Federal Aviation Administration
Aircraft Certification Service
Small Airplane Directorate

Mitsubishi Heavy Industries MU-2B Series Airplane FFFSCR Report

June 27, 1997

FAA/JCAB FACT FINDING FOCUSED SPECIAL CERTIFICATION REVIEW TEAM

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U.S. Department of Transportation

Federal Aviation Administration

Memorandum

Subject: Mitsubishi MU 2 Special Certification Review Team Charter

Date: January 25, 1996

From: Manager, Small Airplane Directorate
Aircraft Certification Service, ACE-100

Reply to Attn. of:

To: Manager, Standards Office, ACE-110

I am requesting that you initiate the formation of a Special Certification Review (SCR) team. The charter for the team is to:

1. Review the original icing certification of the airplane;
2. Examine the airplane characteristics in the icing environment described by 14 CFR part 25, Appendix C;
3. Examine the airplane characteristics in the freezing drizzle icing environment as we now understand it;
4. Determine if any of the characteristics observed in 1, 2 or 3 above could contribute to an accident scenario; and,
5. Recommend corrective action, if appropriate.

You are directed to notify the Japanese Civil Aviation Bureau (JCAB), Mitsubishi Heavy Industries, Raytheon Aircraft, and the applicable FAA offices of this SCR.

You are to develop an SCR plan of action, an SCR budget plan, identify an SCR team leader and team members, and establish a tracking system for all activity relative to this work. The SCR team should begin its work immediately in preparation for an initial joint FAA and JCAB meeting which should occur no later than the third week in February. This should provide enough time for the JCAB to identify and assign personnel to the team. The team is chartered to continue the SCR until it is completed and recommendations, if any, are forwarded to me.

During the course of the SCR, I expect to be kept informed by the team leader, on a regular basis, of the team's progress and of any significant issues identified.

Michael Gallagher

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FACT FINDING
FOCUSED SPECIAL CERTIFICATION REVIEW (FFFSCR) OF THE MITSUBISHI HEAVY INDUSTRIES (MHI) MU-2B SERIES AIRPLANE

SUMMARY

United States House of Representative, Mr. Tim Johnson from South Dakota, requested the FAA take certain actions including grounding all MU-2B airplanes following the fatal crash of an MU-2B at Malad City, Idaho, on January 15, 1996. In response to the request from Congressman Johnson, an FFFSCR Team was established by the FAA, which included a JCAB representative, to examine the history of the MU-2B airplane.

The FFFSCR Team investigated and evaluated the icing certification of MU-2B airplanes manufactured under both of its type certificates, A2PC and A10SW. The Team requested assistance and participation from the JCAB and the manufacturer, MHI. Officials from the JCAB, MHI, and the FAA held their first meeting on February 20, 1996.

The FFFSCR Team was chartered to:

1. Examine the original icing certification of the airplane;
2. Examine the airplane characteristics in the icing environment as described by 14 CFR part 25, Appendix C;
3. Examine the airplane characteristics in the freezing drizzle icing environment as we now understand it;
4. Determine if any of the characteristics observed in 1, 2, or 3 above could contribute to an accident scenario; and
5. Recommend corrective action, if appropriate.

An initial review of the MU-2B service and accident histories revealed that at least 13 fatal accidents have occurred where the presence of icing conditions was either reported or forecasted. The most recent crash at Malad City is still under investigation, but other MU-2B accidents contain some similar scenario characteristics. Since 1983, eight MU-2B in-flight accidents in known or possible icing conditions, not associated with approach and landing, involved the long fuselage airplanes.

The anti-icing/de-icing and propulsion systems were reviewed for certification compliance and the maintenance data bases were reviewed for service difficulties. Test data from natural icing tests conducted by the manufacturer were examined. Data were also reviewed from another icing tanker test, not conducted by the manufacturer, that was witnessed by the FAA as part of a litigation (FAA sponsored the test to allow it to be per-

formed at the Air Force Flight Test Center (AFFTC)). As part of the FFFSCR, the icing characteristics of the MU-2B were evaluated by conducting a series of icing tests within the current certification envelope and beyond, into the freezing drizzle Supercooled Large Droplet (SLD) environment, using the United States Air Force (USAF) icing tanker at the AFFTC. Other flight tests were also conducted to learn more about the MU-2B's flight characteristics that may have been a common thread among the accidents.

From this review, the Team concluded that the original icing certification of the MU-2B series airplanes was conducted properly under Civil Air Regulations (CAR) by the JCAB in accordance with the Bilateral Airworthiness Agreement and the appropriate United States regulations in effect at the time. A United States Type Certificate, A2PC, was properly issued, including approval for flight into known icing conditions, in accordance with the policies and procedures used at that time. An additional United States Type Certificate, A10SW, was properly issued, which also included approval for flight into known icing conditions, for airplane kits imported into the United States and assembled in San Angelo, Texas.

As part of the FFFSCR, a focused icing evaluation was performed in a more severe area of the current icing requirements of 14 CFR part 25, Appendix C, than was tested in the 1984 Special Certification Review (SCR) natural icing tests. Within the scope of the tests performed, the MU-2B met the current icing certification requirements. However, this focused icing test program behind the tanker in the freezing drizzle (SLD) environment showed that avoidance and immediate exit, if SLD conditions were encountered, was warranted. This is not unique to the MU-2B, but is true for all small aircraft with unpowered flight control systems using wing pneumatic de-ice boot protection. The Team had not completed its review at the start of the 1996 icing season, but felt it necessary to issue an immediately adopted Airworthiness Directive (AD) (AD 96-25-02, dated 12/5/96) to provide appropriate icing related limitations and procedures, and SLD recognition and exit criteria.

Other factors that were determined to have contributed to the accidents were defined and will also be recommended for AD actions. The hazardous condition the Team found was that the pilots of the accident airplanes appear to have relied on the autopilot and, unknowingly, allowed the airplanes to slow well below normal operating speeds. Contrary to the icing procedures and WARNINGS in the Airplane Flight Manual (AFM), one of which specifies 180 knots minimum in icing conditions, the airplanes were allowed to decelerate and stall at a higher than normal airspeed due to ice accumulation. With an inattentive pilot, the airplane probably departed controlled flight and entered a potentially unrecoverable spin or spiral mode. The analyses of 13 accidents show high correlation with low pilot experience levels in the MU-2B; seven low time MU-2B pilots, five medium time and only two high time MU-2B pilots. Eleven of them had high total flight time, two medium time, and no low total time pilots were in the group. All airplanes, but one, were operated under part 91 of the Federal Aviation Regulations (FAR).

The voluntary seminar training program initiated by MHI, called Pilot's Review of Proficiency, or PROP, has apparently had some beneficial effect on the accident rate since its inception in 1994. Unfortunately, PROP seminars are not mandatory. The MU-2B is a high performance airplane with high wing loading that requires a high proficiency skill level to fly safely. The SCR in 1984 contained a Multiple Expert Opinion Team who concluded that this aircraft did not require a type rating to be flown safely. This FFFSCR Team has concluded that the average pilot, although technically qualified in the aircraft, does not have sufficient icing awareness to fly it safely in all icing conditions. Therefore, the Team has recommended a comprehensive list of required modifications to the automatic flight guidance system, the flight control system, the ice protection system, the propulsion system, AFM guidance, and maintenance procedures. In addition, an AD is being recommended to require a formal training syllabus be established. Under the provisions of the new part 61, it will be mandatory for initial and recurrent training on a biennial basis for each pilot who acts as pilot in command (PIC) of an MU-2B airplane. The PROP seminars and other formal training programs (i.e., Flight Safety International and Reese Howell Enterprises) can provide the approved syllabus in their training programs, which will satisfy the AD requirements. We are confident that this training program, in conjunction with the other recommended AD's, will significantly improve the safety record of the MU-2B.

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RECOMMENDATIONS

Master List

AIRWORTHINESS DIRECTIVE (AD) RECOMMENDATIONS:

1. By means of an AD, require all MU-2B pilots (PIC) to attend an initial training course with a biennial requirement to include icing awareness, anti/de-icing system operation, icing severity cues, and icing environment exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

2. By means of an AD, require a longitudinal trim in motion aural notification system (for nose up trim) be installed on all MU-2B's, with an autopilot installed.

3. By means of an AD, require an ice detector be installed on all MU-2B airplanes.

4. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

5. The Team requested an AD be created to incorporate the recommended Garrett P_2T_2 sensor modification. The Los Angeles, California, Aircraft Certification Office (LA-ACO) subsequently drafted an AD, and the Engine and Propeller Directorate will issue a Notice of Proposed Rulemaking which is in the final stages of coordination.

6. Issue an AD to remove Circuit Breakers CB2107 and CB2108 for the essential systems that are protected by combination switch/circuit breakers.

7. An immediately adopted AD was issued (AD 96-25-02, dated 12/5/96) to require changes to the AFM to include: Limitations on minimum speed in icing conditions – 180 knots in level flight; prohibit use of flaps for sustained operations in icing conditions, except for approach and landing; provide cues to allow pilot recognition of SLD conditions; and provide icing environment exit criteria.

8. By means of an AD, modify the airframe de-ice system by installing a pressure switch in the tail de-ice boot pressure line, and revise the circuitry so the cockpit light will illuminate only when both pressure switches read the required pressure, and both pressure switches must have a minimum set point, such that illumination of the light annunciates to the pilot that both wing and tail systems are operating at a pressure that ensures all boots are at least 90 percent of full inflation.

9. Require an AD to incorporate the Auto Re-light ignition system per the manufacturer's Service Bulletin, and require both engines to be modified with the Auto Re-light ignition system.

10. The Team recommends that the manufacturer's Propeller Rigging Service Bulletin be incorporated into the appropriate manufacturer's Maintenance Manual sections. The Team recommends that an AD be issued to incorporate a limitation in the AFM that requires a propeller negative torque sensing (NTS) and feather valve check prior to the first flight of the day.

RECOMMENDATIONS THAT ARE NOT AD's:

1. Support continuing research, and encourage certification of sensors that can measure the extent, thickness and roughness of ice accretions, notify the crew, and automatically operate anti/de-ice systems

2. Recommend the FAA provide funds for NASA to conduct a near vertical spiral mode investigation to determine if the mode is probable following a departure in the MU-2B, and, if probable, determine the recovery procedure. If software is available for similar studies, in lieu of spin tunnel testing, recommend NASA procure and make available to the FAA and National Transportation Safety Board (NTSB) use of the software programs, and assist in analyses.

3. Review FAA ice certification policies, with the intent to improve the process and information to the industry, to determine and test the most critical ice shapes for relevant aerodynamic characteristics. This may require that more than one ice shape be considered.

4. Support further general research to characterize SLD icing clouds, and to sufficiently understand the physics of ice formation in SLD conditions to enable computer modeling that will accurately model ice formations, accounting for the variations due to environmental and configuration dependent variables.

5. Support NASA and industry-wide studies and research to conduct icing wind tunnel testing of SLD ice formations to better understand quantitatively the aerodynamic characteristics due to sharp edged surface roughness elements (often termed ice feathers) and inter-cycle ice shapes. Further research needs to be conducted to ascertain the effects of SLD icing conditions on General Aviation airplane performance and flying qualities.

6. Support research efforts to improve computer ice shape prediction codes so they will accurately model ice shapes in temperatures near freezing that is in Appendix C and SLD conditions.

FEDERAL AVIATION ADMINISTRATION
(FAA)

JAPAN CIVIL AVIATION BUREAU
(JCAB)

FACT FINDING FOCUSED SPECIAL CERTIFICATION REVIEW (FFFSCR) OF THE MITSUBISHI HEAVY INDUSTRIES MU-2B SERIES AIRPLANE

MU-2B AIRPLANE IN ICING

FINAL REPORT

June 27, 1997

Cover Photograph

The cover photograph of the flight test airplane was taken during the April 1996 testing at Edwards Air Force Base behind the United States Air Force NKC-135A Icing Tanker. It is an overall view of the MU-2B test airplane to provide a general perspective.

The yellow or reddish-brown coloration on certain parts of the airplane is the result of dye added to the tanker water to enhance visual detection of the resulting ice and to indicate where the ice accreted after the ice has melted or sublimated. Light fluorescent green indicates liquid water (none visible in the photo), yellow indicates ice, and reddish-brown indicates dried dye where ice has melted or sublimated. Due to inherent limitations of the pigments and dyes used in the photographic and reproduction processes, the coloration of liquid water is not as vivid as when viewed by eye.

The presence or location of ice is visible on the nose, pitot tube masts, windshield, windshield frames, windshield wiper arms and blades, VHF communication antenna on the top of the fuselage, wing and tail leading edges, propeller spinners, engine nacelles, left tip tank, portions of the fuselage, forward surface of the landing gear sponson, and other protuberances. At the time the photograph was taken, the airplane was outside the icing cloud in dry air at temperatures below freezing. In a dry air atmospheric environment, ice that accreted during the icing test, sublimates with time, so the appearance of the ice may differ from other photographs found in Section I of this report.

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7. The FAA, NASA, and industry should support the development and use of accurate icing test facilities, including the new USAF icing tanker, to learn more about simulating SLD conditions, and the effects of SLD ice on small airplanes.

8. Recommend a service bulletin be issued by MHI to require the installation of a water trap/drain in the low spot in the tail de-ice manifold pressure line, and require the trap be drained at each 100 hour inspection.

9. The Team recommends that additional government and industry research into severe SLD conditions be performed, to better understand its affect on engine and propeller anti/de-icing performance, and capabilities for turbopropeller airplanes with pneumatic boots.

10. The Team recommends a service bulletin that requires a calibration check on the engine's torque sensing systems be developed. Also, inform pilots, through training, on the pitfalls of changes to the torque sensing calibrations and its affect on airplane handling characteristics.

11. The Team recommends that service information be published and made available to the airplane operators about the revised maximum fuel control fuel flow settings.

12. Require the manufacturer to release a service bulletin to the maintenance community to inform them that changes to the fuel control can affect the airplane's low speed handling characteristics, which affects safety.

