An Infrared Solution to a National Priority NASA Ice Detection and Measurement Problem

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ABSTRACT

NASA has a serious problem with ice that forms on the cryogenic-filled Space Shuttle External Tank (ET) that could endanger the crew and vehicle. This problem has defied resolution in the past. To find a solution, a cooperative agreement was developed between NASA-Kennedy Space Center (KSC) and the U.S. Army-Tank-Automotive, armaments Research, Development & Engineering Center (TARDEC). This paper describes the need, initial investigation, solution methodology, and some results for a mobile near-IR ice detection and measurement system developed by MDA of Canada and jointly tested by the U.S. Army TARDEC and NASA. Performance results achieved demonstrate that the pre-launch inspection system has the potential to become a critical tool in addressing NASA's ice problem.

1. INTRODUCTION

The formation of ice (and frost) is a common occurrence on the insulated external tank (ET) of the Space Transportation System (STS). The reason being that in Florida's humid and sometime cold weather, frost and ice are formed because the ET contains large quantities of cryogens–in this case liquid hydrogen (LH2) and liquid oxygen

(LO2). Ice is a critical safety concern because of the possibility of it being liberated from the ET during liftoff and assent. Falling ice could strike and possibly damage the orbiter crew compartment windows, Reinforced Carbon-Carbon (RCC) panels on the leading edge of the Orbiter's wings, or its thermal protection tiles, thus placing the crew and vehicle at risk.

NASA-KSC's initial desires and requirements were that an ice detection and measurement system be developed that would be capable of: differentiating ice from water, remotely detect and measure ice with a thickness of 1/16 in thick (0.0625 in) or more, be portable and be safe for use in the launch pad environment. The 1/16 inch thickness requirement is a Launch Commit Criteria (LCC) limit for safe vehicle ascent. Therefore, any ice detection and measurement system should not significantly underestimate ice thickness.

The system was to be portable for use by the NASA-KSC ice and debris inspection team on launch pad access walkways and platforms during cryogenic tanking tests and T-3 hour pre-launch inspections. As a result of launch pad planned use, it was also required that the system meet launch complex safety requirements (e.g., be explosion proof and within EMI/EMC limits).

NASA and TARDEC directors signed a collaborative research agreement in 2004 and members of TARDEC's Visual Perception Lab (VPL) performed a technology search and evaluation of potential electro-optical systems capable of detecting the presence and determining the thickness of ice on STS ET SOFI. Previous research by VPL investigators, following NASA inquiries, indicated that it might be possible to detect and image ice-covered areas with an infrared (IR) camera. In addition it was realized that methods were needed to detect clear ice (invisible to the naked eye), and to discriminate between ice and water on ET SOFI surfaces.

A technology search initiated by members of the VPL resulted in a selection of three electro-optical systems as candidates for further investigation. The VPL comparison of these systems, testing, and analyses was the subject of the first report submitted to NASA-KSC in June 2004[1]. As a result of that report, VPL investigators and NASA engineers determined that an Ice Camera system developed by MacDonald, Dettwiler and Associates Ltd. (MDA) of Canada offered the greatest potential to support tanking tests and T-3 hour ice debris team inspections on the launch pad prior to STS launches[1].

Because of initial favorable test results and the potential for a possible solution to NASA's ET ice assessment problems, system requirements and specifications were developed, and a contract was let to MDA by TARDEC for the purchase (with NASA provided funds) of a proof-of-concept ice detection and measurement system. The MDA system, referred to as the Ice Camera was calibrated for SOFI surfaces, and delivered to the TARDEC VPL for independent testing and evaluation.

2. SOLUTION METHODOLOGY

The TARDEC-VPL team performed various tests to determine the effectiveness of the system to detect the presence and estimate the thickness of ice on ET SOFI test samples provided by NASA-KSC. Testing of the MDA proof-of-concept Ice Camera at TARDEC confirmed the potential for it's application to ET inspection. The system was found to be able to differentiate between water and ice and provided estimates of the ice thickness but it exhibited noise in ice thickness readings, and required better calibration[2]. Regardless, this system was a breakthrough in remote ice detection and measurement. NASA decided that an improved system would contribute to NASA's ice detection and measurement needs and add a valuable tool to their toolbox of methods and visual inspection capabilities and experience. The improved camera was to be further evaluated during Shuttle pre-launch ET inspections.

