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Applied High-Speed Imaging for the Icing Research Program at NASA Lewis Research Center

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ABSTRACT

The Icing Research Tunnel at NASA Lewis Research Center provides scientists a scaled, controlled environment to simulate natural icing events. The closed-loop, low speed, refrigerated wind tunnel offers the experimental capability to test for icing certification requirements, analytical model validation and calibration techniques, cloud physics instrumentation refinement, advanced ice protection systems, and rotorcraft icing methodology development. The test procedures for these objectives all require a high degree of visual documentation, both in real-time data acquisition and post-test image processing. This paper provides information to scientific, technical, and industrial imaging specialists as well as to research personnel about the high-speed and conventional imaging systems utilized in the IRT in support of ongoing icing research programs. The focus on high-speed imaging systems will be on the recent ice protection technology program. Various imaging examples from some of the tests are presented. Additional imaging examples are available from the NASA Lewis Research Center.

1. OVERVIEW OF ICING RESEARCH TUNNEL

1.1. History

On June 9, 1944, the NASA Lewis Icing Research Tunnel (IRT) conducted its first icing run. The IRT was constructed in two years at a cost of $670,000. In 1987, 43 years later, the facility was designated an International Historic Mechanical Engineering Landmark by the American Society of Mechanical Engineers (ASME).[1] Currently, the IRT is one of NASA's busiest and most productive wind tunnels. It logged 1029 hours in 1989 and carries a 2-year backlog of work.

The IRT is the largest refrigerated icing wind tunnel in the world. Two unique capabilities of the IRT are its spray nozzle system that creates the supercooled cloud with droplet sizes from 10 to 40 µm median volume droplet (MVD) diameter and liquid water contents (LWC) ranging from 0.2 to 3.0 g/m^3, and the heat exchanger and refrigeration plant that control the air temperature down to -42 °C. A 5000 hp fan provides airspeeds up to 134 m/sec (300 mph). The test section of the tunnel is 1.83 m (6 ft) high, 2.74 m (9 ft) wide, and 6.1 m (20 ft) long. Figure 1 gives an overview of the IRT and control room. Detailed information about the IRT can be found in reference 2.

1.2. Current programs

NASA's aircraft icing technology program is aimed at developing innovative technologies for safe and efficient flight into forecasted icing.[3] The program addresses the needs of all aircraft classes and supports both commercial and military applications.

The icing technology is guided by three strategic objectives: first, to develop and validate a system of computer codes that will numerically simulate an aircraft's response to an in-flight icing encounter; second, to provide experimental facilities that accurately simulate the natural icing environment and to develop new experimental capabilities and techniques to fully utilize these facilities; and third, to support the development and evaluation of advanced ice protection concepts that offer alternatives to compressor bleed-air anti-icing systems.

The NASA IRT is used extensively for code validation, advanced ice protection development, and actual component testing of commercial and military aircraft with both fixed and rotary wings. Some of the programs tested in the IRT are shown in figure 2.

1.3. Low power ice protection technology program

Throughout the last decade there have been a number of new developments in aircraft ice protection technology. Innovative deicing systems have been designed and tested based on electro-mechanical, pneumatic-mechanical, thermal, and conventional pneumatic techniques. As these systems have matured in development, the aircraft industry has shown increasing interest in them as alternate choices to the current technology. With the advent of the increased use of turbofan engines on modern aircraft the engine core flow has decreased substantially, causing concern about the operation of engine bleed-air equipment, i.e. hot bleed air anti-icing systems. The high cost in electrical power has always been an issue in restricting the application of electrically heated (thermal) anti-icers. The advances in new low power ice protection designs may provide opportunities to overcome the above limitations.

Tests of eight different deicing systems based on variations of three different technologies were conducted in the NASA Lewis Research Center Icing Research Tunnel in June and July of 1990.[4] Six companies participated in this joint United States Air Force/NASA ice protection technology program to assess the current state-of-the-art of these technologies. The deicing systems used pneumatic, eddy current repulsive, and electro-expulsive means to shed ice. The tests were conducted on a 1.83 m (6 ft) span, 0.53 m (21 in.) chord NACA 0012 airfoil operated at a 4° angle-of-attack to provide air loads similar to flight conditions to assist in ice removal. The models were tested at two temperatures: a near freezing glaze ice at -3.9 °C, and a hard rime ice at -17.2 °C. Both produce ice accretions that have historically been the hardest to remove. The systems were tested through a range of icing spray times and cycling rates. Characterization of the deicers was accomplished by monitoring power consumption, ice shed particle size, and residual ice. Shed ice information was captured on high speed videography and high speed 16 mm motion pictures. The data from the high speed videography was coupled to a motion analysis software package to calculate shed ice particle size. The potential for future use of these systems on engine inlets will be determined in part by the size, shape, and quantity of the shed ice particles that the engine can safely ingest. The USAF and NASA are exploring this possibility by first identifying whether the information can be captured and credibly measured. This test provided the first opportunity to develop a database that characterizes several of these low power systems.

1.4. Introduction to imaging systems

Historically, photographic imaging at the IRT has been reserved for documenting hardware installation, tunnel operating status, ice accretion during testing, or the resulting post-shed ice formation. This qualitative imaging was accomplished utilizing 35 mm still cameras and the permanently installed tunnel video system, with additional video, still, or movie cameras as required.

Within the past three years, there has been a strong emphasis on producing quantitative imagery of the ice accretion and ice shedding events for data reduction as well as on improving the qualitative imaging of the tunnel. This new interest has resulted in the upgrading of the tunnel's imaging hardware, lighting equipment, timing systems, view ports, data reduction capabilities, and so forth, so that quantifiable data can be derived from these images in the most efficient manner. The following section describes the various imaging systems and upgrades.

2. IMAGING SYSTEMS

2.1. Lighting system

As with any imaging system, the quality of the final images varies directly with the quality of the light utilized. Tungsten lighting systems, correctly referred to as incandescence sources, have been the standard instrumentation lighting method for many years in the IRT. Tungsten lamps are available in an unlimited variety of sizes, shapes, and power ratings. Generally very affordable and easily replaceable, tungsten lamps provide instrumentation personnel with a relatively intense, 2900 to 3200 K color temperature light source. The major shortcoming of tungsten lamps is infrared output which causes, at times, severe and unacceptable ambient temperature rise. With many programs requiring higher-framing rates and greater resolution, adding more and more tungsten lamps was becoming logistically unacceptable because tunnel visual access and power supplies are limited during research programs.

In order to improve the quality of the imaging and eliminate problems associated with the tungsten lighting system medium arc metal halide lamps are now available to IRT research personnel. Commonly referred to as Hydrargyrum [mercury], medium arc length, iodide or "HMI" lamps, these new light sources offer daylight balanced color temperature (5600 K), improved efficiency over conventional tungsten lamps, and approximately one-half the heat build-up for a given lamp size compared to the old tungsten Quartz King 1000 W lamps. Special electronic ballasts allow for flicker-free lighting up to framing rates of 10,000 pictures per second (pps). Two 6000 W and four 575 W lamps are available.

