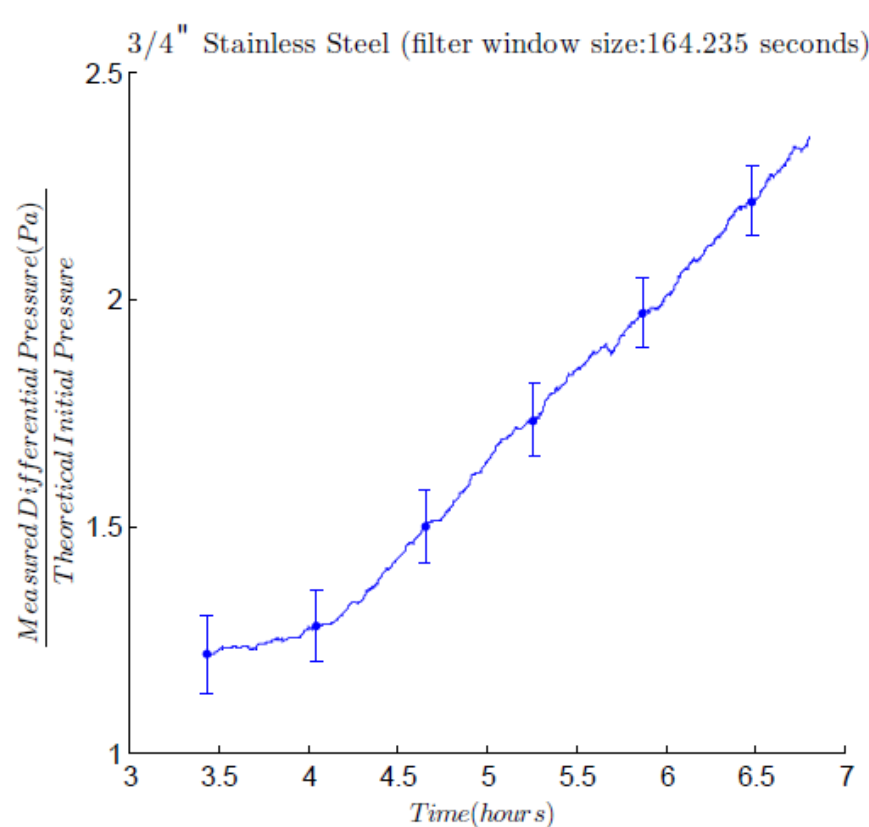


Un-Insulated

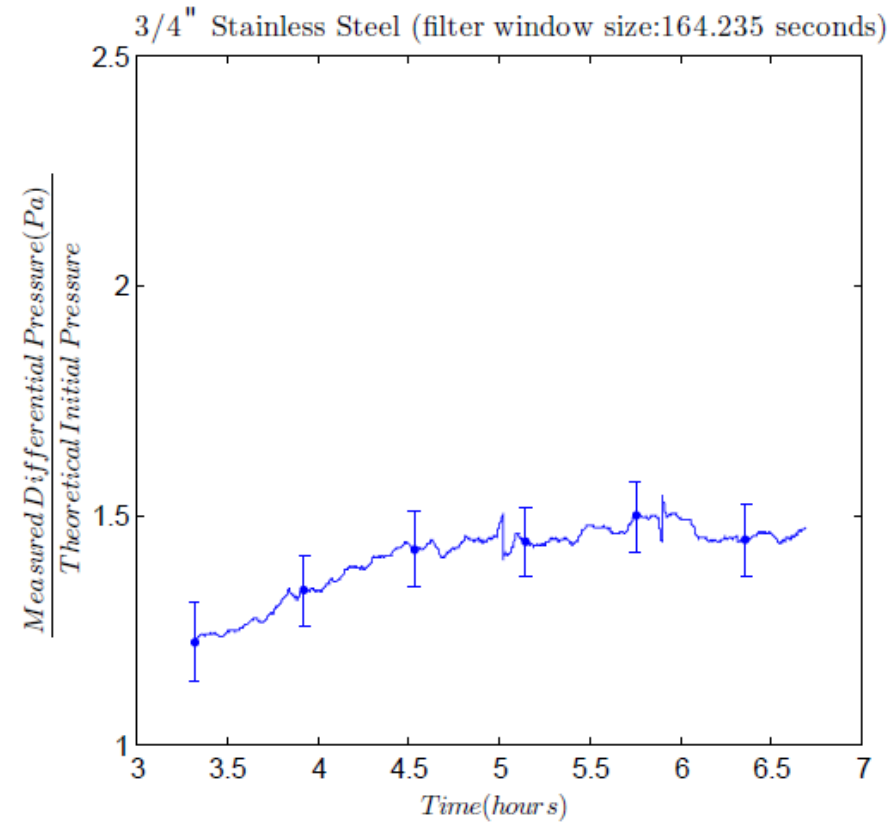


Insulated

# Results of test condition variation (Heat Transfer)

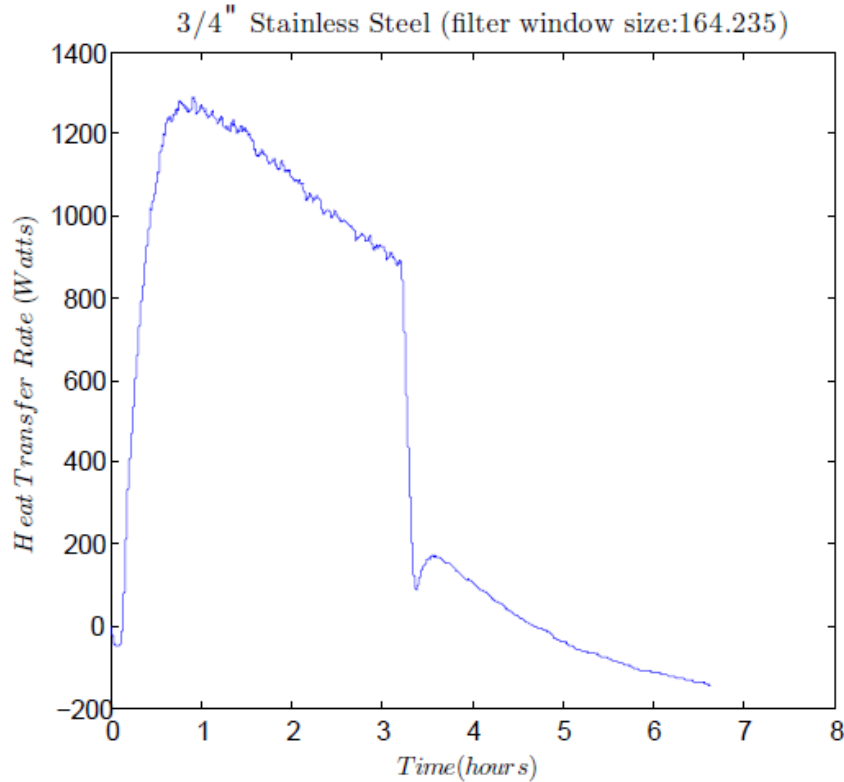


Un-Insulated

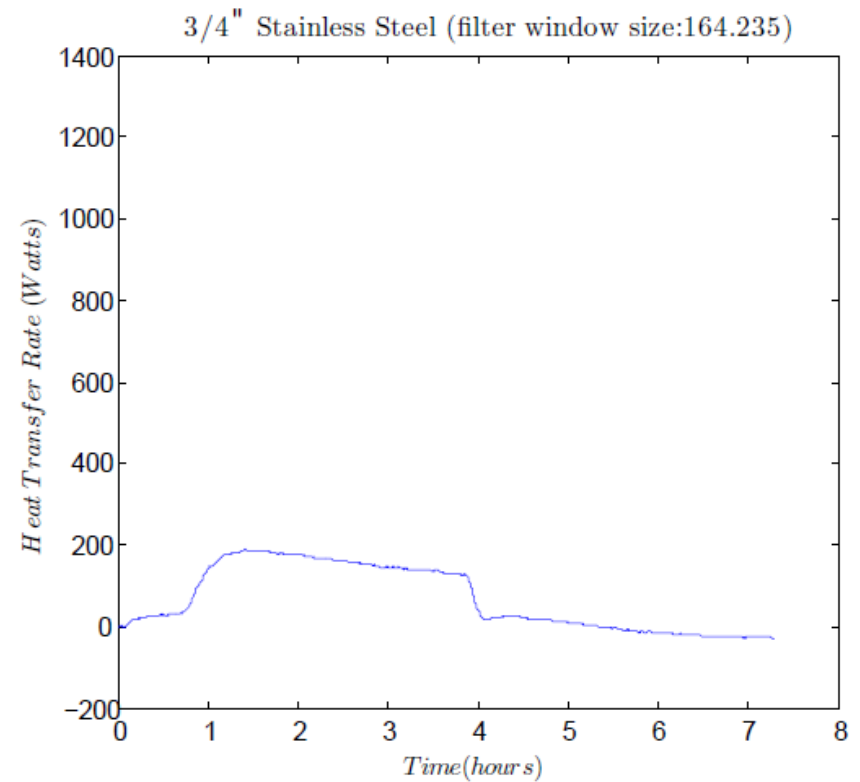


Insulated

# Results of test condition variation (Heat Transfer)



Un-Insulated



Insulated

# Conclusions for test condition variations

- Repeatability was shown to exist visually with the pipe images and quantitatively with pressure increase.
- Higher Re decreased total accumulation because of an increase in shear stress
- The ice accumulated the most at -11 °C.
- A greater heat transfer from the pipe increased ice accumulation.



# Other observations

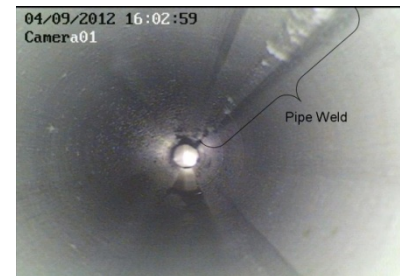