Description and Physical Principle of the MDA Ice Camera

Main components of the Ice Camera include a visual and IR camera, an IR strobe, a video tape recorder, and power supplies housed in N_2 purged enclosures and mounted on a two-wheeled portable cart. The inspection cart with camera and strobe mounted in the sensor enclosure and other components are shown in Fig. 1. The IR strobe is low power and is used to illuminate a surface (in this case ET SOFI) on which there may be ice. Internally, the Ice Camera uses the IR strobe, a focal plane sensor array and filter wheel to collect successive images over a number of sub-bands. The system then processes returned and created IR images to determine whether or not ice is present, and then computes and displays ice thickness values to the system operator.

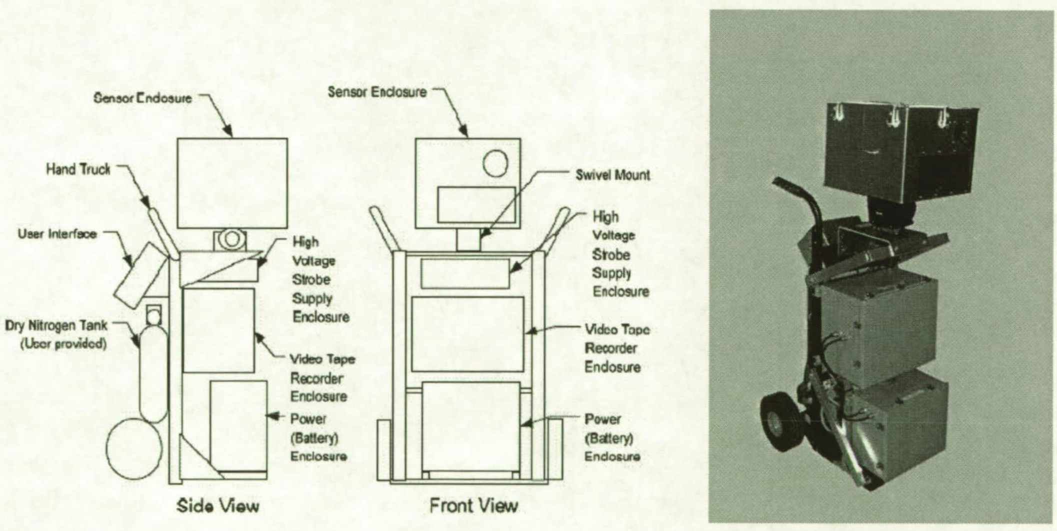

Fig 1: Ice Camera

Measured ice thickness ranges are color-coded for display on the system monitor. They are: 0-0.020 in gray, 0.021-0.050 in green, 0.051-0.060 in yellow, 0.061-0.070 in red, 0.071-0.250 in blue, and 0.251-0.500 in magenta. These color indications help the operator interpret quantitatively the information and measured ice thicknesses displayed.

The Ice Camera detects ice or water by measuring the light reflected from the ice or water layer. [3] The Ice Camera collects the reflected light intensity in a specific wavelength band over which the near infrared reflectance and absorption spectra of ice and water are significantly different and it measures this difference. The principle of operation is explained by referring to Fig. 2: As light is incident on a thin dielectric (e.g. ice), a fraction of the light is reflected at the air/dielectric interface, and the rest of the light is transmitted through the dielectric. The transmitted fraction propagates through the dielectric until it reflects off the substrate. The light reflected off the substrate returns through the dielectric until it reaches the dielectric/air interface, where it is again partially reflected into the dielectric and the air. Some absorption of the light occurs as it travels through the dielectric, and this is what discriminates between ice and water. The internal reflection continues until all the light is absorbed completely by the dielectric.[4]