By switching to the HMI lighting system, significant improvements in image quality are obtainable. Because light intensity in the test section will be increased from an average of approximately 2000 footcandles to 25,000 footcandles, forced processing of film is no longer required. Kodak 7250 Extachrome film has been previously "pushed" 1 or 2 stops in processing in order to achieve the necessary exposure for a given test requirement. Our new instrumentation film, Kodak 7296 color negative, is also tungsten balanced but can easily be color corrected during printing to eliminate the color shift caused by the HMI daylight balance. Another advantage of switching to an HMI lighting system is reduction in the number of lights required in the tunnel. Previously, anywhere from 10 to 15 Quartz King 1000 W lamps were required to minimally meet the lighting requirements of a program. HMI lighting requires only 4 lighting fixtures to provide over 10 times the amount of illumination in the test section compared with a tungsten lighting system. Since less IRT visual access window space is occupied by lights, cameras can be positioned more optimally. Figs. 3 to 5 show the IRT's visual access. Finally, another benefit is increased depth of field as lens apertures are stopped down to more optimum positions versus shooting "wide-open." The increased depth of field provides for sharper edge definition on film which in turn allows for a greater ability to track "sharp" ice particles with image processing software.

2.2. Still imaging systems

Used extensively in support of icing research programs, still imaging systems are both conventional silver-halide and electronic in nature. Still imaging systems serve to document control room setups, ice events, close-ups of final ice formation shapes, and various public relations-type photos. Traditional silver-halide based systems are composed on Nikon F3's and F4's with conventional or 250 frame exposure databacks. Utilizing high-intensity Quartz King lamps or the new HMI lamps, the fastest shutter speed of 1/8000 of second and continuous motor drive setting of 5 pictures per second can be used on the Nikon F4 for low time resolution work of 0.2 sec (200 ms). The Nikon F4 with these settings was used to capture ice shedding events during the low power ice protection technology program. The Nikon F4 was initiated just prior to an activation of the de-icer and it typically provided one or two frames of an ice shedding event for a given field of view through the tunnel windows and tunnel speeds between 150 and 300 mph. A low dispersion, coated, Nikon 400 mm focal length lens with appropriate extension ring is employed to obtain the required field of view through tunnel windows. With traditional tungsten lighting, Kodak Ektapress 1600 ASA film provides researchers with high quality images. With the HMI lighting installed, Kodak Kodacolor 100 or 400 ASA film will be used for even sharper images. The Nikon F3's are usually equipped with macro capable lenses, flashes, and Kodacolor 100 for close-up photos of ice formations, control room setups, or additional documentation.

The newest addition to the Icing Research Tunnel's still imaging capabilities is an electronic still photographic system made by Sony. In order to meet researchers' need for "fast" turn-around time for visual data, electronic still photography was incorporated into the IRT facility. The system provides researchers images by utilizing industry standard 2 in. still video floppy disks to record 25 video frames or 50 field images per disk with an electronic still camera. Although the system provides significantly less resolution than conventional film-based 35 mm systems, image quality is more than acceptable for researchers to have an instant review of on-going program results which then enables researchers to evaluate test parameters and modify them if necessary. The camera incorporates two 2/3 in. charge coupled devices (CCD) chips, one each for luminance and chrominance information, and produce a resolution of 500 T.V. lines with an ISO rating of 100 (frame mode) or 200 (field mode). Tunnel lights or an attached strobe provide enough illumination for the low sensitivity of the camera. Additionally, 9.6 sec of audio can be included for each image through a built-in microphone or external microphone providing researchers with an audio notebook of the particlular image. The audio is recorded on a separate track. The camera uses interchangeable Sony bayonet lenses and also has the capability to adapt certain Nikon lenses. Images can be printed out via a Sony video printer or transmitted to other facilities for analysis over telephone lines via Sony's "digital information handler". Images can also be entered into image processing and data reduction computers for analysis by using the red, green, and blue (RGB) outputs from the disc player. The camera has the ability to act strictly as a video camera, outputting composite video via a BNC connection, thus offering additional flexibility to IRT researchers. The camera has automatic white balancing and memory settings for daylight or tungsten lighting. Currently, neither still imaging systems is able to be IRIG B timed with the rest of the imaging systems.

2.3. Video imaging systems

A variety of conventional (60 Hz) video camera systems and accessories are available to IRT researchers. Cameras serve as test section and tunnel monitors and low-time-resolution data systems for certain programs. Both black and white and color cameras are used with all cameras being CCD to eliminate tube technology artifacts and are "C" mount or Nikon mount adaptable. This makes them compatible with most existing still and motion picture imaging lens systems used by the Lewis Research Center's Photographic and Printing Branch. Cameras are generally selected for their low light sensitivity and image quality because it is desirable to minimize lighting fixtures whenever possible. Camera systems provide composite National Television Standards Committee (NTSC) outputs. All cameras can be genlocked with a common video or synchronization signal in order to eliminate vertical roll when cameras are switched to monitors and and to eliminate synchronization disturbances when recording.

All video camera control units, adapters, and system components are centrally rackmounted in the IRT control room (Fig. 6). The controal racks allow researchers a wide variety of video imaging options. Active switchers in the rack can handle up to six composite video inputs. All inputs of the switchers are looped through to each other so any input signal is available on any of the six switchers. Output from all the switchers is routed through a Datum 9710 IRIG B time code generator. This way all signals are timed together. The Datum 9710 can handle 12 composite video inputs. IRIG B time code is window-burned over all inputed video signals by means of expansion slots containing video insertion cards. Custom built IEEE "talker" cards allow interface with the high-speed Kodak Ektapro 1000 system. Once all video signals are time coded, they are routable to any monitor, video tape recorder (VTR), video printer, or the Laird 1480 character generator. The video output of a switcher is wired to the rack-mounted Laird 1480 video character generator which allows for annotation over any selected video input signal prior to recording.

The increased resolution of the video cameras in the IRT required an improved recording method. The Lewis Photographic and Printing Branch chose the S-VHS video format. Panasonic industrial S-VHS VTR's are the main recording VTR's in the IRT. All VTR's are serial interfaceable (RS-422A), and provide over 400 lines of horizontal resolution in S-VHS mode because of the increased bandwidth of the format's luminance channel (1.6 MHz). Improved resolution is achieved with S-VHS recording even with black and white and color composite cameras because resolution improvements are obtained on the luminance channel of the video signal which all cameras output. Only improved colorimetry information, not important in icing research, is lost by not utilizing the luminance/chrominance (Y/C) circuit of the VTR's with a color camera. Additionally, the S-VHS format selection is compatible with the Lewis Photographic and Printing Branch's editing production equipment. This facilitates the creation of technical video report supplements with minimal generational loss.

Switcher input signals are provided by various cameras - a Panasonic D5000, 2 Sony AVC-D7's, a Xybion, and a high-speed Ektapro system. The Panasonic D5000, a single 2/3 in. color CCD camera, provides IRT researchers with a modular design that enables custom configuration for versatile test section monitoring, data acquisition, or public relations work. The system provides remote operation including all lens and pan/tilt functions from a camera control unit located in the control room. This camera is "C" mount or Nikon mount adaptable, genlockable, and provides electronic shuttering or gating up to 1/1000 of a second. This enables researchers to receive low millisecond time resolution during a given 60 Hz output. System output is composite National Television Standards Committee (NTSC) with resolution limited to approximately 380 T.V. lines and a minimum illumination requirement of 0.7 footcandles. The camera is typically mounted on the tunnel ceiling upstream of the test section to record an overall view of the test model for general documentation or to monitor tunnel operations.