13. The Team recommends that MHI provide AFM Power Assurance Charts on all models of the MU-2B airplanes that use the TPE-331 series engines.

14. The Team recommends that MHI establish a new section in the MU-2B Maintenance Manuals. Include in this section, mandatory compliance for the service bulletins issued for acrylic windows, including acrylic window/windshield inspections, and anti/de-ice system inspection.

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Section I — Table of Contents

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I. Icing Certification Review

Overview

This section addresses the FFFSCR Team's investigation of the icing requirements and other icing aspects of the MU-2B series airplane with recommendations, as appropriate. The first three items immediately below are part of the FFFSCR Team (Team) Charter. Item D is an additional test agreed upon by the Team and MHI to examine the susceptibility of the horizontal tail to ice contaminated tail stall (ICTS). At the request of the FAA, MHI provided additional information on the change in temperature due to engine exhaust by measurement of the temperatures on the horizontal tail.

A. Examine the original icing certification of the MU-2B.
B. Examine the airplane characteristics in the icing environment as described by 14 CFR part 25, Appendix C.
C. Examine the airplane characteristics in the freezing drizzle environment as it is now understood, (Supercooled Large Droplets (SLD)).
D. Evaluate the tailplane stall characteristics of the MU-2B model airplane with sandpaper on the leading edge of the horizontal tail.
E. Conduct temperature measurement of the horizontal tail to survey the change in temperature due to engine exhaust.

A. Original icing certification of the MU-2B airplane

The Team examined the requirements for the airframe icing certification and relevant data including reports, drawings and other information. The Team also examined the systems and the propulsion system with respect to the certification icing requirements. The systems and engine reviews with their findings and recommendations are contained in Sections III and IV of this report.

The original FAA type certification of the MU-2B series of airplanes was conducted under Civil Air Regulations (CAR) 10[1] by the Japan Civil Aviation Bureau (JCAB) in accordance with the Bilateral Airworthiness Agreement and the appropriate U.S. regulations in effect at the time. The certification basis was CAR 3 with special conditions, none of which relate to airframe icing. The MU-2B received a type certificate on November 4, 1965, under this process, and there were periodic amendments to the type certificate as new models were certificated until July 23, 1974, when the Models MU-2B-26 and -36 received type approval.

Type design approval for the MU-2B series of airplanes manufactured by Mitsubishi Heavy Industries, Ltd. of Japan was granted by the FAA under the Type Certificate (TC) A2PC.

The JCAB conducted the certification program on behalf of the FAA.

After type certification under A2PC, Mitsubishi Aircraft International, Inc. of San Angelo, Texas, subsequently applied to the FAA for a second type certificate to facilitate airworthiness approval for the airplanes manufactured in Japan but assembled in the United States. These airplanes were approved under TC A10SW. The first model to receive type approval under TC A10SW was the model MU-2B-25 on January 20, 1976, and the last model was the MU-2B-60 on March 2, 1978. Airplanes approved under A10SW are identified by the suffix "SA" in the airplane serial number.

The original airframe icing certification requirement of the MU-2B as stated in CAR 3 was essentially:

Paragraph 3.712 De-icers

> *When pneumatic de-icers are installed, the installation shall be in accordance with approved data. Positive means shall be provided for the deflation of the pneumatic boots.*

The FAA examined the certification of the MU-2B for flight into known icing conditions under both A2PC and A10SW. The pneumatic de-icers were installed in accordance with approved data. Positive means was provided for the deflation of the pneumatic boots consisting of a partial vacuum applied to the boots when the engines were operating and the boots were not inflated. For A10SW, in addition to the certification requirements, the FAA solicited information on ice protection system performance from pilots of earlier in-service MU-2B's certificated under TC A2PC. The designs of the airplane types produced under TC A10SW were essentially identical to those produced under A2PC. The information was collected by MHI and presented in detail to the FAA.

The in-service pilot testimonials supplemented the process of finding compliance with the requirements for flight into known icing. It should be noted that the entire spectrum of icing conditions that exist in the natural environment experienced by the airplanes in service, especially those infrequently encountered icing conditions that may be more adverse, may not have been as extensively explored as compared to the current understanding of the icing environment with the associated testing required today. However, analysis of the reports provided useful qualitative information about the general characteristics of the airplane in the most frequently encountered icing conditions.

Other analytical data were also examined by the FAA during this review. Among them, there was an airframe impingement analysis (MHI Report MR0144 Systems Analysis).

Conclusion:

The Team found that the MU-2B was certificated properly in full compliance with existing regulations, policies, practices and procedures in effect at the time of the original icing certification. Early icing certification requirements were less rigorous than current icing certification policies interpreted from 14 CFR part 23, Amendment 23-43.

Recommendation:

There are no recommendations with respect to the original certification.

B. Airplane characteristics in the icing environment described by 14 CFR part 25, Appendix C

The intent of the FFFSCR Charter was to examine the impingement, operational and performance characteristics of the wing with ice accumulated from within the Appendix C icing envelope to determine if there was adequate wing de-icing boot coverage. The Team carefully examined the data that MHI submitted with respect to work conducted jointly during the previous 1984 SCR, MHI's previous testing and analyses, and work conducted under this FFFSCR. Accordingly, the aspect of certification addressed during this investigation relates only to the ability of the MU-2B airplane to meet Appendix C conditions. Appendix C of 14 CFR part 25 (Airworthiness Standards: Transport Category Airplanes) describes the variables of the icing conditions that are currently required in 14 CFR part 23 (Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes). Part 23 is the successor to CAR 3, which defined the standards used for the MU-2B. The investigation involved:

1. Examining impingement analysis of the MU-2B airfoils;
2. Reviewing instrumented measurements in natural icing conditions by MHI;
3. Testing in simulated icing conditions behind the USAF icing tanker; and,
4. Examining other relevant data and reports.

Appendix C defines the Liquid Water Content[2] (LWC) and droplet sizes appropriate to various altitude and temperature conditions. Current industry practice in the design of pneumatic de-ice systems is to provide sufficient coverage to capture all of the 20 micron[3] drops and as many of the 40 micron drops as practical over the operating range of angle-of-attack (AOA). An accepted technique for limiting the impingement[4] of the larger droplets on the lower side of the aerodynamic surfaces is to limit the minimum speed in icing conditions which reduces the AOA and thus limits the aft extent[5] of ice.

Appendix C conditions were simulated on the long fuselage model MU-2B-60 in icing tanker flights conducted on April 26 and 27, 1996, at the AFFTC. Testing confirmed that Appendix C ice on the upper wing surface collected on the protected portion of the boots. Cycling of the boots removed all of the upper wing surface ice. Impingement on the lower surface was approximately 6 to 8 inches aft of the boot. Typical ice collection on the airframe can be seen in figure I-1. These results are similar to those obtained in the 1984 SCR flights and are characterized by a drag increase without any observed control problem. During the original MU-2B icing certification and the 1984 SCR, these drag increases were judged to be acceptable based on the maximum power available. It must be understood that the tanker testing could not examine the effects of ice on the entire airplane simultaneously. The impingement on the MU-2B was also compared to another airplane (figure I-2) and the impingement characteristics were found to be consistent with the other airplane.

Impingement on the lower surface of the wing aft of the boots has been observed many times, including the 1984 FAA SCR, and has been accepted to result in a drag increase with minimal change to the maximum lift[6] or controllability of the airplane. Many research reports verify this conclusion as well as MHI sponsored flight tests on the MU-2B. Since

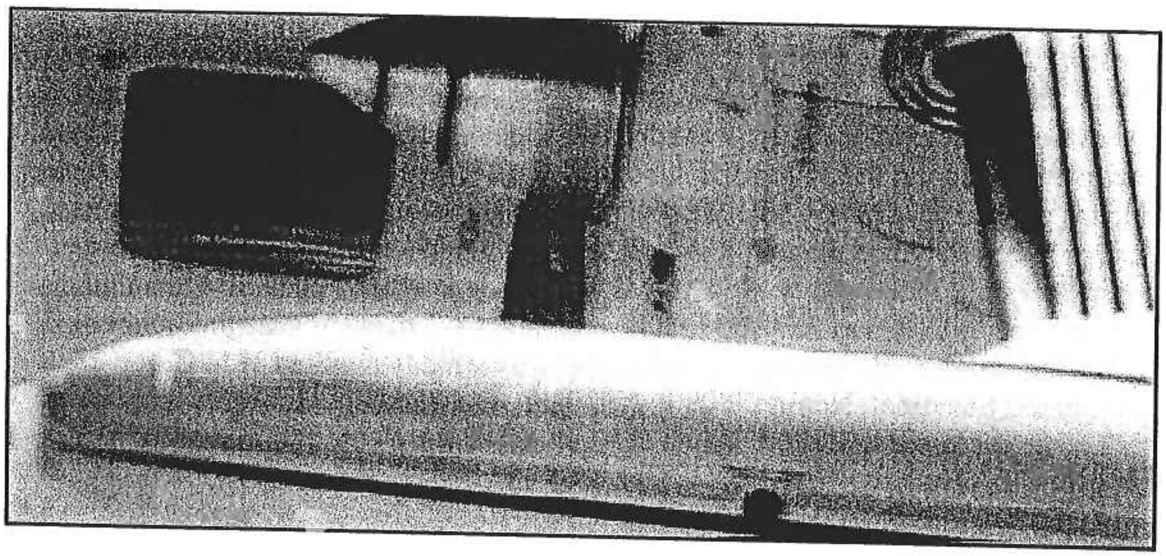


Figure I-1
Ice impingement on MU-2B wing upper surface in icing tanker testing. The icing cloud contained droplets larger than Appendix C. The yellow color of the ice is from dye added to the tanker water to aid visual detection of the ice.

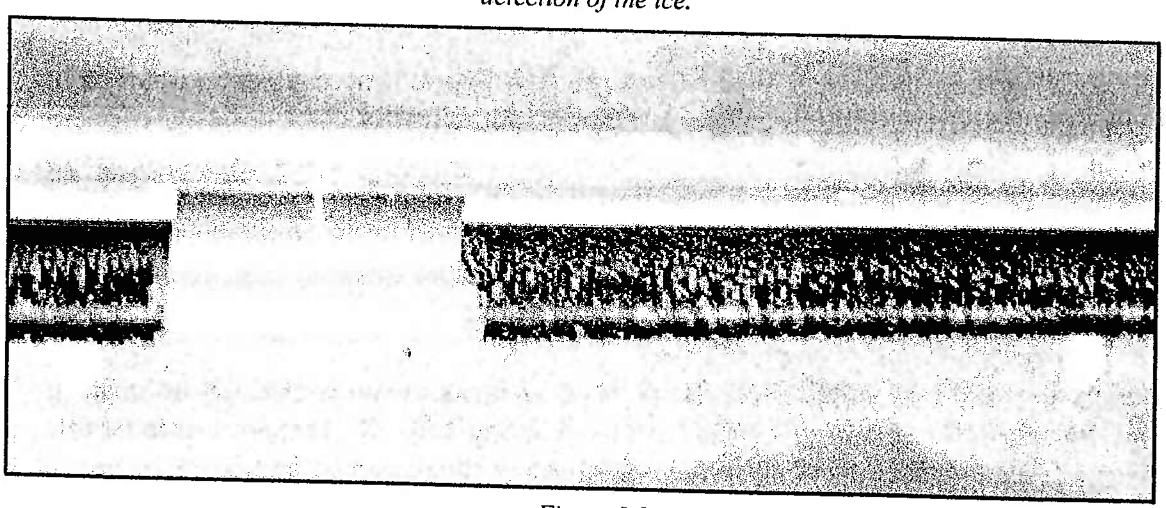


Figure I-2
Impingement on ATR-72 wing upper surface typical of 70 micron icing tanker cloud testing (larger than Appendix C).

nearly all of the ice on the de-ice boots protecting the lifting surfaces is shed on activation[7], handling qualities of the MU-2B are not significantly degraded by flying in those conditions assuming all of the ice protection systems are functioning properly, and are selected ON by the pilot.

Based on the best available test conditions, it was determined that the MU-2B could not be tested for extended periods at speeds beyond the 180 knots used in the icing tanker testing. It was agreed by the Team that a computer analysis based on the testing was one means that could be used to evaluate other speed, altitude and configurations that were not tested.

One of the objectives of the icing tanker tests was to determine the impingement limits and residual ice associated with operation in Appendix C conditions. The impingement limits determined from these tests and applied to 14 CFR part 25, Appendix C, conditions are conservative because approximately 25 percent of the measured LWC was contained in droplets between 100 and 300 microns. Such large droplets, often associated with icing tankers, are outside of Appendix C conditions and impinge further aft. Analysis of the droplet distribution for these conditions showed that an LWC of 0.05 gm/m^3 was contained in droplets of 225 microns or larger. Upper surface impingement limits for the entire span were developed from the photographs taken during the first three icing tanker flight tests. The following limits were determined by visual means for the test condition of 180 KIAS and a gross weight of approximately 10,500 pounds:

Observed Impingement Limit

Wing Station (millimeters)	Percent Local Chord at 180 KIAS 225 microns
660	3.8
2607	7.2
4950	6.9

An analysis by an MHI contractor, KEY Industries, using its computer program, was then made to estimate the effect on impingement when the droplet size is reduced to 40 microns and the AOA is decreased by 2° (simulating flight at cruise speeds of 220 knots). The KEY analysis estimates that the impingement for the 40 micron drops on the wing upper surface is concentrated right at the leading edge as shown below:

Estimated Impingement Limit

Wing Station (millimeters)	Percent Local Chord at 220 KIAS 40 microns
660	0.5
2607	1.3
4950	2.4

During the icing tanker tests, ice was observed to accrete on the protected areas of the outer wing upper surface within Appendix C conditions (see figure I-1). The outer wing was selected for this test because the impingement analysis conducted by the current de-icing boot manufacturer, B. F. Goodrich (BFG), predicted slight accretion beyond the protected area. Further analysis by MHI contractors based on the results of the tanker testing showed that when corrected for other conditions such as speed and weight, the impingement was still within the limits of the active portion of the de-icing boot on the upper surface. The results of the tanker testing was compared to the impingement analysis performed by BFG and showed acceptable agreement.

