Appendix L

Correlation of ESATAN TMM with Ice Sublimation Test

Anna Schubert
(EADS Astrium, Germany)

Abstract

During ascent of a previous ARIANE 5 launcher, the stage separation system (SSS) of the cryogenic upper stage (ESCA) exceeded its qualified lower temperature limit at the event of stage separation. Although a proper stage separation could be achieved for that flight, detailed studies followed this unexpected cold temperature drop. These investigations identified the formation of frost/ice on ground and its subsequent sublimation during ascent as the important contribution to the observed phenomenon. Consequently, counteractive measures have been successfully applied for subsequent flights, where up to now a temperature limit violation of the SSS has never been encountered again. For a better understanding of the sublimation effects which were caused by the ice layer on the launcher structure, sublimation tests have been performed. In these tests, an ice layer was applied on two different substrates, one of Plexiglas and one of Aluminium, which were equipped with thermocouples. The test setup was then placed in a vacuum chamber, which was evacuated, causing sublimation of the upper ice layer. During the evacuation, the pressure in the chamber was recorded, and the temperatures were measured in different positions in the ice layer and on both substrate surfaces.

In order to establish a correlation of thermal analyses with the results of the a.m. tests, two small thermal mathematical models (TMMs) were established with ESATAN, one for ice on Aluminium and one for ice on Plexiglas. They represent both the substrate and the ice layer and regard the sublimation heat flux through both, based on the pressure dependent sublimation mass flow rate. Both for the ice on Plexiglas and the ice on Aluminium, the results of the calculations show a very good overall accordance with the measured test results. The applied model, which is the focus of this presentation, is based on the Hertz-Knudsen relation with an evaporation coefficient of $\gamma = 0.3$, where the temperature dependent vapour pressure of ice is respected according to the Goff-Gratch-Equation.