Because visual access space is at a premium, two Sony AVC-D7 black and white cameras were chosen for their compact size (2-1/4 in. H x 2 in. W x 5 in. L). They provide detailed overview images and monitoring of selected tunnel areas. The AVC-D7's utilize a single density 2/3 in. 768(H) x 493(V) interline transfer CCD which provides over 550 T.V. lines of resolution with a minimum illumination requirement of 0.3 footcandles. Electronic shuttering is available down to 1/10,000 of a second (10 ms) and camera adapters allow for remote operation up to 300 m away via a standard 75 Ω coax cable. Cameras can be externally genlocked together and a built-in camera identification system allows researchers to easily identify camera positions in multiple camera operations.

An electronically gated and intensified black and white video camera from Xybion Electronic Systems provides ultra-high electronic gating capabilities down to 25 ns and extreme low light capabilities of 1×10^{-6} footcandles. Exact gating values can be determined by outputing the gate signal to an oscilloscope thus enabling researchers to calculate event duration exactly. The camera is "C" mount adaptable, externally genlockable, and provides about 350 T.V. lines of resolution. The camera is commonly mounted on the hatch above the tunnel test section and aimed downward, parallel to the pressure surface of an airfoil. The images from this camera provide information about how far ice particles travel away from the airfoil as they go downstream during the ice shedding event. For this purpose a numbered grid map (0.0254 m squares) on the floor of the test section is included in the field of view. The data are then used to generate scaling factors to correct the Kodak intensified imager (see High-Speed Imaging Systems) field of view information.

2.4. High-speed imaging systems

The KODAK EKTAPRO Motion Analyzer consists of an intensified imager, a controller, and the EKTAPRO 1000 Processor. The KODAK EKTAPRO 1000 Imager has an image intensifier assembly behind the lens and in front of the sensor which functions as an electronic shutter and light amplifier. This increases the imager's ability to capture events in low light and reduce the blurring of objects moving rapidly through the field of view. The intensified imager sends its video output to a standard KODAK EKTAPRO 1000 Processor and in addition is connected to a KODAK EKTAPRO Intensified Imager Controller. The gate time (the amount of time the electronic shutter is open during each frame) can be adjusted from 10 μs to 5 ms.

The EKTAPRO 1000 Analyzer, whose resolution is 240 pixels/column by 192 pixels/row, provides a video output signal compatible with either NTSC (North American) standard or PAL (European) standard video recording signal formats. The processor is équipped with two video output jacks through which the image from the EKTAPRO 1000 cassette can be copied or down loaded to a video cassette recorder or single frames can be sent to a video printer. The Ektapro is IRIG B timed with the rest of the imaging systems by the Datum's "talker only" interface. The Ektapro 1000 only listens and cannot communicate (i.e., talk) with the Datum 9710 and thus requires the custom built "talker only" box.

A recent example (Fig. 7) of the use of the EKTAPRO system in the IRT is for the Low Power Ice Protection Technology Program described in the Overview of Icing Research Tunnel section. Ice accreted on the surface of the wing model is debonded as the deicer activates and the air flow carries the debonded ice away from the model. Since the main concept of de-icers is to induce a rapid displacement of the surface to break the bond between ice and the surface, the whole process occurs in a very short period of time, typically less than a millisecond. Therefore, high speed photography is required to capture any details during the ice shedding event. The details we needed to see during an icing event for the low power ice protection test were the behavior of ice particles as they break off from the surface and are carried downstream by the air flow, and the size of shed ice particles. The size of the shed ice particles was of particular interest to researchers because if deicers are installed at engine inlets, the engine has to tolerate ice ingestion without incurring structural damage. A KODAK EKTAPRO 1000 high speed video camera system provided nonblurred images to define ice particle edges. At a recording rate of 1000 frames per second it supplied enough images to analyze shed ice particle size before particles left the field of view.

Dimensions for the field of view for this particular test were about 0.33 m high (13 in.) and 0.41 m (15 in.) wide. The camera was positioned 1.64 m (64.5 in.) away from the airfoil, shooting perpendicular to the airfoil chordwise axis to minimize the optical distortion caused by angularity. Although the EKTAPRO system is able to provide nonblurred images at 1000 frames per second under the ambient light condition, it was subjected to high intensity light during the test because of the 16 mm high speed film camera lighting requirements. The IRT test section had to be illuminated for the least sensitive imaging device, the 16 mm camera system.

Each recording started just prior to an activation of the de-icer and typically lasted 2 to 3 sec. All information was stored on specially designed KODAK video tapes to preserve the original resolution for later data reduction. Prior to testing, a grid map was located parallel to the airfoil chordwise axis at several different distances from the airfoil and recorded to provide reference lengths for magnification corrections.

2.5. High-speed film systems

Traditional 16 mm high speed photography is used in the IRT in support of secondary data acquisition requirements. These include capturing ice shedding events from a wider field of view to analyse overall patterns, providing a suitable record of testing for public relations and historical records and providing back-up imaging for the particle size cameras (Ektapro systems) should a failure occur. All cameras use 16 mm double perforated film with the exception of the HULCHER camera, which is designed to use 100 ft rolls of 70 mm film (Kodak spec 475). As mentioned earlier, Kodak 7250 Extachrome had been the instrumentation film of choice for IRT programs. The film offered the highest sensitivity of any color film and acceptable results were obtained when the film was "pushed" by 1 or 2 stops during processing. But Kodak's new 7296 color negative film will replace 7250 in all upcoming tests. By using color negative film instead of a chrome during programs, greater exposure latitude is achieved. Although color fidelity is not an important aspect in icing research, color correction because of light and film spectral imbalance (daylight versus tungsten) is easily corrected during printing. Kodak 7296 is more sensitive than 7250 with an ISO of 500 versus 400 and incorporates "T" grain technology for unsurpassed resolution with maximum sensitivity.

Currently there are four types of high speed motion picture cameras available for use in the IRT. Depending on testing parameters, specific camera attributes, and equipment availability, one or all of them may be used. These cameras are: NAC model E-10, NOVA model 16-3, FASTAX model WF30, and the HULCHER 70 model 100.

Recently purchased by the IRT research group, the NAC model E-10, a rotating prism camera, is capable of shooting 300 to 10,000 frames per second. Utilizing "C" mount lenses, interchangeable shutter discs, start-stop operation, 400 and 1200 ft film magazines, electronically regulated framing rates, event synchronization, oscilloscope recording, continuous reflex viewing, and internal optics of f/2.5, the NAC provides the IRT with a versatile, state-of-the-art camera.

For ice shedding event filming, the NAC is fitted with an 18° shutter and run at a framing rate of 3000 pps. This yields an effective shutter speed of 1/60,000 second (16.7 μs). Nominally, 400 ft film loads are used, with the option of installing the 1200 ft magazine for start-stop operation or long duration filming. Built-in LED timing lamps are connected to the IRIG "B" time code so that data from this camera can be matched to data from the other imaging systems and chart recorders. The time code correlation between all recording systems is a vital part of reducing quantifiable data.