The FAA concludes that the aft limit of the de-icing boot upper surface is consistent with industry practices, FAA policy and procedures. This conclusion is based on observations of the ice accretion on the upper surface of the leading edge of the wing, combined with the knowledge that the simulated icing cloud for the MU-2B test contained a substantial percentage of droplets larger than the 40 micron size.

As a check for reasonableness, a comparison of the impingement characteristics of another airfoil was made with an icing cloud containing droplets distributed in approximately the same diameter range. Measurements of the cloud physics were made using the same equipment by the same individuals. Figure I–2 shows the results of similar testing with the ATR-72. Although the de-icing system of the ATR-72 is operated in an automatic cycle, thus removing the ice more frequently, the yellow color of the ice can be observed on the leading edge.

Conclusions:

1. Adequate impingement analysis has been conducted consistent with practices and policies in existence at the time of certification of the MU-2B, and the analysis shows that the coverage of the de-icing boots is consistent with regulations, policies, and industry practices in effect at the time that this FFFSCR was conducted. An additional analysis was presented by MHI to show acceptable penalties in drag. No such reports were required in the original icing certification. The original certification program did evaluate the airplane for any unsafe condition in icing conditions and the MU-2B was found to comply with the requirements. The 1984 SCR validated the original airplane's certification handling characteristics for Appendix C within the conditions available.

2. During icing tanker testing of the MU-2B in conditions simulating the largest size of the droplet size spectrum of Appendix C, the demonstrated impingement of droplets and the formation of ice was on the active part of the upper surface of the de-icing boots. This impingement was extended to other conditions of weight and speed based on analysis. FAA agreed that analysis could be used to examine other conditions. The analysis showed acceptable impingement characteristics. While the FAA agrees with the conclusion, it does not have sufficient data to assess the precision of the methodology and the assumptions used to arrive at that conclusion. The limits of accuracy of computer prediction programs used to predict SLD impingement and ice shape have not been established, but will be the subject of future research.

3. The Team did not request that MHI present data to comply with the current icing regula-

tions, nor were they required to under the Team's Charter. Therefore, it should not be construed that the MU-2B airplane complies or does not comply with the present icing regulations and policies (14 CFR part 23, Amendments 23-1 through 23-43). The current requirements are more rigorous than the rules in effect at the original certification.

4. The FAA believes that industry practices on the subject of impingement and the determination of critical ice shapes needs to be standardized. The FAA supports research in this area to help develop the necessary guidance.

Recommendation:

Review FAA icing certification policies with the intent to improve the process and information to industry to determine and test the most critical ice shapes, conditions, and configurations for relevant aerodynamic characteristics. This may require that the FAA consider more than one ice shape.

C. MU-2B characteristics in freezing drizzle range of the SLD spectrum

Background

The Team's analysis of the accident history of the MU-2B in known or forecast icing conditions including freezing precipitation (or SLD[8]) was sufficient justification for the FAA to consider freezing drizzle as a possible causal factor in some of the MU-2B accidents. Thus, the FAA theorized that the effects of freezing drizzle may result in increased drag or extreme disturbances in the local airflow similar to that found in other airplane models previously evaluated. Accordingly, the Team chose to examine the potentially adverse effects of SLD on the MU-2B airplane.

The Team conducted simulated SLD icing tests as part of the icing tanker testing at the Air Force Flight Test Center, Edwards Air Force Base, California, and artificial ice shape flight testing at Clinton-Sherman, Oklahoma. The artificial ice shape tests were based on the results of the icing tanker testing. The Team evaluated the performance and handling characteristics of the MU-2B in freezing drizzle conditions. The Flight Test Reports for these tests can be found in Section II of this report. The SLD criteria applied to the MU-2B were developed from previous research conducted by the FAA to evaluate Transport Category Airplanes for handling characteristics in freezing drizzle conditions.

The object of the icing tanker testing was to determine the location, shape, texture, and thickness of ice accretion on selected parts of the airplane[9]. The data thus gathered was then used to fabricate artificial ice shapes and test the airplane to evaluate flight characteristics in either a wind tunnel or in full scale flight testing. Safety considerations must be made whenever artificial ice shapes are used in flight testing and these considerations were employed. Customary safety practices involve increasing thickness and coverage of ice shapes in a progressive buildup process.

SLD ice accretion aft of the boots was observed to some extent on all surfaces. The ice accretion was not uniform across the span of the wing. Within the propeller slipstream, the wing aft of the down-going blade experienced a lower AOA and more aft-wise impingement on the upper surface and less aft-wise impingement on the lower surface than the area aft of the up-going blade which exhibited the opposite characteristic.

In SLD test conditions, the wing upper surface did collect some ice aft of the last active de-ice tube in a ridge with a ragged profile and sharp edges. After 20 minutes and several boot cycles, the ice ridge was observed from the chase plane to be stabilized with dimensions of approximately one inch wide and a maximum height of approximately ¾ inch (see figure I-3). The ridge was observed to build to approximately ¾ inch in height and then some spanwise portions would self-shed in the air stream. The growth and self-shedding process stabilized at a spanwise fraction coverage estimated at 40 percent. The artificial shape configuration shown in figure I-4 was developed to represent the SLD ice ridge aft of 7 percent chord on the upper surface of the wing. Ice buildup was not totally removed from the boots with every cycle of the boots. Some residual ice was observed on the wings as shown in figure I-5 and the horizontal stabilizer as shown in figure I-6.

The lower wing surfaces collected ice asymmetrically, best defined as distributed ice elements to approximately 30 to 40 percent chord as shown in figure I-7; and aft of the up-going propeller blade, a sharp lip of ice immediately aft of the active portion of the de-icing boots that extended with smaller, more distributed ice elements, to approximately 30 to 40 percent chord as shown in figure I-8. Post-flight documentation of the lower wing surface

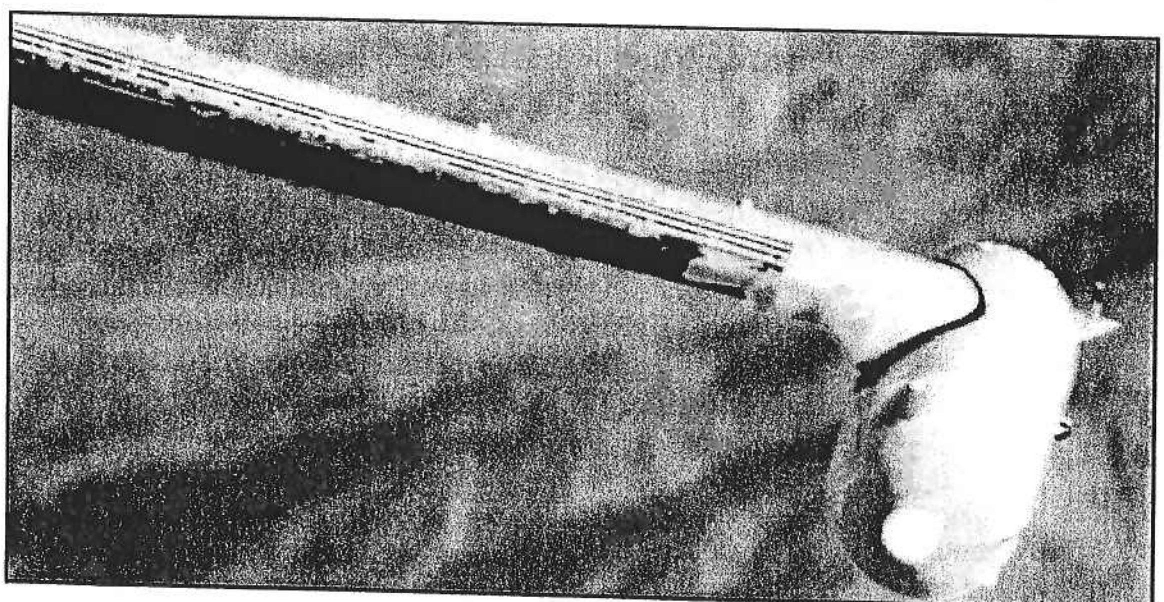


Figure I-3
MU-2B in SLD. Ice ridge is visible at aft upper edge of de-icing boots.

revealed staining from dry tanker water dye revealing more widely spaced ice features that extended aft to 40 to 50 percent chord, with some widely separated stains caused by ice formation on surface irregularities all the way back to the trailing edge of the wing and flap lower surface. These shapes contribute to a large drag increase, but do not materially affect lift or controllability of the airplane.

The left inboard upper wing surface (between the fuselage and the engine) collected ice on the de-ice boot and essentially all of the ice was removed with boot activation. The right

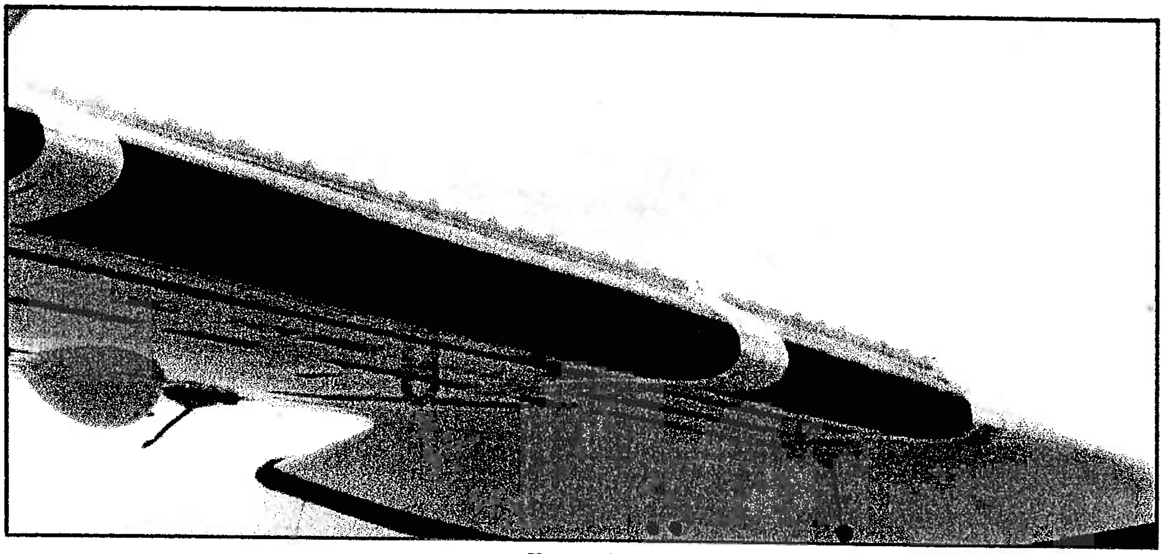


Figure I-4
MU-2B artificial ice shape viewed from the pilot's perspective.

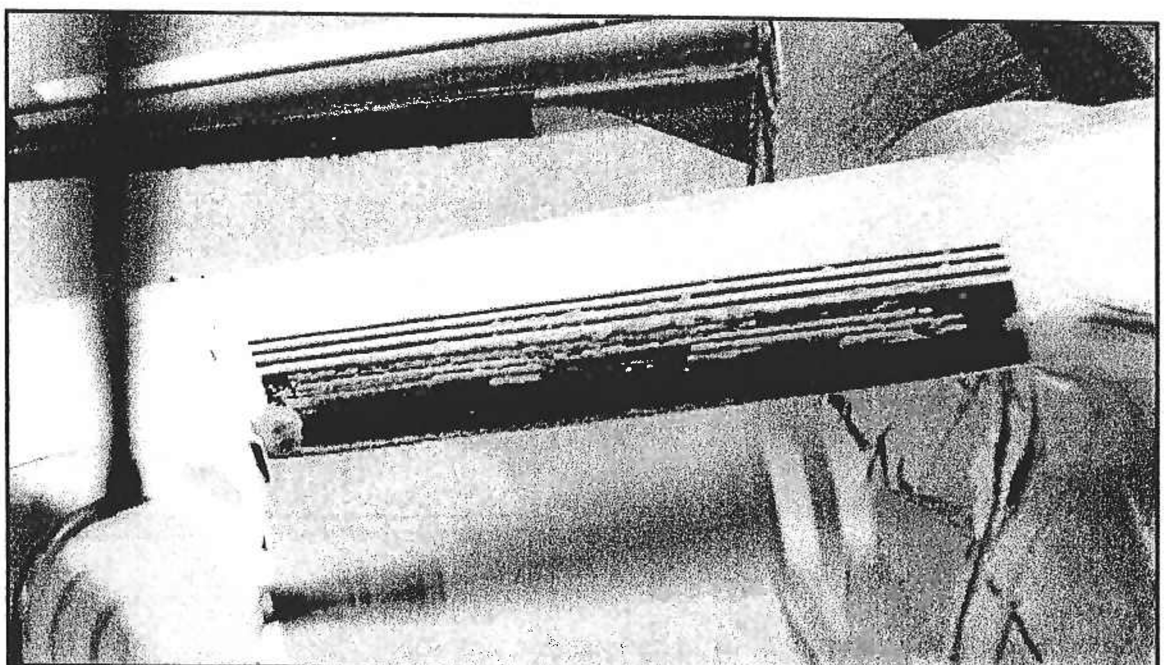


Figure I-5
MU-2B post-boot cycle residual ice on right inner wing in SLD. Note ragged edge of ice visible on lower surface of horizontal stabilizer.

Figure I-6
SLD ice on MU-2B lower surface of the right stabilizer with some ice visible aft to leading edge joint. Ice is visible on the vertical stabilizer.