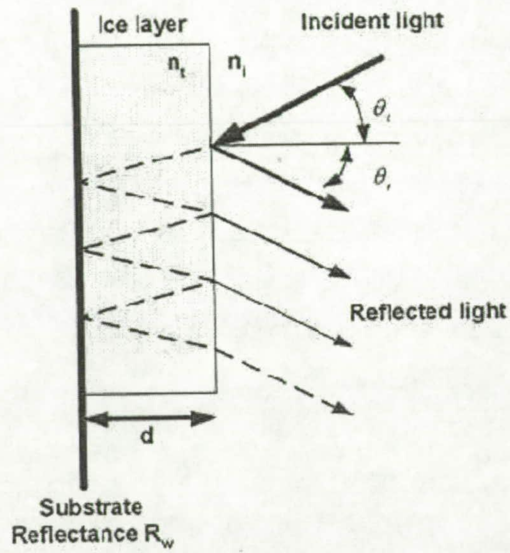

Fig. 2: Reflection of light from a thin ice layer

For a dielectric of thickness *d*, the effective spectral reflectance, $R_e(\lambda,\theta_i)$, of the dielectric layer is given by:

$$R_e(\lambda,\theta_i) = R(\lambda,\theta_i) + \left[\frac{R_w(\lambda)(1-R(\lambda,\theta_i))^2 e^{-2a(\lambda)d}}{1-(R_w(\lambda)R(\lambda,\theta_i))^2 e^{-2a(\lambda)d}}\right] \tag{1}$$

where,

$R_e(\lambda,\theta_i)$ is the effective reflectance

$R(\lambda,\theta)$ is the dielectric spectral reflectance

$a(\lambda)$ is the spectral absorptivity

$R_w(\lambda)$ is the substrate spectral reflectance

λ is the wavelength

θ is the viewing angle with respect to the surface normal.

Fig. 3, shows the computed effective reflectance as a function of wavelength for 0.50 mm ice and water layers with light incident normal to the surface.

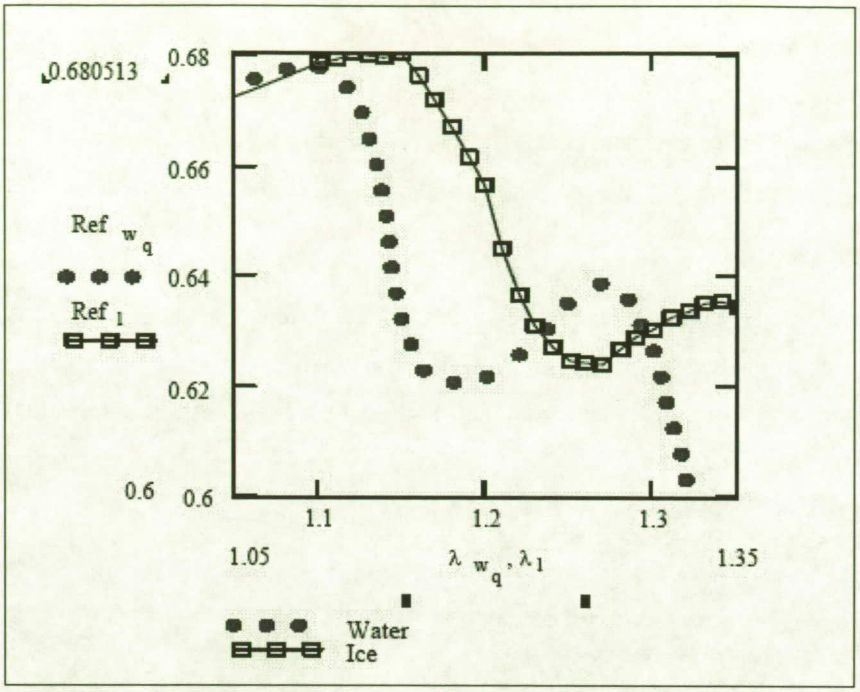

Fig. 3: Computed spectral reflectance of ice and water versus wavelength[3]

It is clear from Fig. 3 that the IR reflectance of water and ice is different. This difference can be measured by using specific sub-bands within the near IR region of 1.1-1.4 microns, and calculating the spectral contrast defined as,

$$C = \left[\frac{R_l - R_u}{R_l + R_u} \right] \tag{2}$$

where *l*, and *u* are the lower and upper bands respectively in Equation 2. Measurement of the reflected energy and the computation of the spectral contrast allows for the detection of ice or water on a surface. Ice produces a positive spectral contrast whereas water generates a negative contrast. The magnitude of the contrast is proportional to the quantity of the ice or water which enables the thickness d, of the ice or water layer to be estimated. However, ice thickness estimates must account for the ice density because ice may exhibit very different densities from low density frost to high density solid ice. Higher density ice will appear to have a greater thickness than lower density ice because there is more ice present per unit volume.