Also available is a NOVA model 16-3 rotating prism camera. Typically this camera is used to record the overall shed characteristics and is mounted in one of the forward section windows looking aft at the model. From this angle, shed particles are viewed qualitatively as they are expelled from the model and travel downstream. Additionally, this camera provides a limited view of the suction side of the model leading edge not imaged by any of the data reduction cameras.

The NOVA camera is set to run at 3000 pps by adjusting the input ac voltage through a Variac. This is necessary because the NOVA motor does not have electronic speed control nor a built-in governor, which translates to a constantly varying motor speed until stabilizing near 3000 pps. The approximate framing rate, or pps, is derived by consulting a framing rate versus input voltage graph.

The camera is usually configured with a Wollensak lens mount, however an optional Fairchild mount is available. Three fixed aperture slits are available for this camera at shutter factors of 3 (full slit), 6 (half slit), and 12 (quarter slit). With a transmission aperture of f/2.8 and a shutter factor of 12, this camera yields, at 3000 pps, an effective shutter speed of 1/36 000 sec (27.7 μs). Image size is reduced in the vertical dimension because of the narrower aperture slit, which affects the vertical field of view. This artifact does not pose a problem for filming leading edge models, as the camera is rotated 90° to utilize the horizontal camera field of view for the model's vertical tunnel installation.

The FASTAX WF30 camera is also of a rotating prism design and is capable of 300 to 3000 frames/second. Standard configuration consists of a 1200 ft film capacity, rotating disc shutter, start-stop operation, and electronic speed control. This camera now serves as a back-up to the NAC E-10 (although it does not incorporate some of the features found in the NAC), and as a secondary view camera requiring a large film capacity.

With a loaded magazine, the WF30 weighs a hefty 86 lb. This is nearly twice the weight of the NAC E-10, and does not include the required individual camera control units. Also the WF30 has only the 1200 ft magazine which requires darkroom load spools. Prior to acquiring the NAC E-10, the WF30 was used to film ice shedding from rotorcraft scale models tested in the IRT (Fig. 8). To achieve a satisfactory shutter speed, the standard shutter was replaced with a custom fabricated rotating sector disc, providing a 12° opening and yielding a shutter factor of 30. This resulted in a shutter speed of 1/60,000 second (16.7 μs) when running at 2000 pps.

Pictorial and public relations photos are shot with the HULCHER 70 model 100 camera. This unit operates on 120 V ac and can run up to 50 pps (2-1/4 in. square format) or 25 pps (5 x 2-1/4 in.). The 50 pps rate is used in the IRT, producing a medium format negative suitable for quality enlargements. Normally a focal length of 125 mm or greater is required for this camera, but because of restricted camera placement, a 50 mm lens is specified. This is accomplished by modifying the lens mounting assembly on the camera and permitting a 50 mm view camera lens to be moved closer to the film plane. This modification requires the removal of the built-in ground glass focusing system and accompanying mirror. Focus is now performed by removing the camera's pressure plate and focusing on the ground glass at the film plane. Another modification to this camera is the installation of LED timing lamps for film edge marking with IRIG or other timing information in order to synchronize the camera with other timed imaging systems.

3. IMAGING DATA REDUCTION AND IMAGE PROCESSING

3.1. Vanguard data reduction

A Vanguard data reduction system allows image data measurement from 16 mm motion picture film. Film is loaded onto the Vanguard's 16 mm projection head, which also contains an optically aligned 3 chip CCD NEC video camera for composite or RGB output, and is rear projected onto a large viewing screen (15.5 x 22 in.). Actual image size on the viewing screen is 10 x 13.5 in. The system can handle up to 1200 ft of film and is interfaced with an IBM compatible 486 computer which contains the data reduction software, Motion Analysis Package (MAP) by Concurrent Processing Incorporated and a frame grabbing board to handle video information. Researchers load film onto the optical head and choose selected frames to be analyzed. Data is entered into the computer via a digitizing tablet or keyboard. An ASCII file is then transferred to MAP and a variety of data reduction can be perfotmed.

The Vanguard system is just one of the main input devices for the Lewis Research Center's Photographic and Printing Branch's data reduction and image processing system shown in Fig. 9. The system was designed to handle a variety of data input sources including 16 mm film, composite video, and RGB video signals into either a PC- or Unix-based system depending on the researchers requirements. Images can then be image processed, data reduced, outputted to video or computer printers, or patched into video editing suites for easy incorporation into research video productions.

3.2. Motion pro data reduction software

Motion Pro is a menu-driven software package designed to facilitate the task of digitizing object motion recorded with high-speed video systems. Motion Pro is used under the Disk Operating System (DOS). It can collect points, centroids, angles, or line segments and provide fully scaled measurements of linear and angular displacements and speeds. It can also scan tapes and compile lists of the sessions to help organize tape libraries. This Motion Pro was modified to map the particle boundary so that it calculates the ice particle size from the ice shedding images on Ektapro tapes.

A particle is defined by enclosing its boundary using a PC-DOS mouse; then Motion Pro counts the number of pixels occupied within the boundary. The pixel count is converted to an area with a physical dimension by applying a scale factor. A scaling factor is necessary to provide image plane depth correction because it was found from the overhead shots that ice particles travel outward from the airfoil as they go downstream. The distance out depended on system, airspeed, and time, so a number of reference lengths were chosen. This scale factor is determined from images of a known grid scale that are specified distances from the airfoil lower surface. The grid scale was suspended parallel to the plane containing the airfoil chordwise axis; the distances were measured at the maximum thickness of the airfoil. The grid, composed of 0.0254 m (1 in.) squares, was displayed in the EKTAPRO camera image plane at four different reference lengths: 0.0254 m (1 in.), 0.127 m (5 in.), 0.254 m (10 in.), and 0.381 m (15 in.). The images were recorded and placed in the EKTAPRO processor nonvolatile memory where they were used to provide the correlation between scale factor and particle distance away from the airfoil.

A typical procedure for ice particle size measurement follows. The ice shed event is monitored in a frame-by-frame sequence until the particle displays the largest frontal area. The boundary of the particle is mapped with a mouse (through Motion Pro), then a corresponding overhead shot from the Xybion camera is found to determine the linear distance of the particle from the airfoil surface. This is used to calculate a scaling factor which is applied to the pixel area representing the size of the particle. For each shedding event, size measurements were typically made for the three biggest particles.

As described above, data reduction using Motion Pro is labor intensive and very time consuming. It became apparent during the data reduction phase that an automated process is desirable because there is a large volume of data. An effort is underway to develop software which will automate the data reduction process by utilizing pattern recognition techniques.

4. FUTURE IMAGING SYSTEMS

Even as these new imaging systems are being incorporated into the IRT, the next generation of imaging improvements and systems are being considered for the facility. Digital video recording formats and cameras as well as improvements in computing power are quickly becoming available, providing users with unprecedented flexibility and signal quality not previously attainable. Two of the major future thrusts for IRT imaging are in the areas of three-dimensional and stereo imaging.