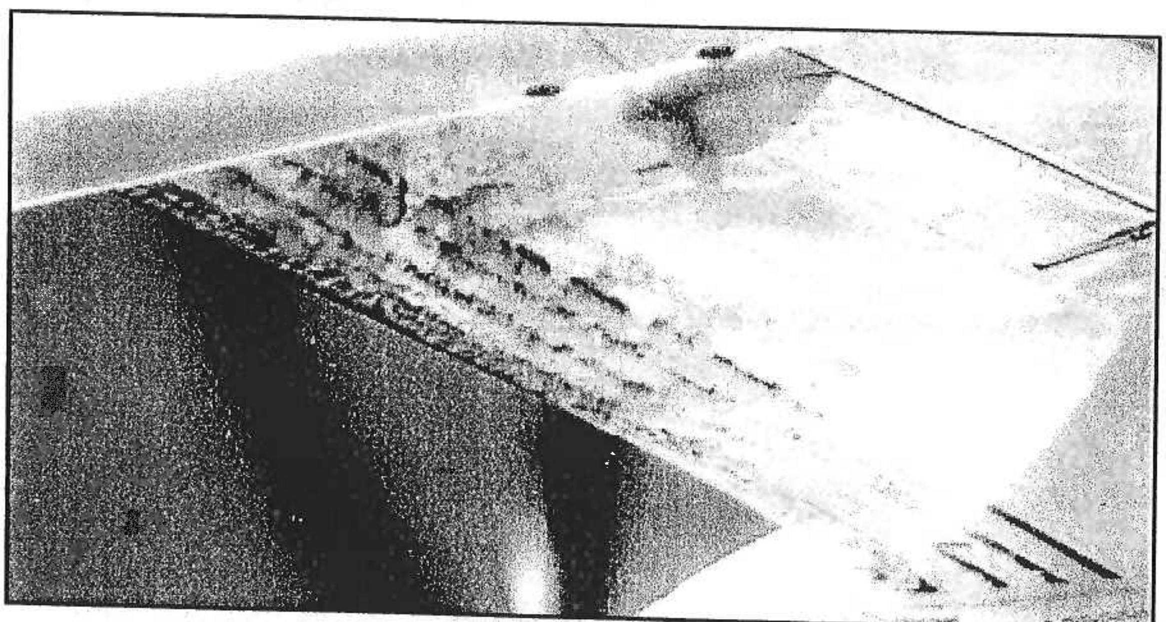


Figure I-7
SLD ice on the MU-2B left wing lower surface.

wing inboard exposure was limited to 10 minutes due to reaching a preflight test limit of the control wheel deflection (35° of the 90° available). Once the airplane was clear of the tanker wake, the lateral control wheel deflection requirement reduced to 20°. No similar control limit was reached during the exposure of the left inboard wing.

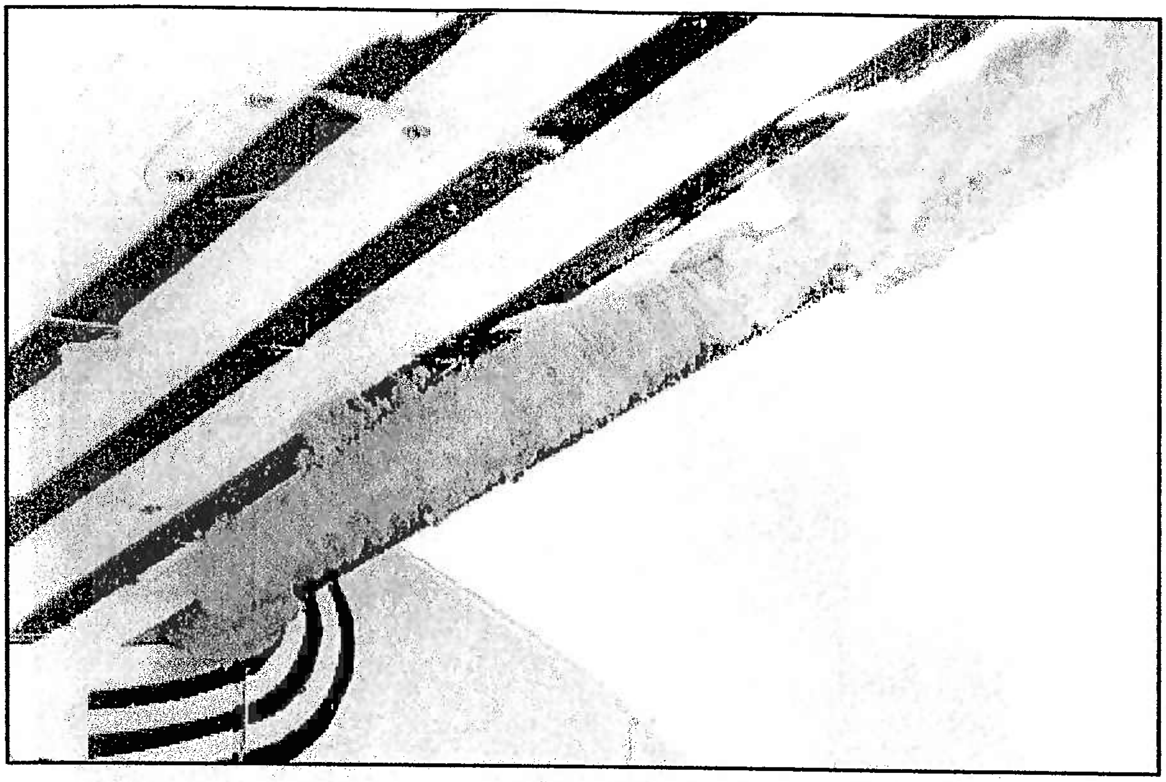


Figure I-8
SLD ice on the MU-2B left inner wing lower surface.

A one minute and forty second exposure of the right inboard wing to SLD icing at a speed of 200 KIAS resulted in a buildup of visually detectable ice on the wing upper surface directly aft of the mid-span of the propeller blade, extending to the aft edge of the third stripe. This speed was only achievable for a short time at a reduced weight close to the end of a test. Roughness associated with the ice observed on the right inboard wing upper surface was simulated in the SLD portion of the artificial ice shape tests. The left inboard wing SLD exposure was terminated after 15 minutes due to a large asymmetrical ice shape developing on the left propeller spinner (see figure I-9) that resulted in an out-of-balance vibration that was a concern of the flight crew. Lateral control was not a limiting factor. In the 10 to 15 minute inboard wing exposures in SLD conditions, the ice collected on the propeller spinner all the way back to the root of the propeller blades. Prolonged exposure on the outer wing sections produced ice on the tip tank to the welded joint. The windshield collected substantial ice on the unheated portions (see figure I-10).

Flight test pilots of the MU-2B concluded that these conditions would be clearly recognizable to any pilot as an unusual icing environment and could be used as an SLD icing indicator (see figures I-8 through I-11). These visual indicators were published in AD 96-25-02.

Ice observed on the horizontal stabilizer accumulated primarily on the leading edge and the active area of the de-ice boot. There was some ice observed aft of the de-ice boot in SLD conditions (see figures I-5 and I-6). There was an ice formation at the leading edge of the horizontal stabilizer on the right-hand side outboard of the boot that extended approximately one inch beyond the active part of the boots or approximately 10 inches more out-

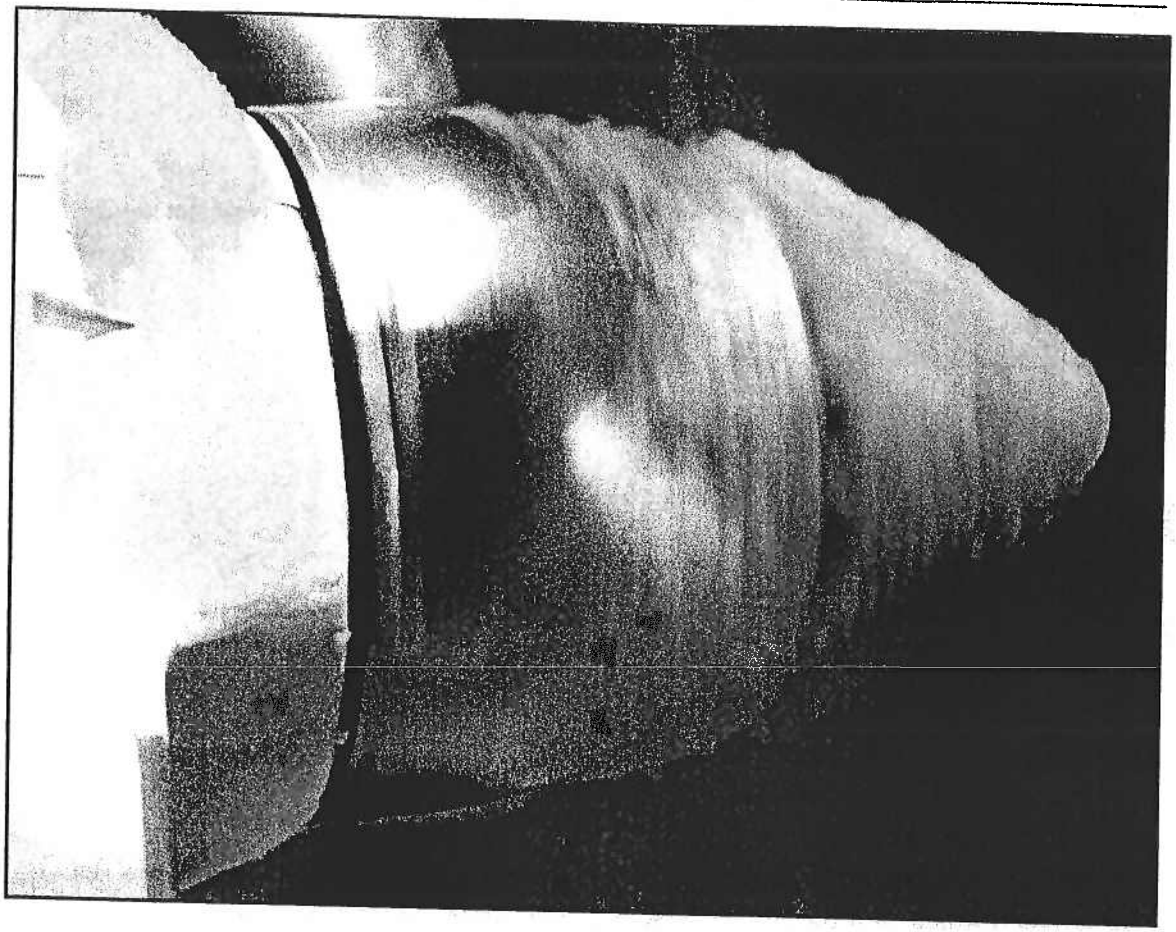


Figure I-9
MU-2B left propeller spinner in SLD. Ice extends aft to propeller blade roots. Appendix C ice covers approximately the forward half of the spinner. Ice is visible on the unheated upper inlet surface.

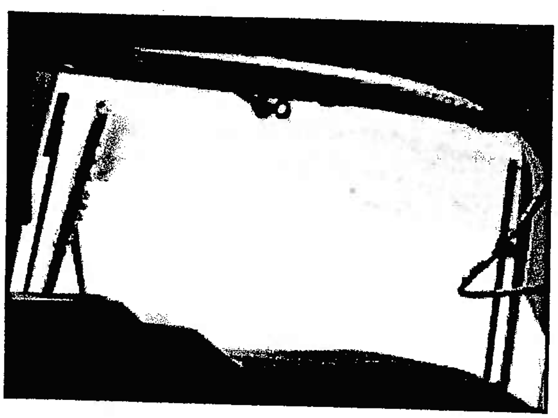


Figure I-10
MU-2B windshield ice visual cue in SLD.

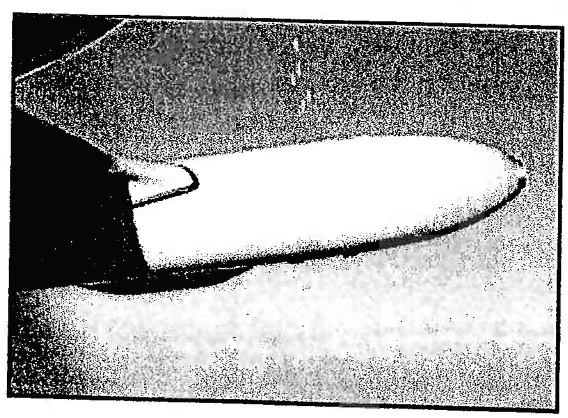


Figure I-11
MU-2B tip-tank ice visual cue in SLD.

board than the left-hand side (see figures I-14 and I-15). There was some residual ice observed on the horizontal stabilizer.

The impingement pattern on the empennage exhibits left/right asymmetry induced by propeller wash. Ice accretion asymmetry was observed on the horizontal stabilizer as shown in figures I-14 and I-15 and the vertical stabilizer as shown in figure I-16. Ice limits aft of the up-going blade extended farther aft on the lower surface and farther forward on the upper surface with exactly the opposite pattern aft of the down-going blade. Since a large percentage of the MU-2B wing area is immersed in the propeller wash, these asymmetric shapes may induce asymmetric effects upon the aerodynamic characteristics of the airplane under certain icing and operational conditions. Approximation of asymmetry on the wing and the vertical stabilizer was modeled in the artificial shape testing.

Ice accretion stages

The icing tanker SLD tests resulted in ice that accreted on and aft of the active part of the de-icing boots on the upper and lower surface of the airplane's airfoils. This was not unexpected, as the FAA has seen similar accretion characteristics on other types of airplanes evaluated in comparable icing conditions.

SLD ice accreted in three distinct stages:

1. Initial stage: Ice formed in widespread surface roughness elements early in the exposure sequence. These surface roughness elements tended to collect in greater density on surface irregularities including the spanwise stitch lines[10] in the de-icing boots and very minor discontinuities on the surface of the leading edge. The impingement pattern on the empennage exhibits left/right asymmetry induced by propeller wash. Ice accretion asymmetry was observed on the wings (figures I-12 and I-13), horizontal stabilizer (figures I-14 and I-15), and the vertical stabilizer (figures I-16 and I-17).