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Correlation of ESATAN TMM with Ice Sublimation Test
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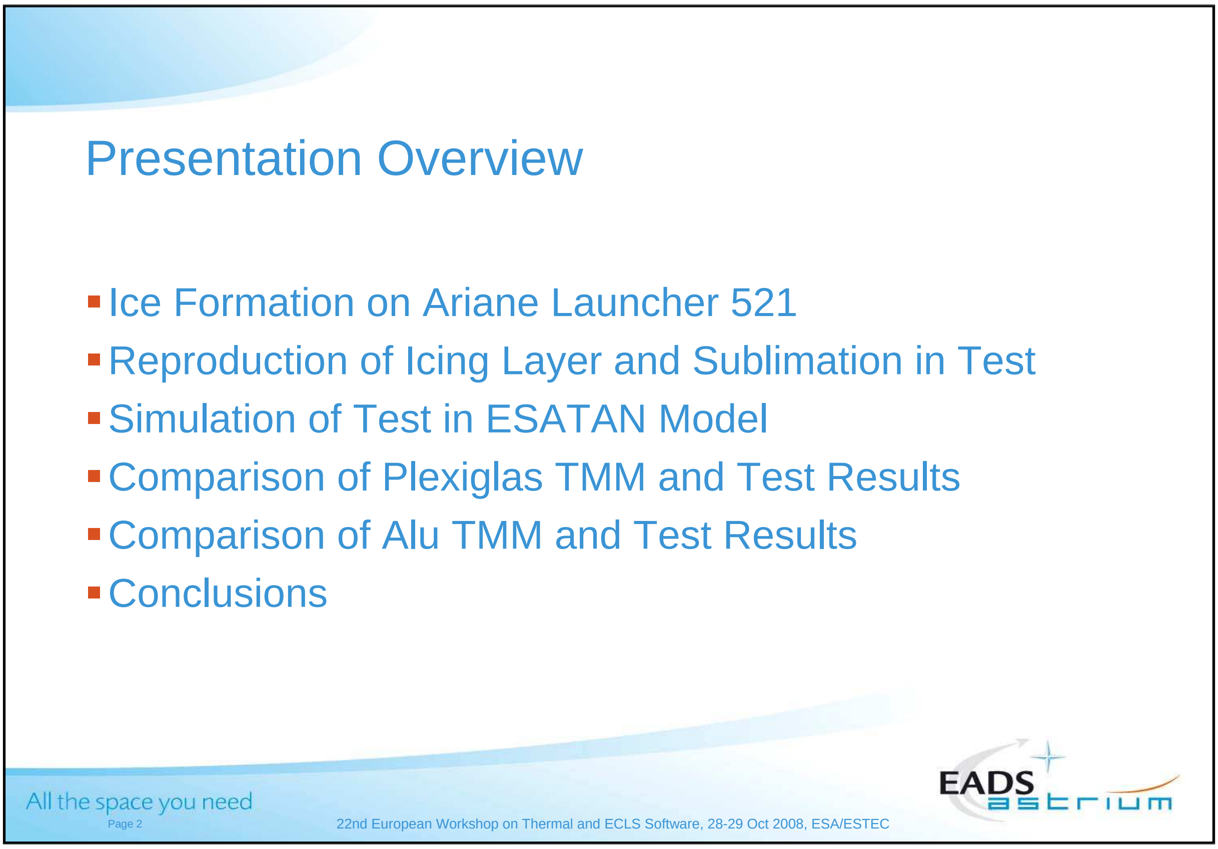
Presentation Overview
Ice Formation on Ariane Launcher 521
Reproduction of Icing Layer and Sublimation in Test
Simulation of Test in ESATAN Model
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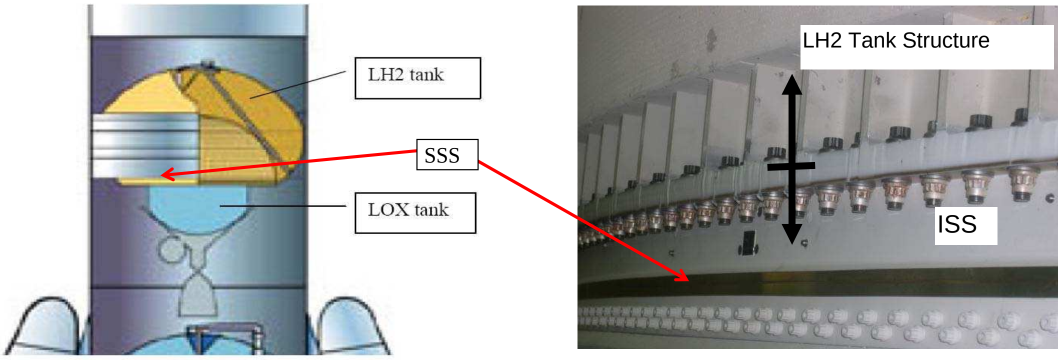
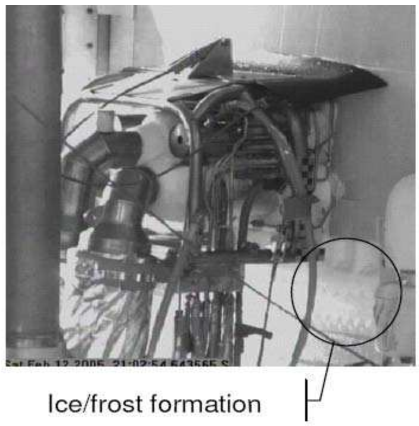
Ice Formation on Ariane 5 Launcher 521 (1/2)

- Description of A5 ESC-A and Stage Separation System (SSS)



Ice Formation on Ariane 5 Launcher 521 (2/2)

- Below LH2 fill and drain coupling, the structure temperature reached values below 0°C.
- Ice layer formed due to humid environment
- During flight, the ice sublimated, and the adjacent structures temperatures dropped even further.
- Countermeasures for following flights: Flushed cover below LH2 and LOX fill and drain coupling and heater system on whole SSS (<u>S</u>tage <u>S</u>eparation <u>S</u>ystem) circumference to avoid ice layer formation



Reproduction of Icing Layer and Sublimation in Test (1/4)