Documentation of cross-sectional ice shapes is an important part of icing research in the IRT. Code developers often compare experimental ice shapes with their predictions to validate the codes. The current method used for ice shape documentation in the IRT is a manual tracing using cardboard templates and a pen. This technique is simple and requires a very small amount of time. This is important to minimize changes in ice shapes caused by sublimation. However, this method involves human factors which could make ice shape tracing dependent on personnel taking the data.

Surface roughness information is also of great importance for code developments in both flow and heat transfer modelling. These data cannot be obtained from ice shape tracings because of the small size and three dimensionality of roughness elements.

One way to eliminate human factors and to document both ice shape and surface roughness is to make a mold of the ice shape and to digitize the mold using a three-dimensional scanning system at a later time. An important concern in using a three-dimensional scanning system is the ability of the system to provide resolution high enough to catch roughness information. Some of the details of surface roughness may be lost in the process of making a mold. The sensitivity of the molding process will be examined in an upcoming test. The three-dimensional scanning system will be linked to a workstation to perform various post-test analyses. A study to develop this technique and an appropriate system is currently underway.

Stereo photography is another technique that can be used to measure ice accretion size and shape. This technique has been used for NASA's natural icing flight research program which uses a DeHavilland DHC-6 Twin Otter aircraft. Stereo photography does not intrude on the test and three-dimensional shapes can be constructed after processing images. The major concerns are its resolution and its ability to produce suitable imagery through clouds.

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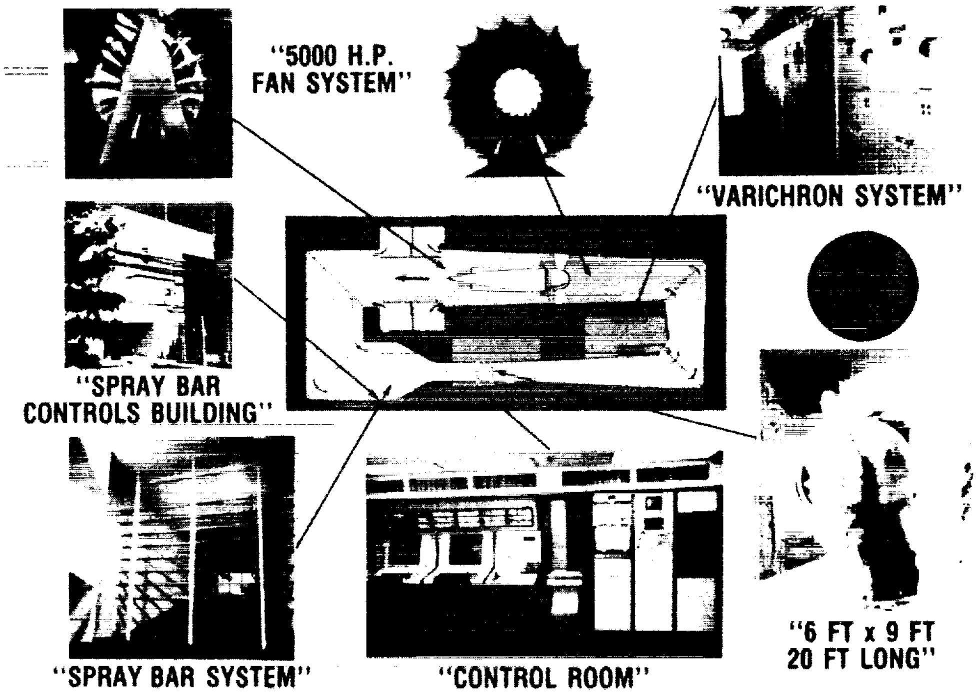

Figure 1.—Overview of NASA Lewis Research Center IRT.

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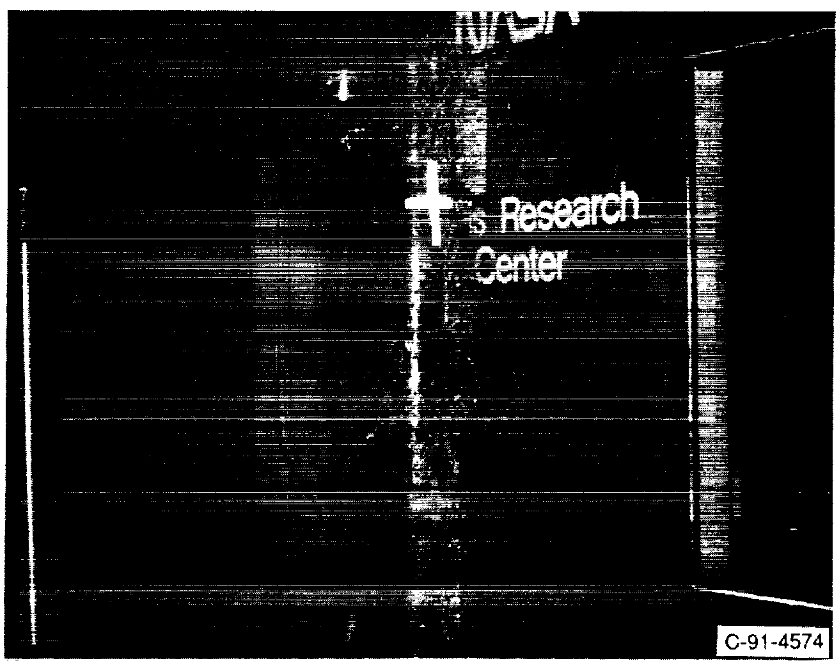
(a) Boeing 737-200 ADV half model with ground plate undergoing ground de-/anti-icing test in NASA Lewis Research Center IRT.



(b) Eddy-current repulsion deicer undergoing development tests in IRT as part of a NASA Small Business Innovative Research contract.

Figure 2.—Recent test programs in the NASA Lewis Research Center IRT.