2. Inter-cycle stage: On the wing and the horizontal stabilizer, roughness elements were arrayed in distinct spanwise patterns forming on surface irregularities or associated with horn formation. These spanwise ridges provide sites having high local collection efficiency;

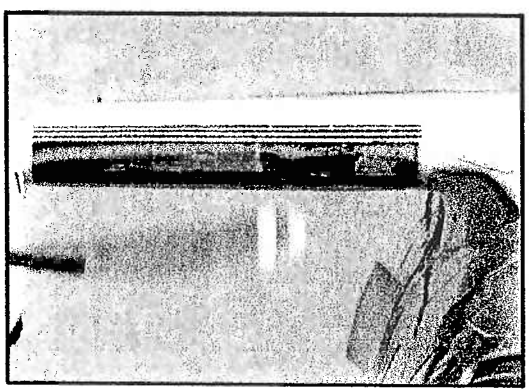


Figure I-12

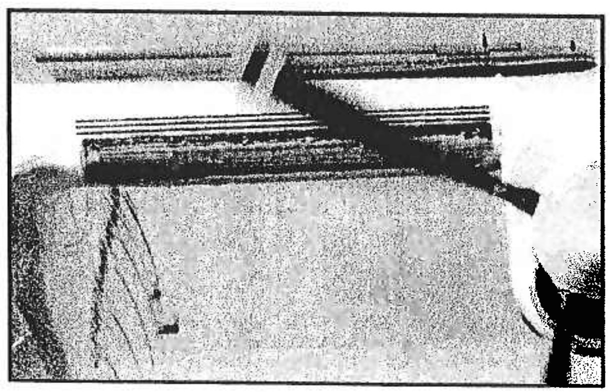


Figure I-13

MU-2B in SLD. Assymetry of ice accretion results from propeller wash effects with co-rotating propellers. Above left: Down-going blade decreases AOA resulting in more aft-wise impingement on upper surface. Above right: Up-going blade increases AOA aft resulting in less aft-wise impingement on upper surface. The light green color (seen in both figures above) at the stagnation line is liquid water.

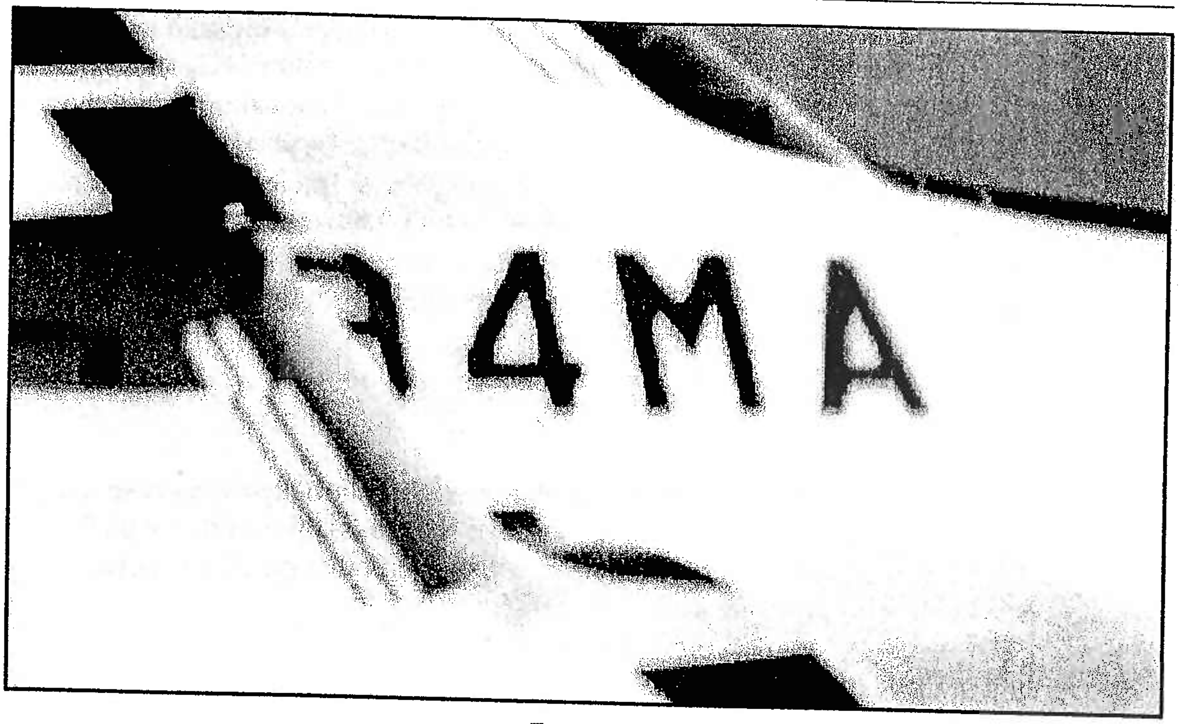


Figure I-14
MU-2B right stabilizer in SLD. Ice can be seen extending approximately 10 inches further outboard than the left stabilizer (figure I-15 below). Observe ice on the leading edge of the vertical stabilizer.

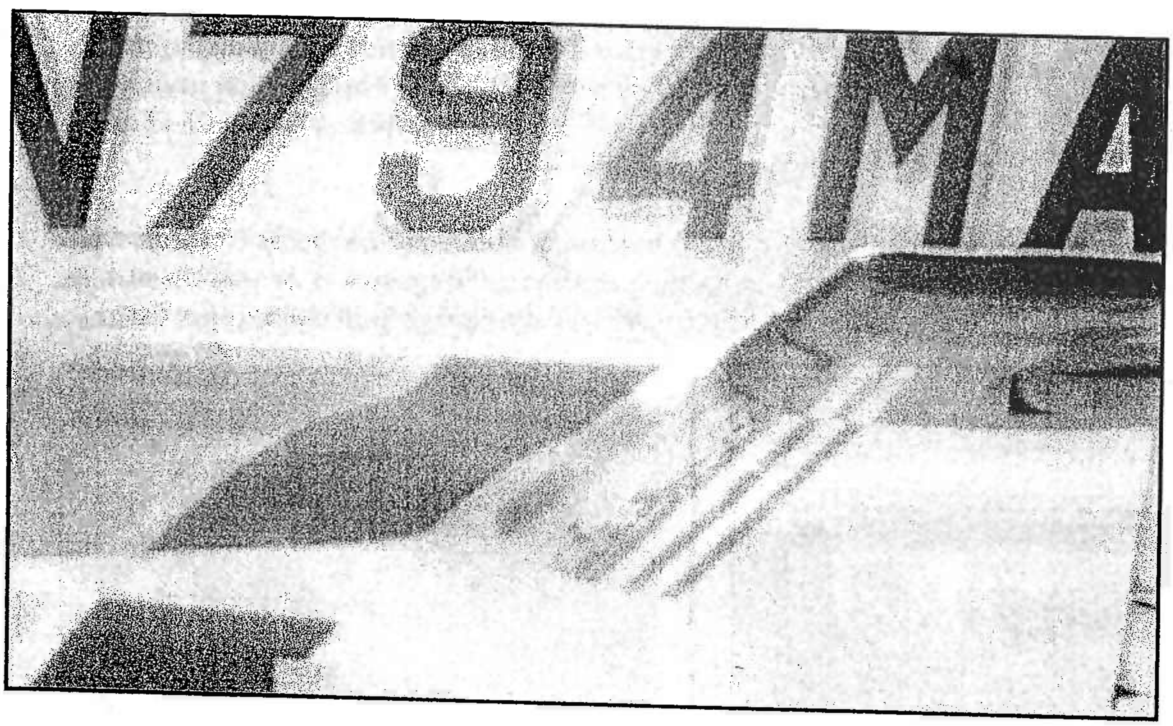


Figure I-15
MU-2B left stabilizer in SLD. Ice does not extend as far outboard as the right stabilizer. Distributed roughness elements are visible aft of the boots but to lesser extent than the right stabilizer.

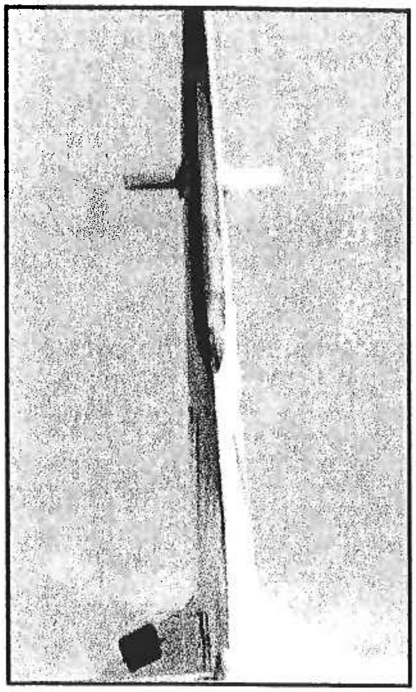


Figure I-16
Ice on the vertical stabilizer is not symmetric due to propeller wash effects.

Figure I-17
Assymetry on the vertical stabilizer is represented by roughness elements.

thus, favoring rapid buildup (within approximately 3 minutes) of distinct spanwise ice ridges on and aft of the active portion of the upper and lower surfaces of the de-icing boot. Clear ice was observed to form on the stagnation line (see figure I-3). These ice features were allowed to grow to approximately ½ inch in height which is the maximum recommended ice dimension for operating the de-icing boots. The ice formed with distinct spanwise and chordwise asymmetry due to local effects of the propeller flow field.

3. Mature stage: After manually cycling the de-icing boots, thicker ice was generally removed effectively on the active part of the de-icing boots. Less cohesive ice often required several de-icing boot cycles to shed completely. Ice remaining aft of the active part of the de-icing boots then matured into larger ice features across the span of the wing. There was a ridge of ice approximately ¾ inch high aft of the last active de-ice tube on the upper surface of the outboard wing. The shape was a ridgelike array with ¾ inch high "fingers" and smaller sharp "feathers".

By comparing observations, video and photos from many different angles, a composite shape representing the SLD ridge was developed for artificial ice shape flight testing. Spanwise elements of the ridge tended to self-shed in a random manner and then to regenerate. The lower surface of the wing had ice buildups to about 30 percent of wing chord and varied from a nearly continuous ridge to widely spaced ice elements. Spanwise density of the ice ridge was approximately 40 percent.

As a result of observations on several other aircraft during USAF Icing Tanker and NASA

Icing Research Tunnel (IRT) testing in SLD, it appears that the primary factors that affect self-shedding characteristics of the ridge are dynamic air pressure, adhesion of ice to the boot, and the physical strength properties of the ice. Adhesion to the boot is generally a function of boot surface condition and temperature. Ice adhesion to the boot is lesser at warmer temperatures, therefore with other factors constant, as the height of the ridge increases, it will reach a certain height which results in a shedding force causing separation of part of the ice ridge.

Local minor variations in boot surface texture, local airflow conditions, and the form of the ice will influence the self-shedding characteristics. While increased LWC is normally associated with severity in icing, in the case of the ridge formation, the result of higher LWC appears to be a factor in the rapidity of the regeneration of the ridge and at a given temperature may actually reduce the height or the spanwise coverage of the ridge, because of the increase in ice temperature caused by release of more latent heat of fusion in the higher incoming mass. Conclusions linking the severity of effect of an SLD ridge with LWC must therefore be considered carefully in light of all factors. Additionally, it must also be mentioned that in some cases, adverse affects of ice are disproportionate to size so that small ice shapes with certain texture characteristics can be more adverse than larger shapes.

Ice shape testing

Artificial ice shape testing is a means of evaluating the effects of the ice accretion during flight testing, while maintaining integrity of the ice shape through the entire test period without sublimation, melting, self-shedding, or erosion. Artificial ice shape testing was conducted on the MU-2B after the icing tanker tests. During the icing tanker tests, three ice shapes were observed during the SLD testing. The shapes described below were proposed for the artificial ice shapes for the MU-2B wing:

1. Roughness elements;
2. An inter-cycle ice shape that existed just prior to boot cycle; and,
3. A mature ice ridge.

The shape proposed to represent inter-cycle ice was ½ inch by ½ inch spanwise ridges located on the stitch lines of the de-icing boot. Figure I–4 shows the artificial ice (ridge) shape derived from the icing tanker test. Later in this report, figure I–22 shows ice formed on a wing other than an MU-2B as a result of a brief exposure to conventional icing and freezing drizzle conditions. The resultant ice formation exhibits a clear pattern of spanwise ice elements.

Since larger, more angular shapes might pose safety hazards for the flight testing during the takeoff phase, especially in the event of an engine failure, the Team and MHI agreed to use the de-ice boot inflation as a means to simulate leading edge ice contamination effects in flight to conduct performance and handling characteristic evaluations. No unusual performance or handling affects were observed.

The Team and MHI agreed to test the mature ice ridge. The ice ridge shown in figure I-3 was estimated by visual means to represent the SLD ice ridge observed during the tanker testing. The Team and MHI agreed on the mature artificial ice shape to be tested.

The artificial ridge used was represented by random elements each having approximately the same height (see figures I-4 and I-19). MHI and the Team also tested roughness with 3 to 5 mm roughness elements (see figure I-18) aft of the active portion of the deicing boots on the upper surface of the wing to approximately 12 percent chord with additional chordwise coverage on the right inboard wing, and the right side of the tail (see figures I–20 and I–21). MHI also conducted other roughness element testing and presented data to the Team. This testing evaluated artificial roughness on the lower surface of the wing and the vertical tail to simulate the ice roughness shapes and ice buildups identified by the icing tanker tests. Handling characteristics and performance were evaluated in flight testing employing artificial shapes and roughness elements[11]. The results of this testing provided data to determine performance (drag) and power required estimates.