- For better understanding of ice formation and sublimation during launcher ascent, the following tests were performed:
  - Frost formation test
  - Sublimation test with ice layer (2mm) on Plexiglas substrate
    - Plexiglas substrate: 70mm x 70mm x 2mm
    - Thermocouple within ice layer at 1.5mm above Plexiglas
  - Sublimation test with ice layer (5mm) on Aluminium substrate
    - Aluminium substrate: 60mm diameter, 5mm thickness
    - Thermocouples within ice layer in different heights, relevant for model correlation: 2mm and 4.5mm
    - Thermocouples on upper and lower side of Aluminium substrate

To be reproduced with ESATAN TMM

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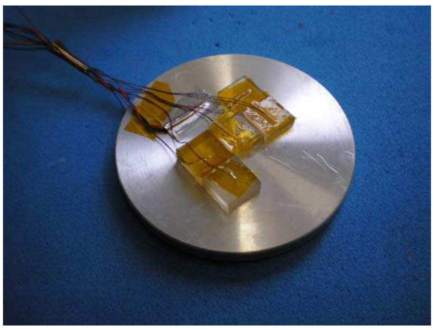
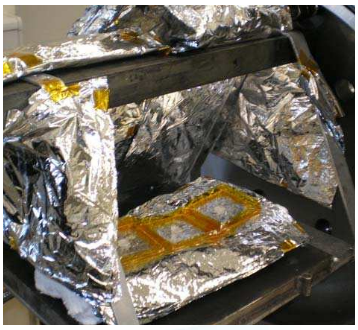
Reproduction of Icing Layer and Sublimation in Test (2/4)

- Sublimation Test Procedure:
  - Substrates equipped with thermocouples and prepared with ice layers were placed in a small chamber, which was evacuated. During evacuation, local temperatures and ambient pressure were measured.



Aluminium substrate equipped with thermocouples



Plexiglas substrates placed in vacuum chamber

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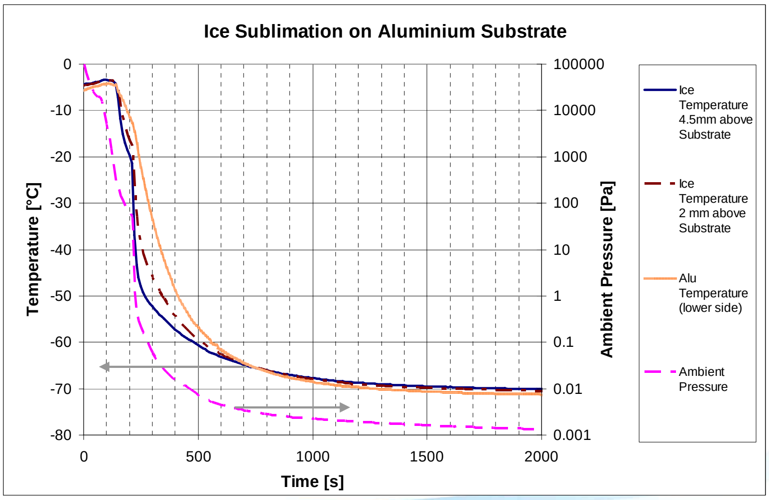
Reproduction of Icing Layer and Sublimation in Test (3/4)

- Test Results with Ice on Aluminium



- Ice temperature 4.5mm above substrate is decreasing until the end. This leads to the conclusion that the thermocouple is covered with ice until the end.

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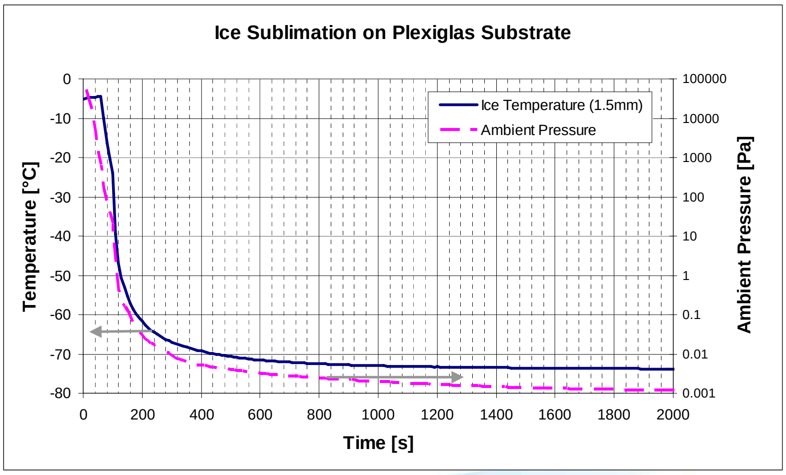
Reproduction of Icing Layer and Sublimation in Test (4/4)