- **Contamination increases ice accumulation.**
- **Ice accumulated more on pipe welds than elsewhere in the pipe**



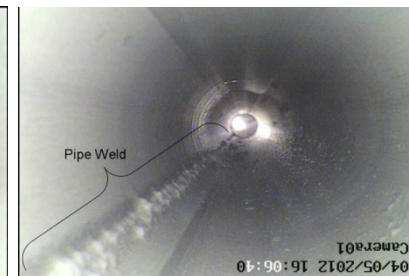
More Contaminated



Less Contaminated



Pipe Oriented right-side-up



Pipe Oriented up-side-down

# Conclusions

- **Initial Conditions Variations**

- The softer ice may stick to the pipe material surface but it stuck to hard ice substantially more.

- **Pipe Configuration Variations**

- Materials with a greater adhesion force to water will therefore collect more water and have a greater potential to collect soft ice.
- Pipe geometry variations lacked a defined region of ice accumulation immediately downstream.

- **Test Conditions Variation**

- Higher  $Re$  decreased total accumulation because of an increase in shear stress.
- The ice accumulated the most at  $-11\text{ }^{\circ}\text{C}$ .
- A greater heat transfer from the pipe increased ice accumulation.

# Questions?



# Citations

- [1] Lao, Liyun, David Hammond, Colin Ramshaw, and Hoi Yeung. *Part 2 Ice Accretion*. Rep. 2011. Print.
- [2] Department for Transportation, Air Accident Investigations Branch. *Report on the Accident to Boeing 777-236ER, G-YMMM, at London Heathrow Airport on 17 January 2008*. Working paper. Crown, 2010. Print.
- [3] Scotty, Leonard R. "Above and Beyond: Fire and Ice." *History of Flight, Aviation, Space Exploration / AirSpaceMag.com*. Web. 14 Nov. 2011. <<http://www.airspacemag.com/military-aviation/Above--Beyond-Fire-and-Ice.html>>.