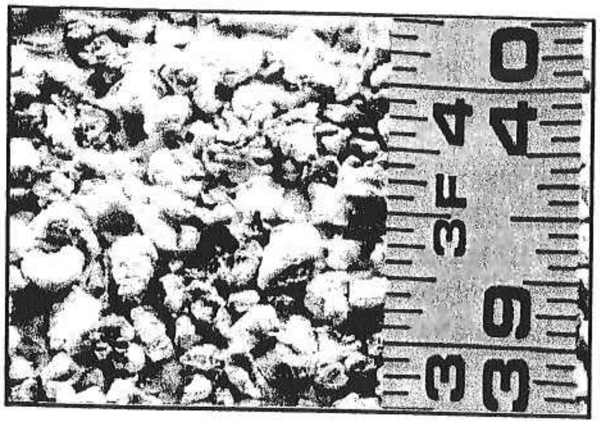
SLD effects

The Team and MHI exposed the MU-2B airplane to only one SLD condition selected by the FAA. The MU-2B was observed to exhibit no unusual handling characteristics, and was evaluated to have performance to satisfactorily exit SLD icing conditions as soon as the icing condition is detected. However, adverse effects of ice are not always just a function of large size. While large ice shapes may cause adverse effects, accretion of ice with a visual appearance of less severe ice or of smaller dimensions may also cause dramatic increases in drag, and substantial decrements in performance combined with adverse changes to other aerodynamic characteristics, such as stall angle or hinge moment. The tests conducted focused on spanwise ridge ice formations. Ridge formations can be especially disruptive to lift and/or stall angle, and such adverse effects are usually accompanied by an increase in drag.

Adverse effects are highly dependent on the characteristics of the airfoil, and the characteristics of the ice including location, thickness, shape and texture. A ridge on the lower surface of the wing would be adverse to drag, but would have little effect on lift or stall angle. Because of the unknown factors that can exist in natural icing conditions and the less understood conditions that exist to create SLD icing buildups, the Team concluded that the pilot needed additional performance and icing condition information.

Simulated artificial ice shape flight testing was conducted at Clinton-Sherman using artificial ice shapes (in dry air) based on the shapes observed during simulated SLD icing conditions behind the USAF icing tanker. The ice shapes were evaluated, selected and agreed upon by both MHI and the Team as representative of those observed during the testing conducted at AFFTC.

There was a clear trend that related certain ice accretions to increased drag, and increased stall speeds. Ice accretion on the lower surface increased drag and ice accretion on the



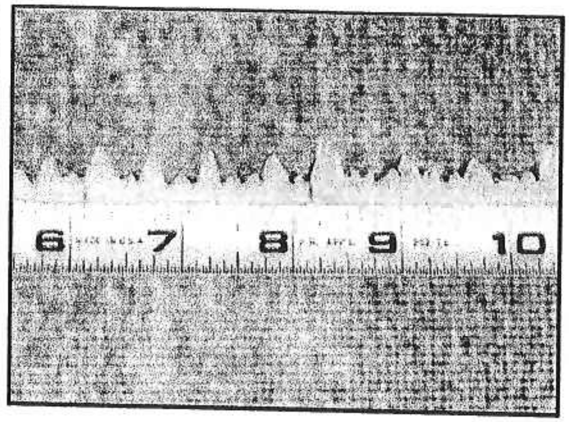


Figure I-18

Figure I-19

Above left: Artificial roughness elements approximately 3 to 5 mm in diameter.
Above right: Ice shape simulator on upper wing surface both singly and in combination with roughness.

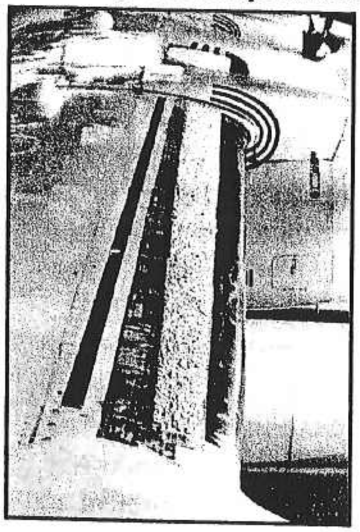


Figure I-20
Simulated roughness elements, right wing leading edge.

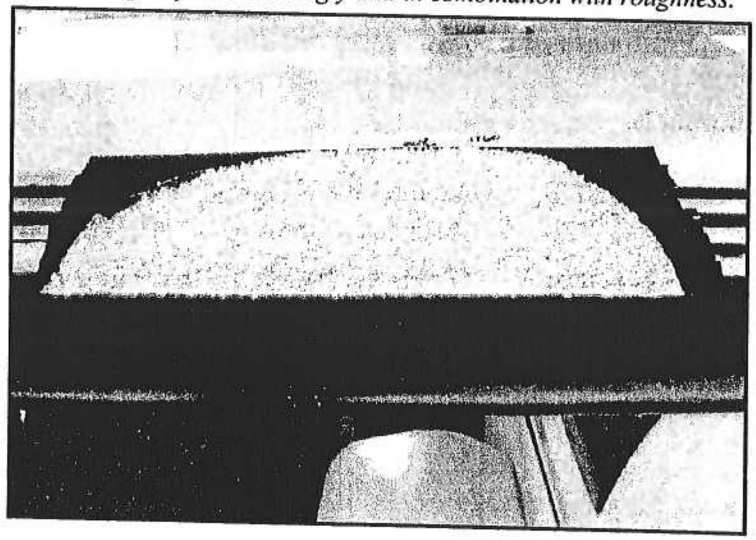


Figure I-21
Artificial roughness elements on right inner wing simulates texture and asymmetric accretion.

upper surface affected stall speed, increased drag and reduced AOA at stall. This was not unexpected as other airplane types evaluated by the FAA demonstrated similar effects. The simulated SLD conditions used were severe, and are known to occur in nature. Further, it is not unusual that some ice shapes, large in size, can be relatively benign, while ice of lesser dimensions can actually be more adverse. An icing research pilot,[12] flying an instrumented Beechcraft BE-200, made the following observation relating to the effects of various ice formation on drag aerodynamic characteristics. The BE-200 airplane does not have the same airfoil as the MU-2B.

> *The most surprising aspect of these encounters was the small amount of ice which was required for significant performance degradation. In small droplet regions we have often flown with five inches of ice on the leading edges with little drag increase and no significant performance degrada-*

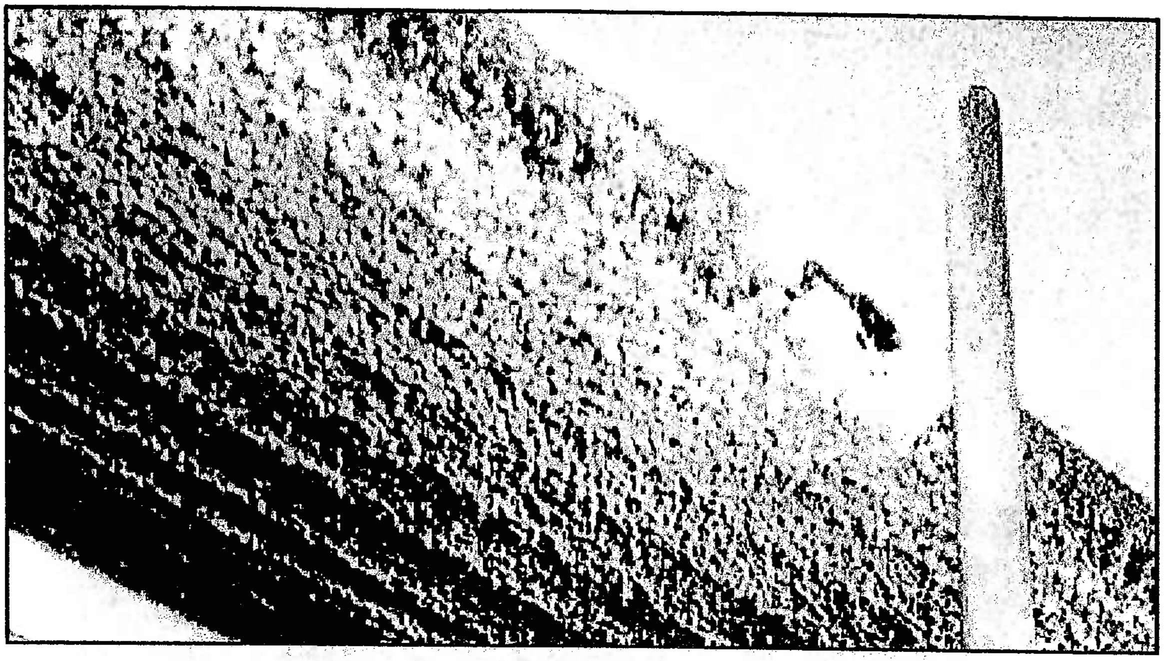


Figure I-22
Natural freezing drizzle ice formation showing spanwise features. This airplane was not an MU-2B and was involved in a landing accident. Clear ice at the stagnation line appears to be approximately ½ inch thick, or the recommended maximum thickness for boot operation.

> *tion. In the SCDD* [supercooled drizzle drop] *region less than an inch of visible accumulation resulted in a 25% increase in stall speed and a huge increase in power required to sustain flight.*

Similar, but less detailed, anecdotal reports have been made on the MU-2B by line pilots who did not have the scientific instrumentation to accurately measure icing cloud characteristics. These anecdotal reports were comparable in detail to the reports provided by MHI during the A10SW TC program.

Tanker icing cloud characteristics

Variables that must be established for the tanker icing cloud include exposure time, temperature, median volumetric diameter[13] (MVD) and LWC. SLD exposure of approximately 20 minutes and temperature just below freezing was based on an accident unrelated to the MU-2B; MVD of that accident was not directly measured but was estimated to be substantial; droplets were believed to exist in the size range up to 400 microns. Research by the University of Wyoming suggests that adverse conditions are associated with droplets in the size range of 40 to 300 microns[14]. LWC for the ATR-72 accident case has been estimated from doppler radar data. Determination of the tanker icing cloud boundary can be found in Appendix 1.

The methodology of data processing and the cloud parameters used for the MU-2B behind the tanker were consistent of those used for other airplanes tested behind the icing tanker.

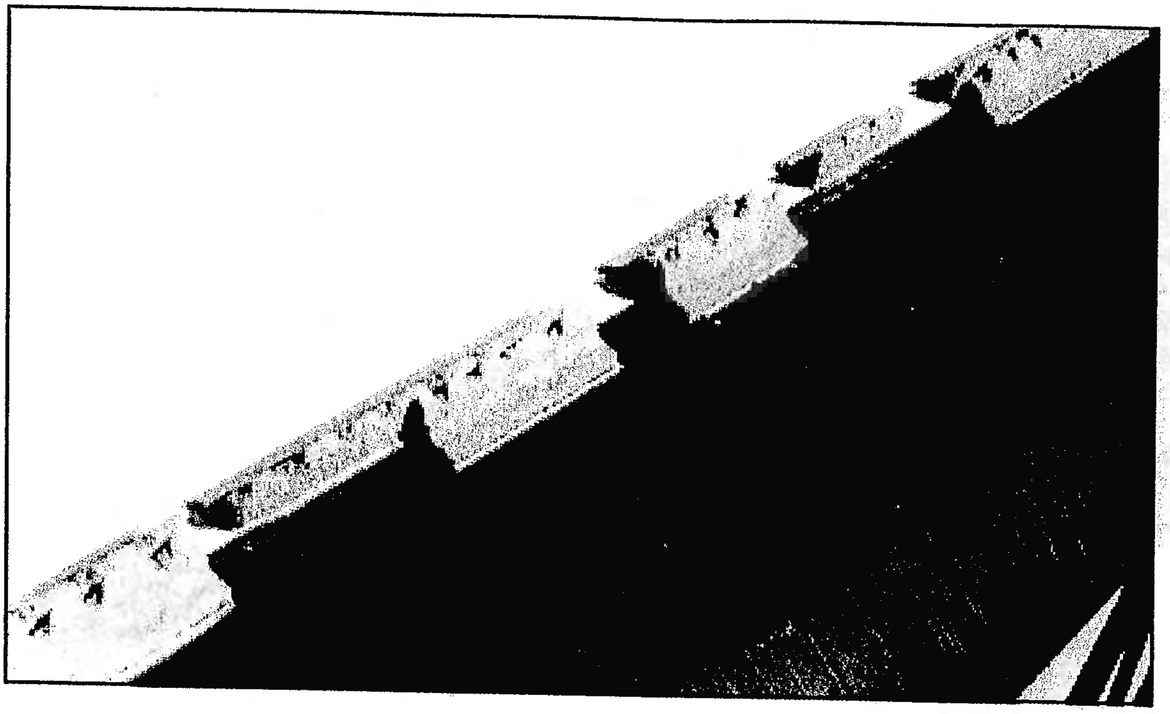


Figure I-23
Artificial ice shapes tested on ATR-72 that closely reproduced the airplane response documented during an SLD icing accident.

In the case of the ATR-72, when tested with artificial ice shapes developed from the icing tanker (figure I-23), the accident scenario was very accurately replicated in all aspects, thus providing a very strong measure of overall confidence in the USAF icing tanker simulation process, and the variables used in determining ridge ice formation. Additionally, the shape, location, dimensions, and texture of the ice accreted in the icing tanker cloud have been compared favorably to the ice accreted in the natural SLD icing environment.

Accordingly, the FAA believes that the test conditions of LWC are consistent with the best current knowledge of the freezing drizzle environment, and reasonably meets or exceeds all available criteria for maximum value.

Forward Scattering Spectrometer Probe (FSSP) measurements behind the tanker

The FSSP is a laser based electro-optical instrument manufactured by Particle Measuring Systems (PMS) used to measure and count droplets generally within the size range of Appendix C conditions. Other Optical Array Probes (OAP's), also manufactured by PMS, were used to count and measure larger droplets during the tanker testing. The size and LWC of the icing cloud is determined by integrating the data from all these instruments.

During the simulated icing conditions in the tanker cloud, progressive temporary degradation/recovery was observed with data sets from the FSSP with each exposure to the cloud. This degradation appeared to be restricted to the FSSP, and after the FSSP was exposed to clear, dry air, in between the cloud measurements, the data sets appeared to correlate well with the data sets from the other instruments in the suite of OAP's. Therefore, earlier measurements tended to be most accurate. Moisture on the optic surfaces or progressive ice accretion on the probe can produce these anomalies, which result in progressively worsening undercounting of smaller droplets within the cloud. Thus higher MVD's and lower LWC's are indicated during longer exposures within the cloud. Data collected by all the instruments were reviewed. The FAA is satisfied that the magnitude and kind of anomaly from the FSSP during this test did not justify repeating the testing nor invalidate the data collected during the MU-2B testing.