- Test Results with Ice on Plexiglas



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Simulation of Test in ESATAN Model (1/4)

- How can the observed effects of ice layer sublimation be implemeted into a TMM?
  - Establishment of Model in ESATAN
  - Correlation of Test and Model Simulation

- Assumptions and Simplifications (1/3)
  - 1-dimensional heat transfer
  - Lower side of substrate is adiabatic
  - Plexiglas supports for thermocouples neglected
  - Radiation neglected
  - Convection due to evacuation neglected
  - Vaporized ice / water has no impact on vapor concentration

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Simulation of Test in ESATAN Model (2/4)

- Assumptions and Simplifications (2/3)
  - Only heat flux caused by ice sublimation: $\dot{q} = \dot{m} \cdot H_{sub}$
  - Mass flow rate (per m²) based on Hertz-Knudsen relation: $\dot{m} = \frac{\gamma \cdot (p_{vap} - p_{amb})}{\sqrt{\frac{2 \cdot \pi \cdot \Re \cdot T_S}{M_{H_2O}}}}$
  - Consequential decrease of ice layer thickness: $\dot{t} = \frac{\dot{m}}{\rho_{ice} \cdot A}$

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Simulation of Test in ESATAN Model (3/4)

Assumptions and Simplifications (3/3)

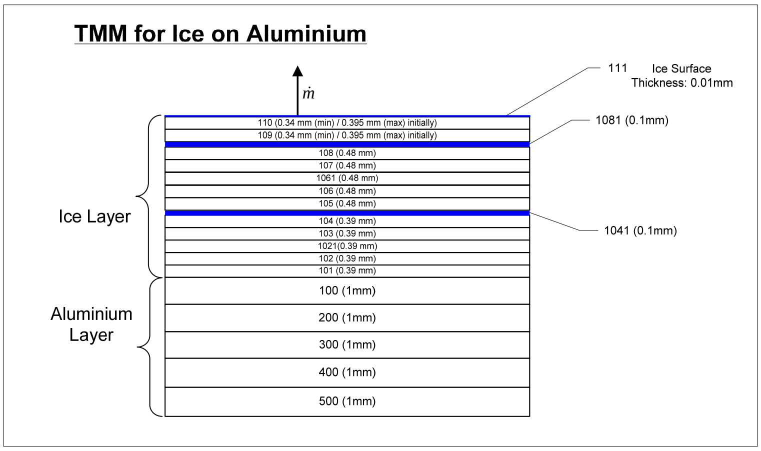
- Temperature dependent vapour pressure of ice [in hPa] from Goff-Gratch Equation:

$$\left.\begin{aligned}\log_{10}(p_{vap}) = &- 9.09718 \cdot (273.16 / T_S - 1) \\ &- 3.56654 \cdot \log_{10}(273.16 / T_S) \\ &+ 0.876793 \cdot (1 - T_S / 273.16) \\ &+ \log_{10}(6.1071)\end{aligned}\right\} \rightarrow p_{vap} \text{ in hPa}$$

- Sublimation enthalpy calculated from melting and vaporising enthalpies:

$$H_{sub} = H_{melt}(T_S) + H_{vap}(T_S)$$
$$= -2.13 \frac{J}{kg \cdot K} \cdot T_S + 248.5 \frac{J}{kg} + 2.33 \frac{J}{kg \cdot K} \cdot T_S - 3134 \frac{J}{kg}$$

Simulation of Test in ESATAN Model (4/4)