The ice thickness calculated by the Ice Camera is a monotonically increasing function of the spectral contrast and is dependent on both the ice density and fixed camera parameters such as the viewing angle to the ice. As the viewing angle moves away from the surface perpendicular, the spectral contrast decreases for a constant thickness of ice. The effect becomes more significant as the view angle is greater than 55 degrees from the surface perpendicular. Consequently, the spectral contrast to ice thickness conversion function must be determined using an empirical calibration process where the ice thickness and density as well viewing angle are controlled.

Test Location and Set-up

The Ice Camera was tested at an indoor test range located at the Selfridge Air National Guard Base (SANG) in MI. Fig. 4 is a photograph of the test setup, showing the relationship between the MDA unit in the foreground and the cryo test panel in the background being inspected. Fig. 5 shows the cryo panel, ice covered SOFI sample with grid references, and supporting test equipment.

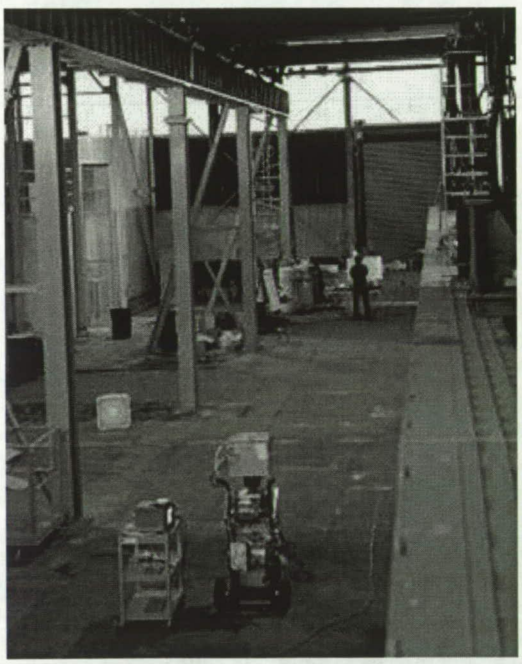

Fig. 4: Test set-up in hanger

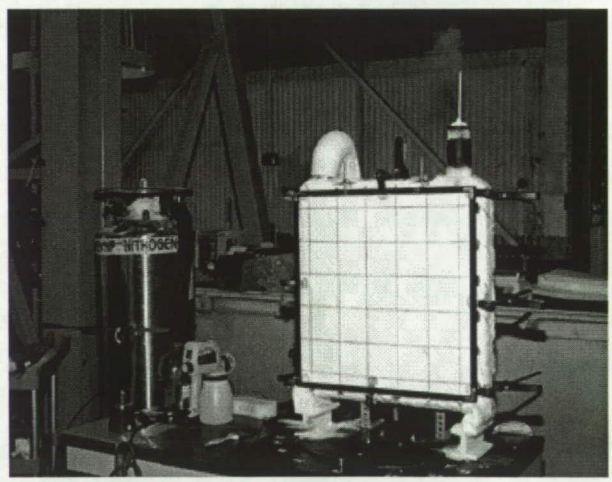

Fig. 5: Ice ice-covered SOFI test panel

The SANG facility could be used for a range of environmental conditions (e.g., 35-86 degrees F and 30-75% relative humidity) but the unregulated ambient environmental conditions complicate consistent ice formation and stability throughout the many repetitive cycles of the test.