Conclusions:

1. While there are some well documented cases of measured natural freezing drizzle conditions, they are insufficient in number to draw confident conclusions about the possible upper boundary conditions that can be expected in the natural environment. The validity of such limited data across all the different geographical regions of the United States must also be considered where different mechanisms of formation occur. The limited data suggests the simulated icing cloud used for the MU-2B testing approximated the natural SLD conditions and was consistent with the conditions used to evaluate other transport category turbopropeller airplanes.

2. The SLD ice accumulated on and aft of the limits of the leading edge de-ice boots on the upper and lower surfaces of the wing, on and aft of the limits of the lower surface of the horizontal stabilizer, the right side of the vertical stabilizer in an unprotected area, on the de-ice boots of the vertical stabilizer, the forward facing portions of the fuselage such as the landing gear sponsons, propeller, propeller spinner, engine cowl and tip tanks. Residual ice on the boots sometimes required several cycles to completely shed. Ice aft of the boots was not shed and formed ice ridges and other distributed roughness ice elements. The sharp edged ice ridge thus had a high local collection efficiency, which caused ice to accrete rapidly. Aerodynamic forces caused parts of the ice ridge to shed in spanwise segments, and then the ice ridges tended to regenerate.

3. The SLD ice causes an increase in drag, an increase in the stall speed, and possible loss of artificial stall warning, which may have been contributory elements to several of the MU-2B accidents reviewed. The tests were performed to evaluate the stall characteristics, handling qualities, and SLD drag increments. Adverse effects of the SLD ice shapes tested did not, however, result in sufficient drag to match the deceleration profile of the icing accidents reviewed. The Team Recommendations will reduce the hazard of inadvertent airplane slowdown that are not recognized during encounters with icing conditions outside of Appendix C.

4. The icing tanker is a valuable tool that allows testing and evaluation of an airplane's anti/de-icing capabilities and handling qualities after a simulated SLD icing encounter.

5. The requirements mandated by the Team's AD 96-25-02 provide information to the pilots to identify when the airplane has entered severe icing conditions that are outside of

the limits of the airplane's ice protection system, and instructions to safely exit the conditions.

6. The MU-2B flight tests with artificial SLD ice shapes confirmed that the airplane remained controllable for a sufficient time to permit the pilot to safely exit SLD conditions.

Recommendations:

FAA should:

1. Support research to further characterize SLD icing clouds and to understand the physics of ice formation in SLD conditions sufficiently to enable computer modeling that will accurately model ice formations, accounting for the variations due to environmental and configuration dependent variables.

2. Support broad based studies and research of SLD ice formations to better understand quantitatively the effect on all aerodynamic characteristics of the sharp edged surface roughness elements (often termed ice feathers), and the effects of inter-cycle, residual, and mature ice shapes. Further research needs to be conducted to ascertain the effects of SLD icing conditions on General Aviation airplane performance.

3. Support research efforts to improve computer ice shape prediction codes so that they will accurately model ice shapes in temperatures near freezing for Appendix C and SLD conditions.

4. Encourage certification of sensors that measure the extent, thickness or aerodynamic effect of ice accretions, notify the crew, and automatically operate anti/de-ice systems.

5. Encourage the development and use of accurate icing simulation facilities including the new USAF icing tanker to learn more about simulating SLD conditions, and the effects of SLD ice on small airplanes.

D. Tailplane stall evaluation

It was agreed, by both the Team and MHI, that flight tests of the MU-2B tail for susceptibility to anomalous characteristics induced by sandpaper on the leading edge of the horizontal tail at Clinton-Sherman, Oklahoma, be conducted to simulate ice contaminated effects. The flight test report is contained in Section II of this report. The FAA conducted previous analyses of the stall margin of the MU-2B tailplane as part of a broad initiative in 1993. The MU-2B was not found to be a problem.

One area of the investigation addressed the potential involvement of the tail in the icing history of the MU-2B airplane. There have been no confirmed reports of pitch anomalies in the U.S., however, the tail can be affected in other significant ways.

The Team reviewed the history of the MU-2B with respect to this issue and also reviewed company reports. MHI has presented data to the Team to demonstrate that the horizontal tail AOA is very low in all normal flight conditions. In addition, a screening analysis was performed by an independent contractor for the FAA. This analysis showed that the MU-2B stall margin was greater than the stall margin of airplanes with demonstrated susceptibility to ICTS. At flaps 20° and at flaps 40° a slight positive stall margin was shown. No accidents reviewed by this investigation appeared to be related to ICTS.

The Team and MHI conducted flight tests using sandpaper to simulate an inadvertent icing encounter, and conducted a pushover maneuver to evaluate the tail stall margin. The configuration tested is shown in figure I-24. The ice shape comprised 60 grit sandpaper wrapped around the leading edge de-ice boot on the upper and lower surface back to the front spar. The airplane was then flown through various maneuvers including push-overs from coordinated flight and in sideslips. The FAA evaluation was limited to flap settings of 20° and 40° at low speeds in coordinated flight, and in sideslips. There was no perceptible longitudinal control force lightening or force reversals throughout the maneuvers. The flight complied with the aspects of the FAA policy set forth in the Small Airplane Directorate memorandum, "Recommended Method of Identification, Susceptibility to Ice Contaminated Tailplane Stall," dated July 12, 1994, with two exceptions. The most critical speed for the

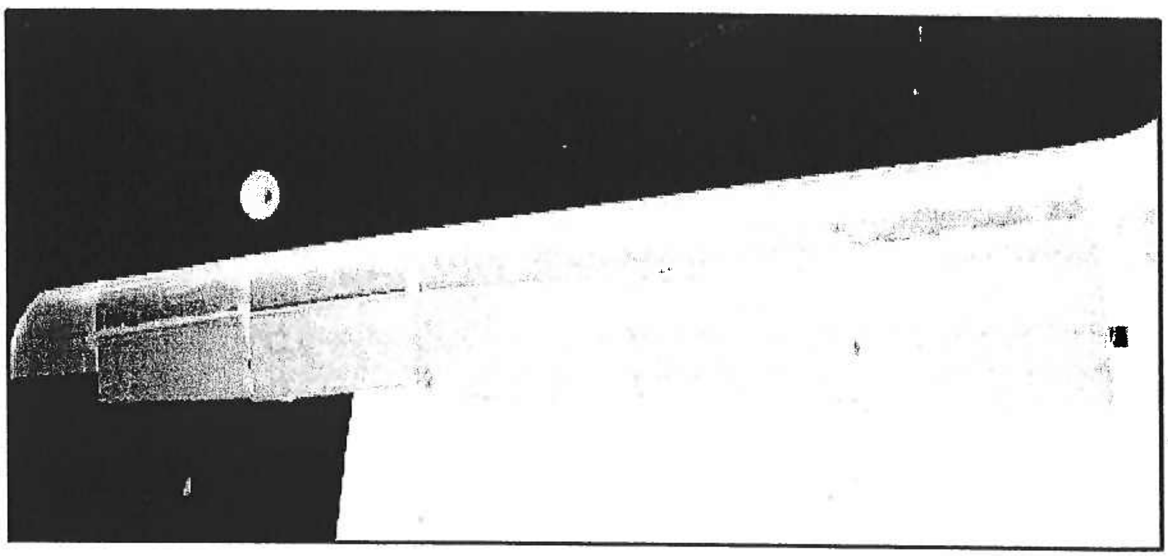


Figure I-24
60 grit sandpaper on lower surface of right horizontal stabilizer of MU-2B.

pushover (0 g load factor) is usually at the low end of the speed range. The lowest speed in the test was flown at 1.3 versus 1.2 V_s specified in the procedures. (At 1 g load factor the largest negative tailplane AOA usually occurs at high airspeeds.) It should be noted that there was no indication of stick force sensitivity to airspeed in these maneuvers. Usually the most adverse effects of power are at high power settings. The highest power setting used in the test was power used in the test was power for level flight.

In response to previous events, the FAA issued airworthiness directives (AD's) against the appropriate airplane types to correct this potentially unsafe condition. The MU-2B was not one of the airplanes effected by the AD action.

Conclusion:

The results of the flight tests at a flap deflection of 20° or 40° showed no tendency to tail stall, no unsafe effect on airplane handling characteristics, or unsafe changes to stick force characteristics. MHI advises that the flap 40° deflection is not normally employed by operators, since it provides little benefit from a performance standpoint, and a maximum deflection of 20° is accordingly recommended in the AFM. In addition, the AFM has a warning in the normal procedures sections that states use of 40° flap settings in icing conditions is prohibited.

Recommendation:

There are no recommendations with respect to the tail aerodynamic characteristics.

E. Tail temperature survey

Tail temperature investigation

Tanker testing showed that ice could form on the unprotected part of the tail on the right hand stabilizer leading edge. Because of the condition observed during the icing tanker testing, further temperature testing was requested by the FAA.

Both outboard horizontal stabilizer tips were immersed in the exhaust plumes of their respective engines to greater or lesser extent depending on configuration. There are no deicing boots on the horizontal stabilizer leading edge aft of the engine (outboard tips) due to the deteriorating effects of the exhaust gases and hot particles. When the engine is operating, heat from the exhaust increases the air temperature on the stabilizer tip aft of it. Thus the stabilizer tips and the elevator horns are afforded some protection from subfreezing temperatures.

There are factors, however, that affect the limits of this protection — the asymmetric flow field in the propeller wash common to airplanes with co-rotating[15] propellers; the airframe interaction on the flow field in various configurations; and, most importantly, the simultaneous presence of supercooled water droplet impingement combined with subfreezing temperatures on the surface of the airfoil.

Mitsubishi report number AES-9314, page 44, refers to an average outside air temperature (OAT) at the test altitude of approximately 29 °F. The report states that the measured temperature at the tail is between 40 and 42 °F at speeds between 180 and 210 KIAS. Those measurements represent a temperature increase of up to 13 °F. Under the same conditions, horn leading edge temperature would enter the subfreezing temperature region at an ambient temperature of 32° minus 13°, or 19 °F. Since the Appendix C temperature range extends to temperatures as cold as -22 °F, the outboard leading edge would be exposed to potential icing conditions for a range of temperatures of 41 °F within the Appendix C conditions.

Mitsubishi's final report, report number AES-9682, relating to post-Edwards testing conducted by MHI confirmed that a temperature asymmetry of as much as 52 °F can exist between the left horizontal stabilizer tip and the right horizontal stabilizer tip in the cruise configuration, and that engine exhaust does not significantly influence the tail at flaps 20°.

Conclusions:

1. The additional tailplane temperature testing showed that there can be areas of the unprotected surface of the horizontal stabilizer leading edge at temperatures below freezing with the airplane in various configurations.

2. There has been no adverse service history suggesting problems with this part of the tail. In addition, no problems were noted during icing tanker tests in both Appendix C and SLD conditions.

Recommendation:

There are no recommendations with respect to the tailplane temperature survey.

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[1] CAR 10, dated March 28, 1955 (Applicable regulations are CAR 3 dated May 15, 1956, including Amendment 3-1 through 3-8, plus Special Conditions stated in FAA letter to JCAB dated May 14, 1965, modified by FAA letter to the JCAB dated January 25, 1971).

[2] LWC defines the mass of liquid water in grams per cubic meter of space (g/m^3). It does not include water vapor.

[3] A micron is one-millionth of a meter, or approximately 0.00004 inches.

[4] "Impingement" means the place on the airfoil where the droplet strikes. The impingement limit is the aft most chordwise position that a droplet will strike under a given set of conditions and is an important factor in determining the aft-most extent of the de-icing boots.

[5] Ice limit or ice extent are sometimes used synonymously with impingement, however, the ice limit or ice extent may be further aft. When the supercooled water droplet (water at a temperature below 0 °C but not yet ice) does not freeze on impact but moves aft, the ice limit is aft of the impingement limit. Such ice is commonly referred to as "runback ice".

[6] Ingleman-Sundberg, M., Sweden, and Trunov, O. K., USSR, 1977: METHODS FOR PREDICTION OF THE INFLUENCE OF ICE ON AIRCRAFT FLYING CHARACTERISTICS, Swedish-Soviet Working Group on Flight Safety, Report No. JR-1, figure 10, shows that a single undersurface ice element can have a small but measurable adverse effect upon maximum lift. This possible effect was considered to be minimal.

[7] Shedding characteristics of the de-icing boot are affected by a number of factors including surface condition of the boots, number of repair patches, temperature, ice thickness upon activation, location of ice, etc.

[8] Supercooled Large Droplets (SLD) are larger than Appendix C conditions and include freezing rain or freezing drizzle.

[9] Tanker testing and natural ice testing each have drawbacks and limitations. Natural icing tests are usually conducted in instrument meteorological conditions (IMC) where the visibility is limited. Safety considerations usually preclude handling and stability flight testing in IMC and the sublimation of natural ice when in visual meteorological conditions changes the ice accreted in natural icing conditions. Tanker testing on the other hand exposes limited parts of the airplane to the icing cloud so that the entire airplane could not be iced at the same time. Tanker ice will sublimate or self-shed when outside the icing cloud similar to natural ice.

[10] Fabrication of BFG pneumatic de-icing boots involves sewing (stitching) the rubber layers together at intervals across the span of the boot. The chambers thus formed are the inflation tubes. When the de-icing boot is deflated, there is a small but noticeable spanwise discontinuity in the surface of the outermost layer of the de-icing boot over the "stitch lines".

[11] "The amount of supercooled water in the large drop sizes was not great, but small accretion on the under surface of wings may have disproportionate effects on performance." Cooper, William A., Sand Politovitch and Veal, University of Wyoming, 1984: Effects of Icing on Performance of a Research Airplane.