- One very thin ice surface layer (0.01mm)
- Two thin ice layers representing the thermocouple locations (0.1mm each)
- Two ice layers with variable thickness (initially 0.34mm (min.) and 0.395mm (max.) each)
- All other ice layers with fixed thickness of 0.39mm / 0.48mm each
- Five Aluminium layers (1mm each)

Simulation of Test in ESATAN Model

- Further assumptions for TMM
  - Filling uncertainty for ice layer: ±0.2 mm
  - Ice layer thickness increased by 3% due to expansion
    - → + 0.06 mm for ice on Plexiglas
    - → + 0.15 mm for ice on Aluminium
  - Ice on Aluminium: Min. thickness constraint, because thermocouple at 4.5 mm is constantly covered with ice → $t_{ini,min}$= 5.24mm instead of 4.95mm
  - **Ice on Alu** initial thicknesses: $t_{ini,min}$ = 5.24 mm; $t_{ini,max}$ = 5.35 mm
  - **Ice on Plexiglas** initial thicknesses: $t_{ini,min}$ = 1.86 mm; $t_{ini,max}$ = 2.26 mm

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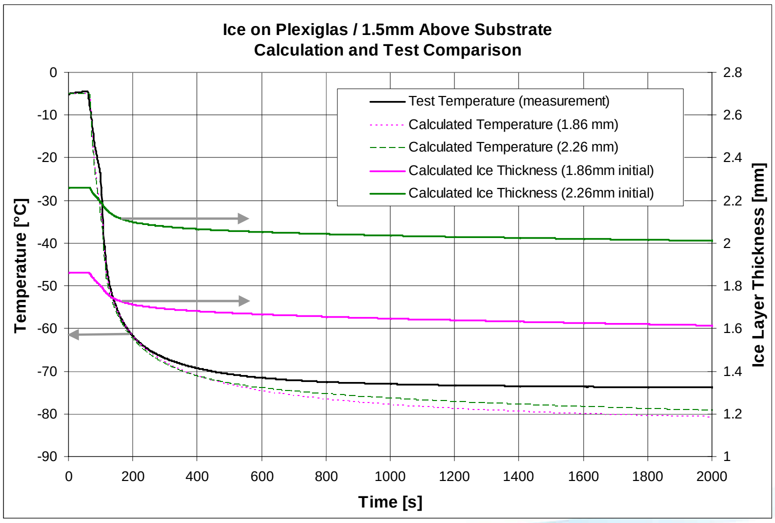
Comparison of Plexiglas TMM and Test Results



- Evaporation coefficient: **γ = 0.3**
- Sensitivity on ice thickness: Min. and max. ice layer thickness, taking into account filling uncertainty
- Good accordance in the beginning, but after 200s, TMM and test results drift apart constantly
- In test, temperature rises during the first 100s. This is not reflected in the simulation, because lateral effects (like radiation, convection, etc.) were neglected

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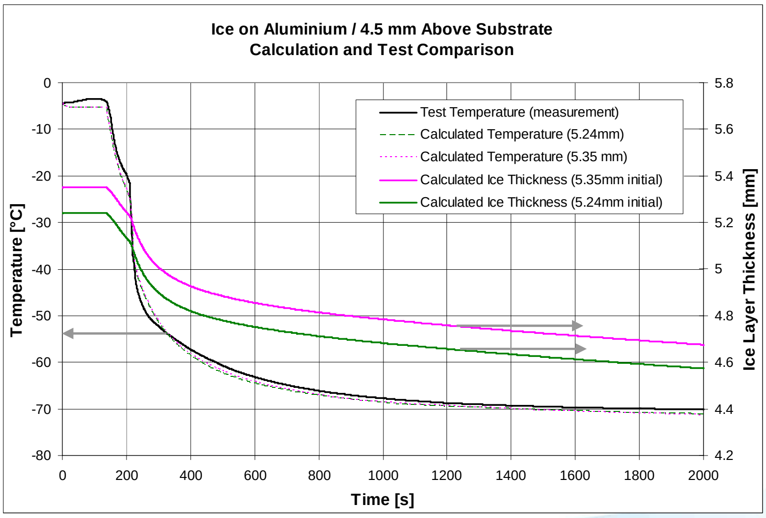
Comparison of Alu TMM and Test Results (1/3)