A Kaman eddy current thickness measurement tool (shown in Fig. 6) with an uncertainty of ±0.001 inch was the standard for measuring ice layer thicknesses. This device measures the thickness of an insulative material, in this case ice on SOFI, above a metal surface in which eddy currents are induced. A three-inch diameter Kaman sensor was used and provided thickness measurements averaged over its diameter. A SOFI baseline thickness was determined using the Kaman sensor after liquid cryogen was present in the test Dewar, but prior to the presence of ice. After ice was formed, the Kaman was placed on top of the test ice and new measurements made. Ice thickness was then determined from the difference of the two readings and the process was repeated. Densities of ice layers were also required to be representative of actual launch site ET SOFI ice. The density of the ice layers were determined by subtracting the weight of the clean SOFI panel, weighed at the beginning of a test run, from the weight of the ice covered SOFI panel. Then Kaman thickness measurements are made of a new layer of developed ice. Knowing panel area, ice volume can be determined. Measurements were made in the English system to conform to NASA's choice of units.

Fig. 6: Kaman sensor being used to measure the average ice thickness over a grid of locations

Fig. 6 above shows the Kaman unit being used to measure ice thickness on an ice-covered SOFI test sample. A reference grid was used to repeatedly measure the ice in each region of the surface.

The general test measurement sequence involved taking Kaman measurements for specific target areas followed by Ice Camera readings. The Kaman was used as the *measurement* standard for accuracy comparisons with the Ice Camera thickness data.

Results

Experimental data were collected with the Ice Camera at various distances from the SOFI panel, viewing angles, ice densities, and illumination levels. Representative summary data and analyses are as follows for multiple test periods.

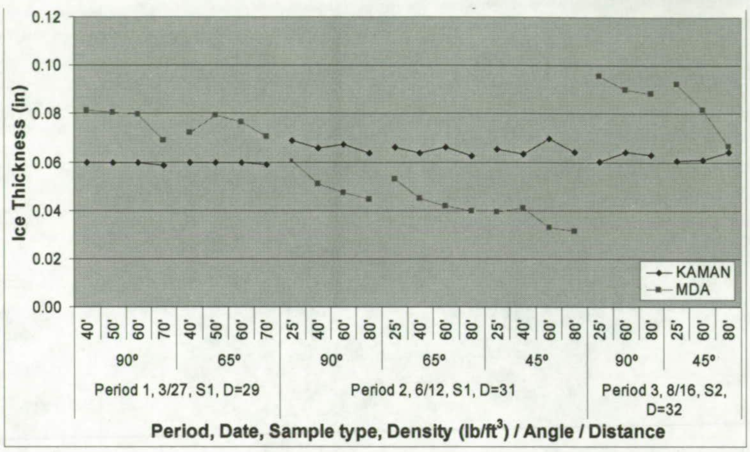

Fig. 7 MDA and Kaman comparison around LCC following a calibration attempt

The chart shown above in Fig. 7 is a consolidation of data from three test periods before and after ice thickness determination. The objective of this combined data is to determine the accuracy of the MDA prototype Ice Camera around the LCC ice thickness of 0.0625 in. The three test densities (D=29, 31, 32) are close to or within the nominal KSC densities of 30 to 40 lb/ft^3, and viewing angles are restricted to 90, 65, and 45 degrees. Represented is a full range of viewing distances from 25 to 80 ft. between the ice test panel and sensor.

The data show that throughout the three periods, the Kaman readings were consistently within ±0.005 inches of the LCC: suggesting that the ice preparation method and hangar environmental conditions were fairly constant. The Ice Camera thickness results indicate a consistent thickness estimate, but with a bias that varies with each calibration attempt. The biases in the first two calibrations were <0.02 inches and the last calibration introduced a larger positive bias of approximately 0.038 inches. The results suggest the importance of the system thickness calibration. As expected, the data show the ice thickness estimates decreases as the angle to the surface perpendicular becomes shallower. For the more accurate calibrations, the thickness estimates are also consistent within 0.01 inches over the 25 to 80 ft range.