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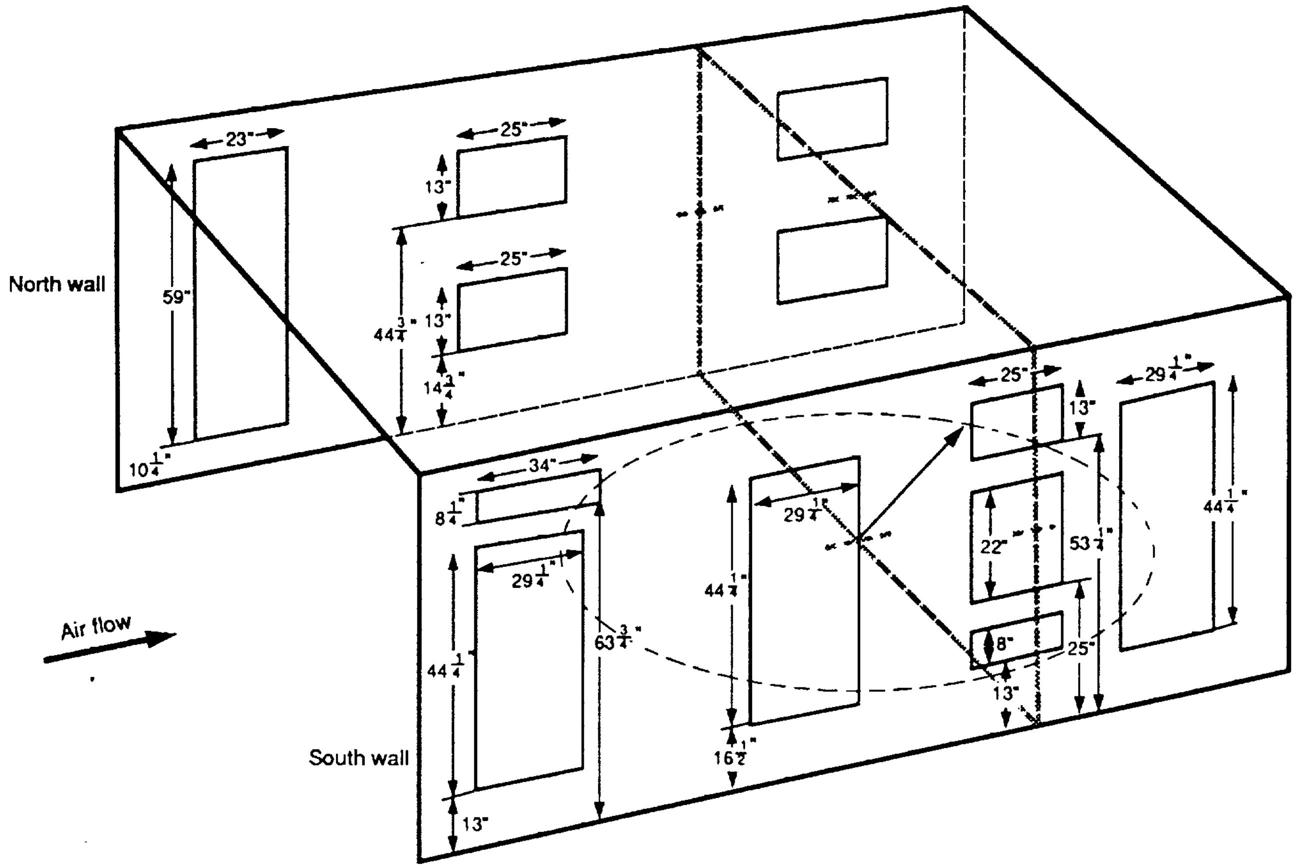

Figure 3.—NASA Lewis Research Center IRT visual access to test section from north and south walls.

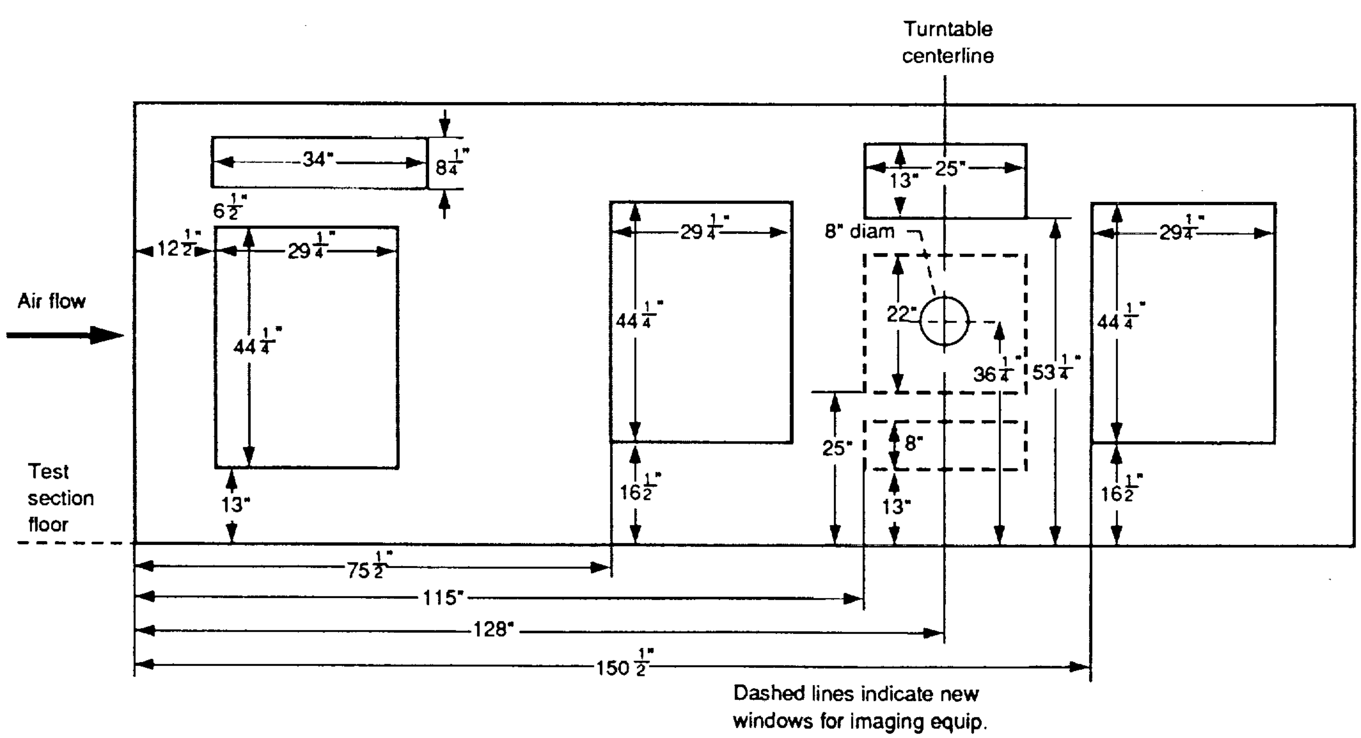

Figure 4.—NASA Lewis Research Center IRT visual access control room - south wall side (looking into test section).