- Evaporation coefficient: γ **= 0.3**
- Sensitivity on ice thickness: Min. and max. ice layer thickness, taking into account filling uncertainty
- Good accordance, especially regarding the „bends“ in the temperature evolution
- In test, temperature rises during the first 100s. This is not reflected in the simulation, because lateral effects (like radiation, convection, etc.) were neglected

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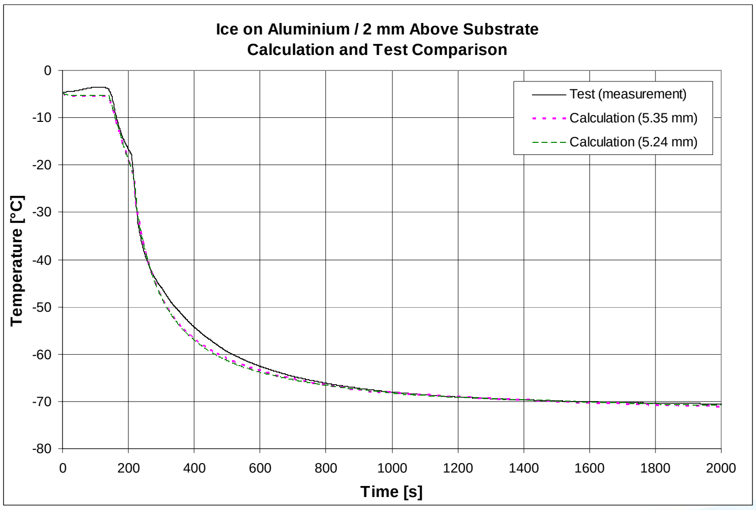
Comparison of Alu TMM and Test Results (2/3)



- Evaporation coefficient: γ **= 0.3**
- Good accordance, especially regarding the „bends“ in the temperature evolution
- In test, temperature rises during the first 100s. This is not reflected in the simulation, because lateral effects (like radiation, convection, etc.) were neglected

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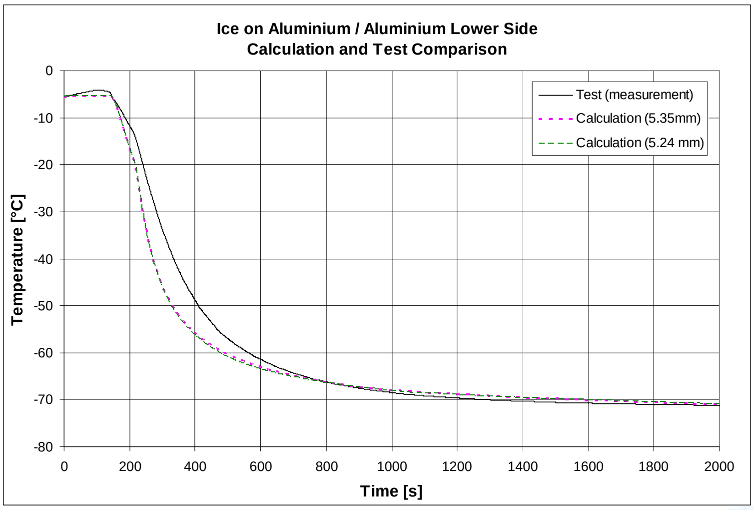
Comparison of Alu TMM and Test Results (3/3)



- Slower temperature drop in reality compared to simulation
- Possible reason: Plexiglas supports for thermocouples constrain heat flux through ice layer

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Conclusions

- Good overall accordance between test results and simulation results
- Evaporation coefficient used in the Hertz-Knudsen relation:

$$\gamma = 0.3$$

- TMM for Ice on Aluminium : Slower temperature drop observed for lower thermocouples (esp. Alu lower side) compared to calculations. Possible reason: Impact of plexiglas supports not negligible
- Refined model extended from 1D to 3D, which regards thermocouple supports, would be favourable.
- New tests, with emphasis on improvement of thermocouple supports and prescision of ice layer thickness would be favourable.

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