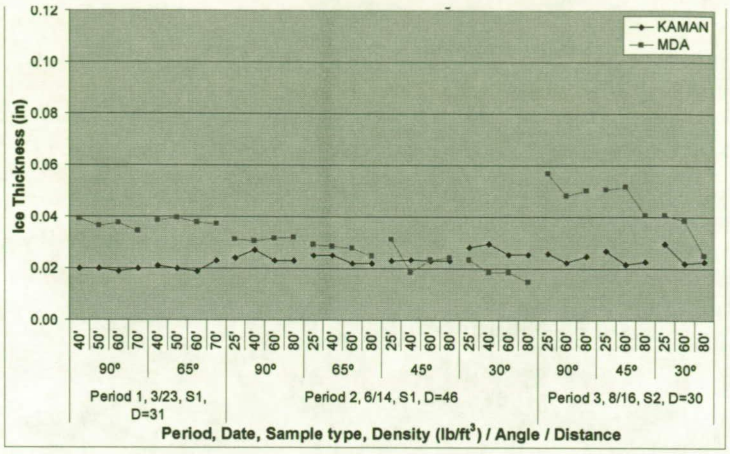

Fig. 8: MDA versus KAMAN comparison for thin ice following calibration attempt

Fig. 8 shows the results for ice layers thinner then LCC ice, around 0.02 to 0.03 in. Two of the test densities are the nominal KSC densities of 30 to 40 lb/ft^3, but the third is for a density of 46 lb/ft^3. For this data representation, viewing angles are 90, 65, 45, and 30 degrees, with a full range of viewing distances from 25 to 80 ft.

Again the Kaman unit shows that the ice preparation technique and the procedural use of the Kaman measurement were consistent. For thin ice around 0.020 in, the viewing angle appears to be less important and there is good agreement between the Kaman and Ice Camera, except in the third period after the latest calibration. The Ice Camera during the second period, agreed within ±0.005 in of ice thickness even for high-density ice of 46 lb/ft^3 except at 30 degrees where Ice Camera readings are less than the Kaman measurements. The first period shows a greater difference but the Ice Camera operation is linear over distance and angle. This data indicates that with a good calibration, the Ice Camera produces consistent measurements over 25-80 ft ranges.

Fig. 9 below shows more recent Ice Camera data comparison collected during Selfridge 2007 winter testing. Pre and post calibration data were collected for a distance of 50 ft. and an 80-degree viewing angle. Fig. 9 shows comparison values between the Kaman measurements and Ice Camera for various ice densities and ice thicknesses. As can be seen, very good agreement exists proving that the Ice Camera can be calibrated to provide accurate ice thickness readings for a variety of ice thicknesses and densities. Other test parameter data indicates close correlation as well.