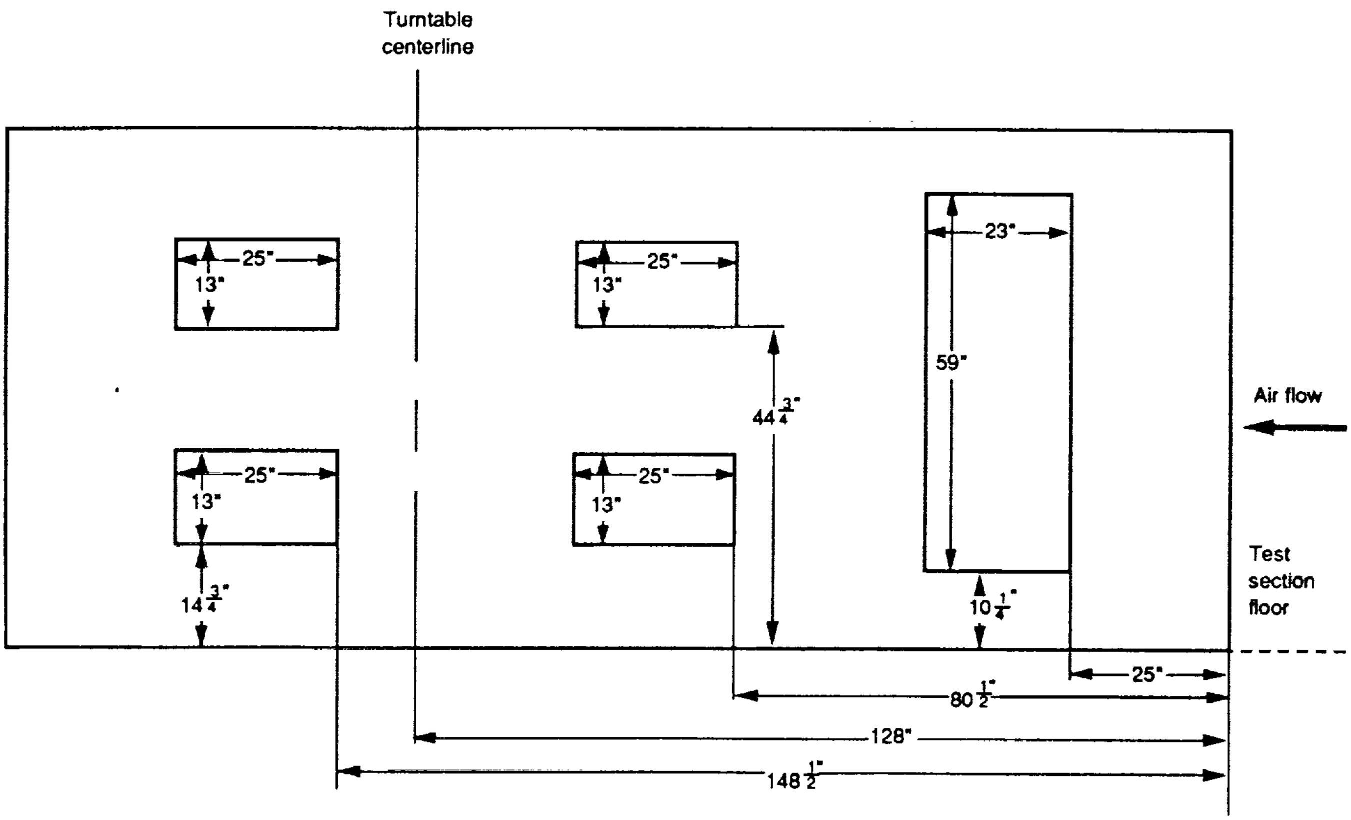

Figure 5.—NASA Lewis Research Center IRT visual access control room - north wall side (looking into test section).

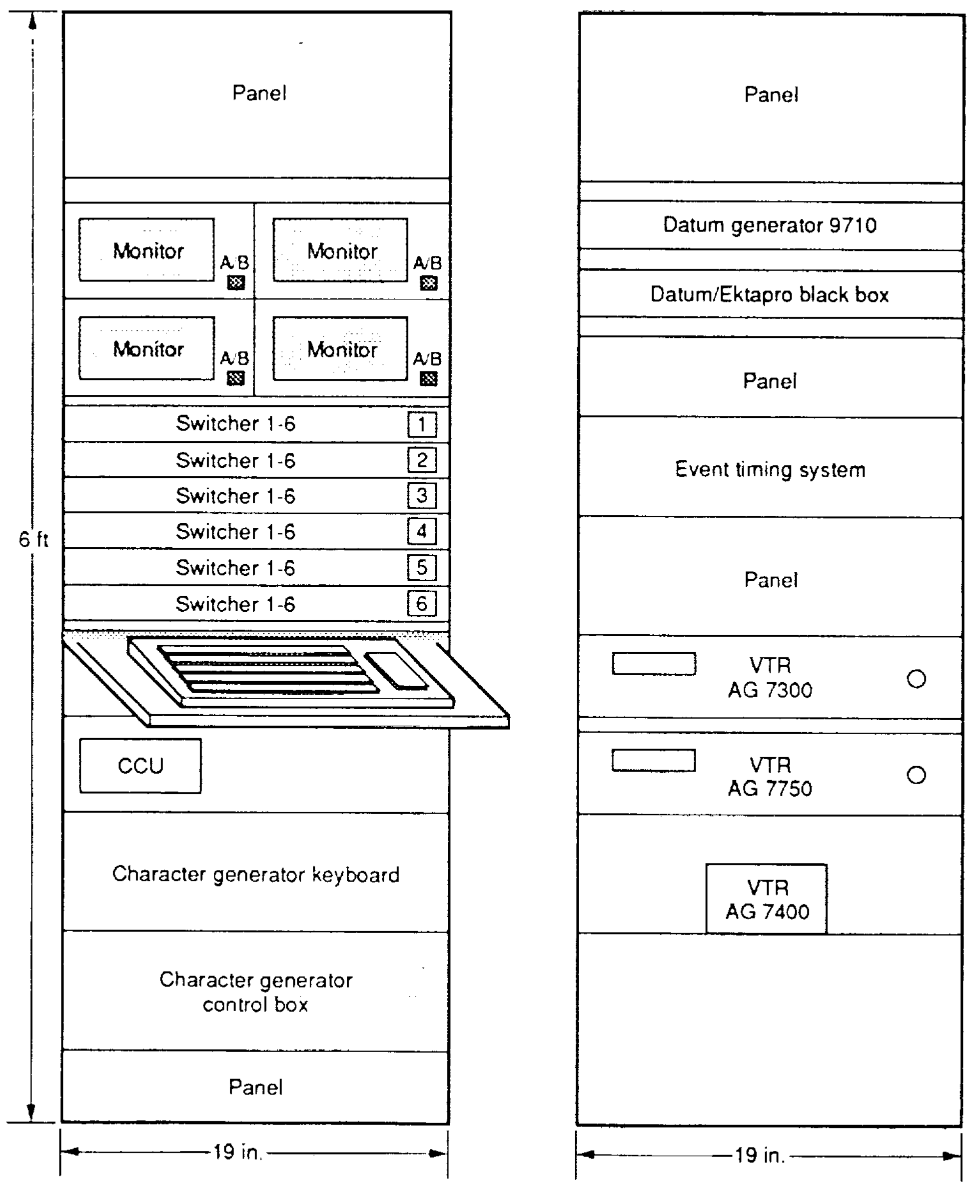

Figure 6.—IRT video imaging rack layout.