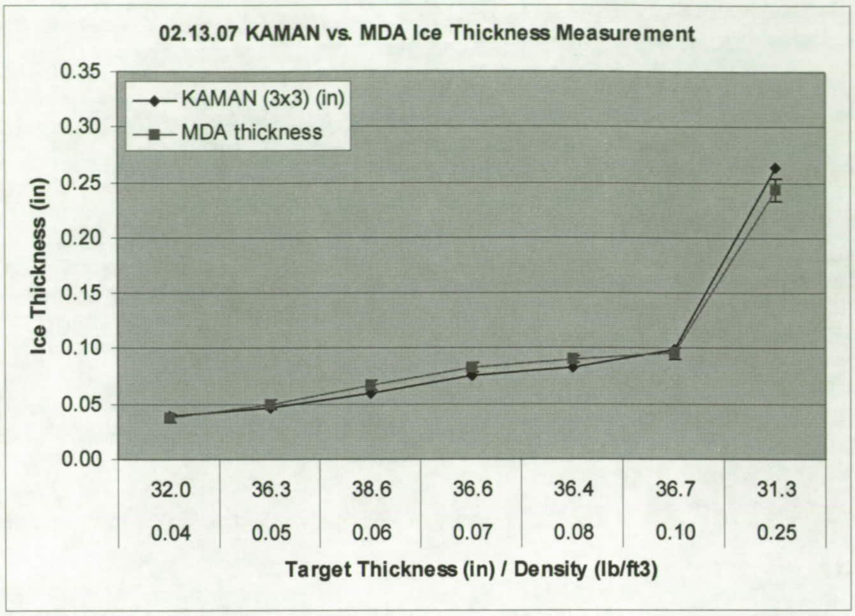

Fig. 9: Feb 07 MDA versus Kaman around LCC calibration results

Application of the Ice Camera for STS-116 Pre-launch Inspection

During the T-3 hour inspection for mission STS-116, the Ice Camera was taken to the launch pad by the ice and debris inspection team and used to image the ET. Various views of the Ice Camera in use are shown below. Fig. 10 shows an Ice and Debris team member using the Ice Camera to make a measurement on the Fixed Service Structure (FSS) 215-foot level crossover to the Rotating Service Structure (RSS). This location provided the views shown in Fig. 11, which is approximately one-half of the LO2 tank acreage that is designated as "no ice zone" because it is above the Orbiter crew compartment. Also shown in Fig. 11, to the right, is the "no-ice' area as imaged by the Ice Camera. The images were taken from about 80 ft. However, no ice was indicated or present at the time. Fig. 12 shows the Hydrogen Tank gaseous vent umbilical disconnect area both visually and using the Ice Camera. The Ice Camera displays thin frost/ice as a green area around on the umbilical connection to the ET.

Fig. 10: Ice Camera in use for STS-116 pre-launch inspection

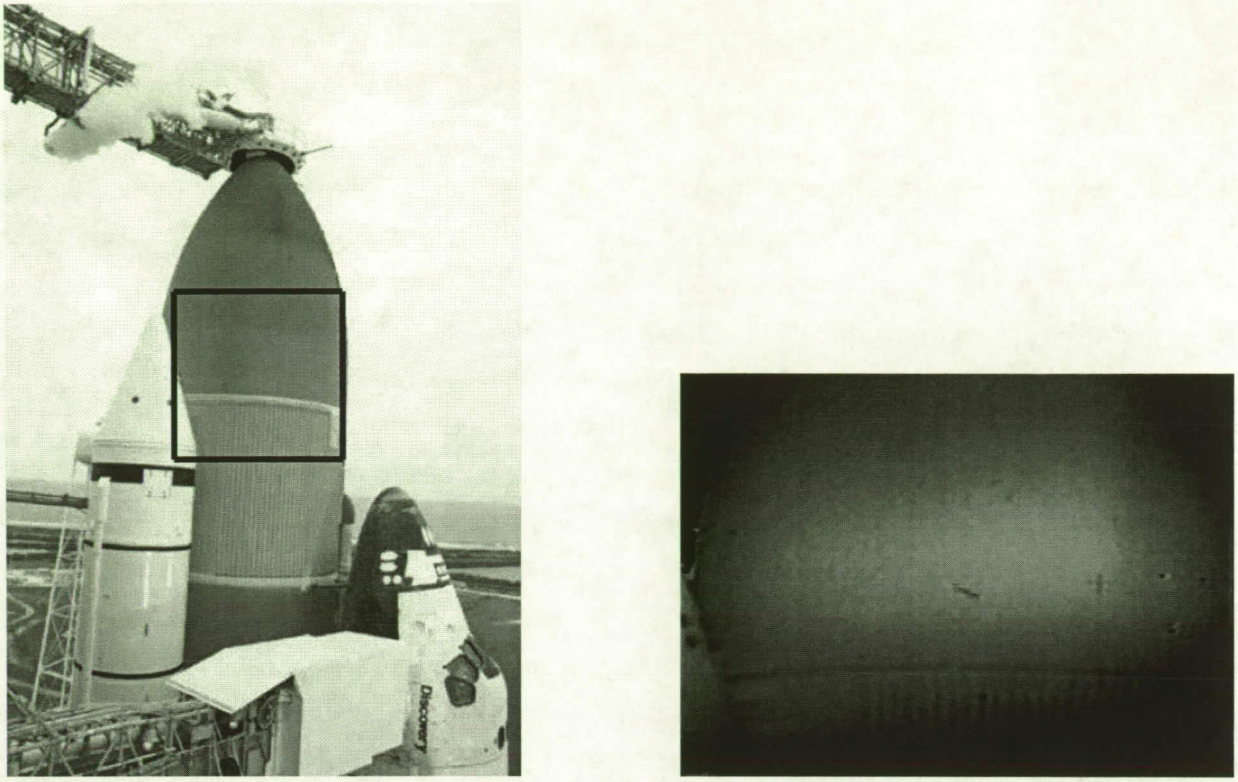

Fig. 11: Visible (left) and Ice Camera infrared images of the ET during STS-116 pre-launch inspection. The square in the visible image outlines the area inspected by the Ice Camera. No ice was detected or present. The camera range to the tank was approximately 80 ft.

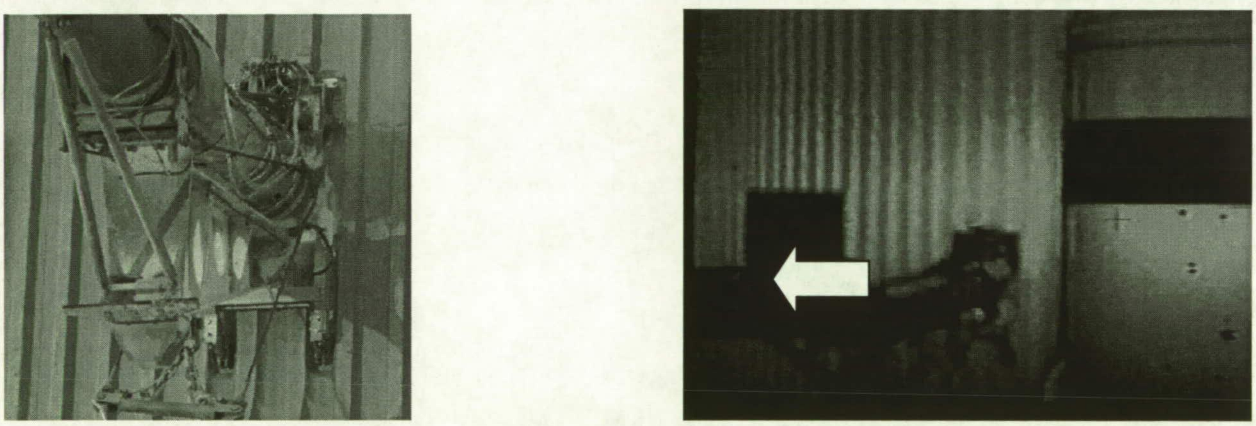

Fig. 12: Visible (left) and Ice Camera infrared images (right) of ET LO_2 umbilical connection. The arrows point to ice/frost and the ice is shown as a green overlay in the Ice Camera image.

3. DISCUSSION

The Ice Camera has demonstrated the capability to remotely detect and measure the thickness of 0.02 to 0.50 inch ice layers on the ET SOFI. In general, the accuracy of the proof-of-concept prototype is within 0.02 inches for near normal viewing angles and ice densities between 30 and 40 lb/ft^3. However, the accuracy of the ice thickness measurements depends on several variables including the quality of the Ice Camera ice thickness calibration function, the density of the ice layer, the viewing angle of the camera to the surface, and Ice Camera measurement noise. The interactions of these independent variables can complicate system calibration.

The quality of the ice thickness calibration is determined foremost by the uniformity of the test ice layer thickness and density built on the SOFI panel. Meticulous care was taken to ensure that the ice developed evenly over the panel and that the test density remained within the range of representative launch site ice densities (30 to 40 lb/ft^3). The second factor determining the quality of the calibration is careful measurement of the physical ice thickness over the SOFI using the Kaman eddy current sensor. A protective, insulative stand-off material between the sensor and the ice must be used so as not to melt the ice. The density of the ice must also be measured after each ice layer is built since the density changes with thickness.

The viewing angle to the surface affects the ice thickness measured by the Ice Camera so during calibration the view angle to the surface is fixed. In addition, the Ice Camera noise contributes to experimental uncertainty which is mitigated by averaging the data for each ice layer. Improving the quality of the calibration reduced bias errors of 0.02-0.03 inches to less than ± 0.008 inches.

The Ice Camera was successfully applied to the inspection of the ET on STS-116. The camera did not produce any false alarms and detected thin ice/frost layers on two umbilical connections that were verified by visual inspection at ranges in excess of 50 feet.

Current testing of the prototype Ice Camera is aimed at determining its ability to detect and measure 1- to 3-inch diameter ice balls formed in ET SOFI breaks. NASA has identified ice ball detection and measurement as an additional requirement of the Ice Camera. It is planned that the system will be used for the next launch of STS-117.

The results of ongoing tests will contribute to an improved next-generation operational ice detection and measurement system that meets NASA's needs. It will add a valuable tool to NASA's toolbox of methods to enhance visual inspection capabilities and operational experience.

4. REFERENCES

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