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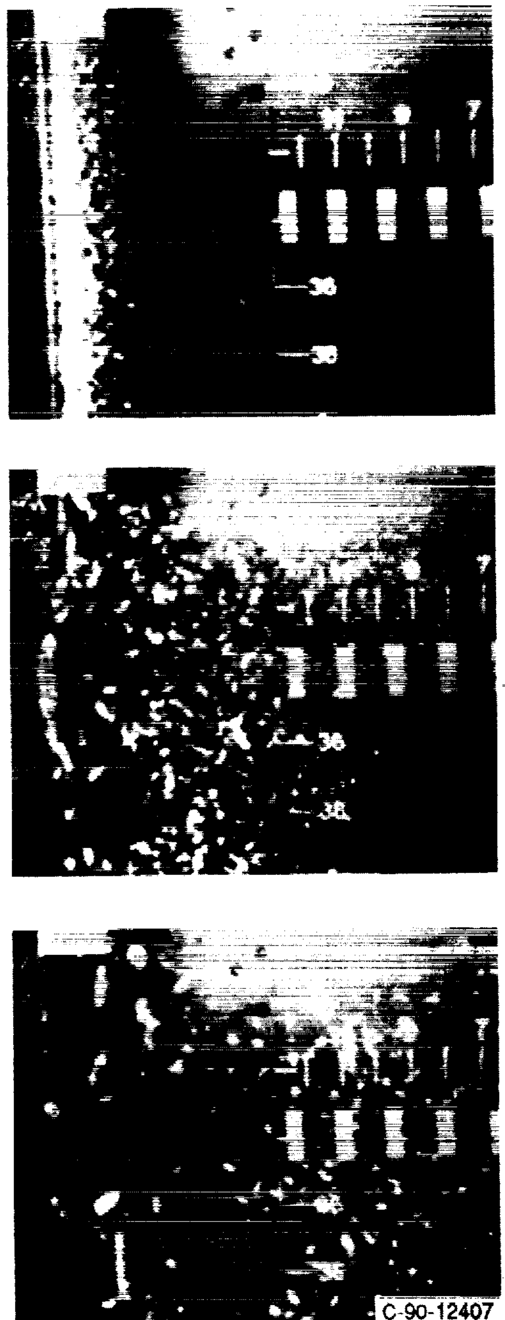

Figure 7.—Air Force/NASA low power ice protection technology program; high speed videography to capture ice shedding event. (6 minute spray-glaze ice).

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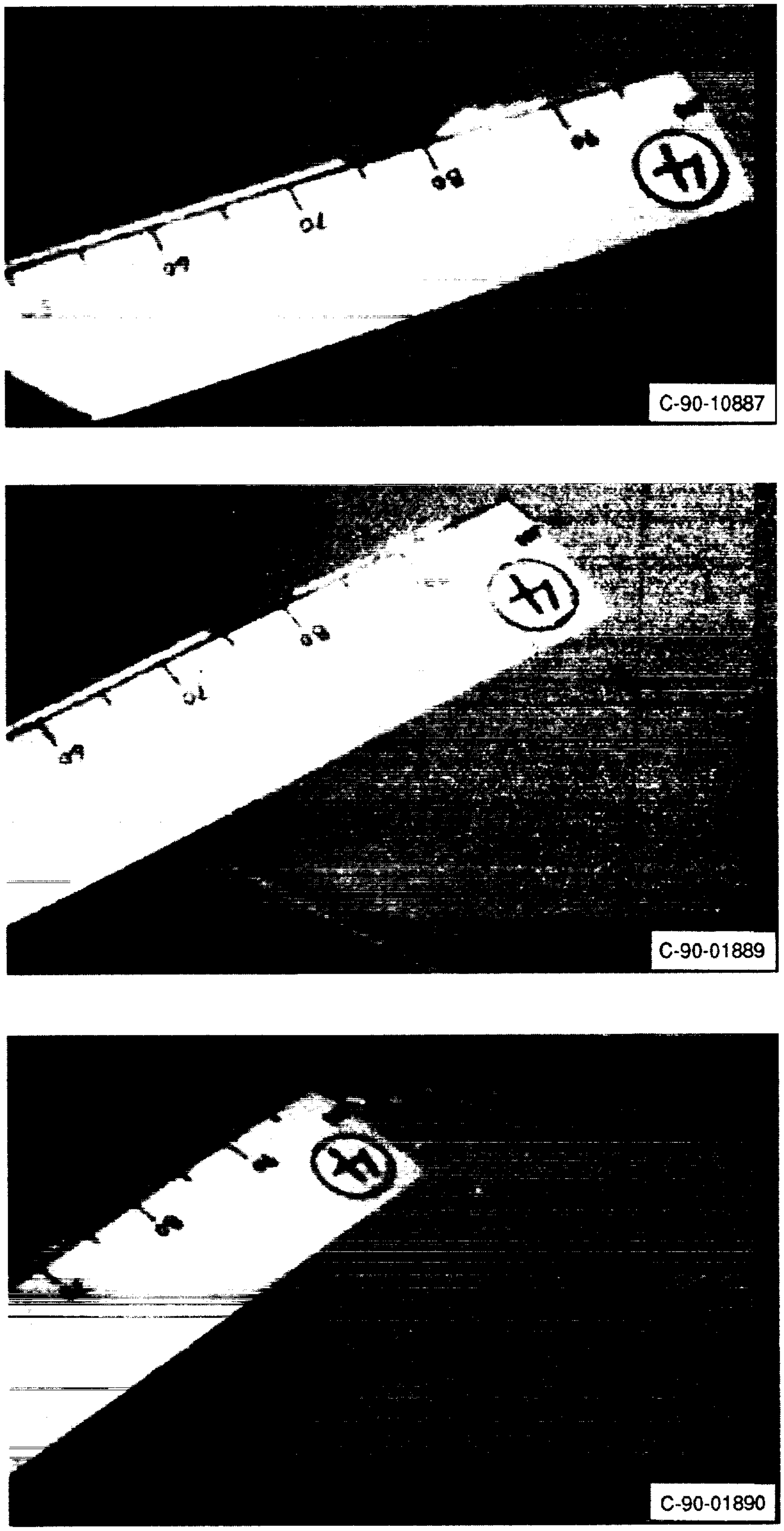

Figure 8.—High-speed camera sequence of ice shedding off scale model Blackhawk rotor blade.

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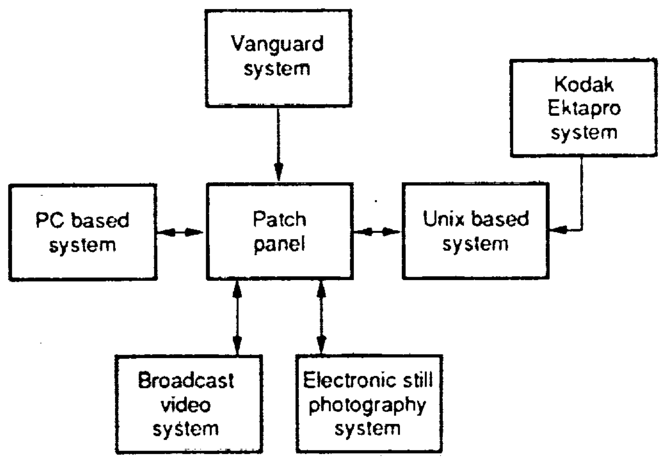

Figure 9.—Data reduction and image processing system in the photographic and printing branch.

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16. Abstract
The Icing Research Tunnel at NASA Lewis Research Center provides scientists a scaled, controlled environment to simulate natural icing events. The closed-loop, low speed, refrigerated wind tunnel offers the experimental capability to test for icing certification requirements, analytical model validation and calibration techniques, cloud physics instrumentation refinement, advanced ice protection systems, and rotorcraft icing methodology development. The test procedures for these objectives all require a high degree of visual documentation, both in real-time data acquisition and post-test image processing. This paper provides information to scientific, technical, and industrial imaging specialists as well as to research personnel about the high-speed and conventional imaging systems utilized in the IRT in support of ongoing icing research programs. The focus on high-speed imaging systems will be on the recent ice protection technology program. Various imaging examples from some of the tests are presented. Additional imaging examples are available from the NASA Lewis Research Center's Photographic and Printing Branch.

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