[12] Bershinsky, George, *My First Time,* undated.

[13] MVD defines a single diameter in a distribution of droplet diameters such that half the LWC is found in droplets larger, and half the LWC in droplets smaller than the MVD.

[14] "'Unusual Icing' with a significant loss of performance capability was found correlated with supercooled droplets in the 40 - 300 micron-diameter range. The normal FAA icing characterization of referencing liquid water content and volume median droplet diameter does not characterize these encounters." Sand, Wayne R., 1985: AIRCRAFT ICING CONDITIONS — "NORMAL AND UNUSUAL," *NINETEENTH JALC AIR LAW SYMPOSIUM.*

[15] Co-rotating means that both propellers rotate in the same direction as opposed to counter-rotating propellers which rotate in opposite directions. The flow field aft of counter-rotating propellers tends to be more uniform. Most twin-engine airplanes are designed with co-rotating propellers.

Appendix 1 — Determination of tanker icing cloud boundary

Establishing a specific value for what is essentially the average LWC of the icing cloud implies that careful consideration be given to measuring the integrated instantaneous LWC, and then determining the diameter of the icing cloud to perform the simple calculation. The issue is to determine a value for the cloud that represents the test airplane exposure. In the normal course of flying in the tanker cloud, there is some variance as the pilot cannot maintain a precise position. The amount of variation relative to the cloud depends upon the size and configuration of the test airplane, and the flap/power configuration of the tanker, the skill of the pilots of the tanker, and the test aircraft in flying in formation, the location of the test point on the test airplane, and the state of the atmosphere.

The tanker cloud has variations that tend to average out in the ice accretion process which occurs over a much longer time interval than in a relatively short data collection interval, so it is important to arrive at a meaningful technique which will produce accurate and repeatable results.

When the icing cloud is traversed laterally and vertically by the instruments on the chase airplane behind the tanker, droplet concentration is measured and differences in these measurements can be portrayed on a graph. The tanker cloud is most dense in the center and the liquid water content decreases away from the center due to several effects. One effect is evaporation and mixing at the periphery of the cloud. An added effect can be observed in the vertical plane caused by gravity, which causes a greater concentration of larger droplets at the bottom of the cloud. Also different from natural icing clouds, the relative humidity of the icing tanker cloud is less than saturated. The precise effects of the humidity on ice formation have yet to be fully understood.

During the icing tanker testing of the MU-2B, two MHI contractors used a different method for calculating the LWC of the tanker cloud than the third MHI contractor. The fundamental difference between the methodologies rests in the definition of the limits of the tanker icing cloud. Discussion of the two methods follows. The essential difference involves the distance that the instantaneous LWC data from the FSSP is averaged over. Hence, the important question relates to determining the cutoff point for the icing cloud.

The cloud definition is treated by testing methods described below:

Method 1: The cloud is defined by the point where the LWC is measurable. This was typically between 0.01 and 0.10 grams. Then the LWC measurement is averaged over the distance between these two points.

Method 2: A visual estimate is made of the cloud LWC trace on a graph which generally corresponds to approximately the highest value of the LWC. The outer periphery of the cloud with measurable water is ignored.

Method 1 provides a better average especially considering normal variations within the cloud. Method 2 is a faster method but does not accommodate cloud variances as well. Method 1 would tend to produce a lower LWC than method 2 for the same cloud.

The current contractor employing method 1 believes that it best represents the conditions that the test airplane actually traverses. His visual impression was that the test airplane experienced normal vertical path variations in the cloud that appeared to move the distance of the cloud diameter. Thus the airplane appears to have been exposed to a cloud dimension consistent with that used in method 1.

While the tanker cloud appears to have a higher LWC than the limited information currently known about natural SLD icing clouds, much of the SLD icing process is not yet totally understood or commonly accepted. For example, the scientific community in the U.S. (including NASA) and abroad has yet to be able to accurately model the complex thermodynamics and the physics of the ice accretion process at temperatures near zero representative of natural icing conditions. Other indices have been used to evaluate the relevance of the icing tanker cloud.

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II. FLIGHT TEST REPORTS

INITIAL AIRCRAFT EVALUATION

April 18, 1996, Tulsa International Airport, Tulsa, Oklahoma (TUL)

MU-2B-60 (Marquise) Registration Number N794MA, Serial Number 794 SA

Ramp weight – 11,249 Lbs. Center of Gravity – 194.66 inches aft of datum (mid-c.g.)

FAA Test Pilot – Joe Brownlee; MHI Pilot – Pat Cannon
FAA Test Pilot – Jon Hannan; FAA MKC-AEG Pilot – Richard McCleish
Video Operator – Mark Boyd, Visual Productions

Flight FAA-1 – Takeoff 1157 Central Daylight Time, 2.5 hour flight

After takeoff, during the climb, it was noted that with both condition levers full forward there was a ½ percent difference in propeller revolutions per minute (RPM). To manually synchronize the propellers, the left condition lever had to be moved a half knob width aft of the right lever; then the propeller synchronizing/synchro-phasing system was turned on and the engines stayed in "sync" throughout the flight.

Longitudinal static stability evaluation by level acceleration method:

At 9,500 feet pressure altitude (ALT) (Hp), propellers at 100 percent RPM, power and trim for level flight at 180 KIAS, power was increased to accelerate at constant altitude without changing the longitudinal trim; then power was decreased.

190 KIAS - 7 Lbs Push; 200 KIAS - 15 Lbs Push; 217 KIAS 24 Lbs Push; 231 KIAS - 31 Lbs Push; 240 KIAS - 29 Lbs Push; 247 KIAS - 27 Lbs Push; after retrimming to 180 KIAS, 165 KIAS - 12 Lbs Pull; 150 KIAS - 15 Lbs Pull; 137 KIAS - 22 Lbs Pull; 115 KIAS - 32 Lbs Pull. A push force was required to maintain level flight with increasing airspeeds from the trim speed with some force lightening at higher speeds, and a pull force was required to maintain level flight with decreasing airspeed.

Pitch attitude vs. airspeed at takeoff power evaluation:

Starting at 12,000 feet Hp, propellers at 100 percent, engines at 100 percent torque or 650 °C maximum exhaust gas temperature (EGT), trimmed at 120 KIAS = 17° pitch attitude on the left attitude director indicator; 165 KIAS = 10° pitch and a 34 Lbs push force; 180 KIAS = 9° pitch at 45 Lbs push. This also substantiates the positive longitudinal static stability of the airplane.

Autopilot longitudinal trim evaluation:

At 9,500 feet Hp, propellers at 100 percent, engine power and trim for level flight at 180 KIAS, autopilot was engaged in heading hold and ALT hold modes with the longitudinal trim 4° nose up; then power was reduced to slowly decelerate the airplane. The trim wheel moved in small intermittent increments, nose up. Passing through 120 KIAS the trim was 11° nose up. Autopilot was disconnected at the stick shaker (stall warning) at 102 KIAS. The airplane was in trim and the longitudinal trim position indicator read 19° nose up, which correlates to 19° elevator trim tab trailing edge down. Accelerating to 120 KIAS required a longitudinal control push force of 24 Lbs to maintain level flight.

Static and dynamic lateral and directional stability evaluation:

Static lateral and directional stability was evaluated in accordance with FAR § 23.177 at 10,000 feet Hp flaps up, landing gear up, at 130 KIAS, propellers at 100 percent, engine power for level flight; and takeoff power for directional stability, and 80 percent torque for lateral stability; and flaps 20°, landing gear down, power for 3° glide slope at 107 KIAS. Stability was positive in all cases with some pedal force lightening, but with landing gear down, the rudder centering was weak, due probably to friction in nose gear steering system. Dynamic stability (Dutch Roll damping) with flaps 20°, landing gear down, propellers at 100 percent, engine power for 3° glide slope at 107 KIAS was well damped in two oscillations with yaw damper off and one oscillation with yaw damper on.

Trim aileron authority evaluation:

At 10,000 feet Hp, flaps 20°, landing gear down, propellers at 100 percent, engine power for 3° glide slope at 107 KIAS, trim ailerons were set to the first "Lower Left Wing" index. Force measured on the right control yoke horn was 9 Lbs to maintain the wings level, and with full "Lower Left Wing" trim, the force was 13 Lbs with the control yoke deflected 40° right to maintain wings level. With trim ailerons set to the first "Lower Right Wing" index, force on the left control yoke horn was 12 Lbs to maintain the wings level and, with full "Lower Right Wing" trim, the force was 18 Lbs with the control yoke deflected 45° left to maintain wings level.

Roll rate evaluation:

Rate of roll was evaluated in accordance with the procedures of FAR § 23.157. At 10,000 feet Hp, flaps up, landing gear up, propellers at 100 percent, engine power for level flight at 191 KIAS (maximum maneuvering speed – V_a), a 30° left bank was established. Timing began at full application of right lateral control (rudder held fixed) and stopped as the bank angle passed through 30° right bank. Left to right timing was 1.61 seconds, right to left was 1.50 seconds. With flaps 20°, landing gear down, propellers at 100 percent, engine power for level flight at 120 KIAS, left to right was 2.17 seconds; right to left was 2.16 seconds. With flaps 20°, landing gear down, propellers at 100 percent, engine power for level flight at 150 KIAS (155 KIAS is V_{fe}), left to right was 2.18 seconds, right to left was 2.22 seconds. These maneuvers were quite dynamic, but the roll control forces appeared to be constant for all conditions.

Stall characteristics evaluation:

At this mid-c.g., stall characteristics were evaluated in accordance with FAR § 23.201 and AC 23-8A at 12,000 to 6,000 feet Hp. With both power levers on the flight idle stops, the engine torques were not indicating equal. Therefore, stalls were performed with the power of both engines set to 20 percent torque in lieu of flight idle. All stalls were performed wings level at one knot per second deceleration rates.

Note. The following descriptions were written from memory, from notes taken during the tests in the aircraft, and by analyzing the videotape. On this first flight, the video camera trained on the pilot's flight instruments was not working, therefore, exact movements of the slip-skid ball could not be discerned. Video views from the camera trained on the overall instrument panel including the attitude indicator and slip-skid ball were from almost twice the normal eye distance, and the instruments were obstructed by arms and elbows during the later stages of these maneuvers:

Test Conditions: Flaps up, landing gear up, 20 percent torque, trim airspeed 150 KIAS: stick shaker (stall warning) 102 KIAS, V_{min} 81 KIAS. Required near full left lateral control to keep the bank angle under 15° right roll, with the longitudinal control held on aft stop for approximately 2 seconds, then the longitudinal control was moved forward to reduce AOA.

Test Conditions: Flaps up, landing gear up, 50 percent torque, trim airspeed 150 KIAS: stick shaker 100 KIAS, some left rudder with near full left lateral control was required to keep the bank angle from exceeding 20° right roll, with longitudinal control held on the aft stop for approximately 2 seconds, then moved forward. The slip-skid ball remained near the center throughout this maneuver.

Test Conditions: Flaps 5°, landing gear up, 20 percent torque, trim airspeed 141 KIAS: stick shaker 94 KIAS. Some left rudder was required to keep from exceeding 20° right roll with near full left lateral control. Same result with 50 percent torque.

Test Conditions: Flaps 20°, landing gear down, 50 percent torque, trim airspeed 123 KIAS: stick shaker 85 KIAS. As airspeed decreased and AOA increased, to hold wings level initially required right lateral control, then a rapid input of left yoke to prevent a right roll.

Test Conditions: Flaps 20°, landing gear down, 20 percent torque, trim airspeed 123 KIAS: rolled 45° right, with the slip-skid ball to the left of center. A repeat of this maneuver resulted in a requirement for right yoke, with the ball slightly left, then as the ball moved more left, there was a rapid need for full left yoke, with a resulting bank angle of 30°, as the AOA was decreased.

Test Conditions: One stall at 20° flaps was performed with de-icing boots inflated just before the stall. Characteristics were generally the same as the other maneuvers, with a roll to the right.

Throughout these maneuvers, the engine torque and fuel flow, as recorded by a video camera trained on the overall instrument panel from almost twice the normal eye distance, appeared to be well matched.

Note. In a brief evaluation of the stall characteristics of another MU-2B-60 some weeks before, the right rolling tendency was also evident for that aircraft.

Autopilot approach mode evaluation:

An ILS approach to runway 36R at Tulsa International Airport was performed with the autopilot coupled in the approach mode. Autopilot control authority was very positive, tracking the glide slope and localizer quite accurately. When the autopilot was disconnected at 500 feet above ground level, the aircraft was in trim.

Flight FAA-2 – Takeoff approximately 1600 CDT, 1.3 hour flight.

Ramp weight – 11,582 Lbs. Center of Gravity – 198.25 inches aft of datum (aft c.g. limit is at 199.4)

FAA Test Pilot – Joe Brownlee; MHI Pilot – Pat Cannon
FAA Test Pilot – Jon Hannan
Video Operator – Mark Boyd, Visual Productions

Before this flight, maintenance was performed on the aircraft. On this flight, the condition lever knobs were equal (side by side) with the propeller RPM synchronized. Throughout the flight, during the maneuvers, the engine torques and fuel flow appeared to be well matched.

Autopilot longitudinal trim evaluation:

Test Conditions: At 12,000 feet Hp, propellers at 100 percent, engine power and trim for level flight at 180 KIAS. Autopilot was engaged in heading hold and ALT hold modes. Then power was reduced to slowly decelerate the airplane. The trim wheel moved in small intermittent increments nose up. Autopilot was disconnected at the stick shaker (stall warning) at 100 KIAS. The airplane was in trim and the longitudinal trim position indicator read 11° nose up, which correlates to 11° elevator trim tab trailing edge down. This trim position is less trailing edge down than the previous test at mid-c.g., and correlates correctly with the aft c.g. condition.

<u>Stall characteristics evaluation:</u>

Note. The following descriptions were written from memory, from notes taken during the tests in the aircraft, and by analyzing the videotape. On this second flight, the video camera trained on the flight instruments was working, therefore, movements of the slip-skid ball could be discerned, except when obscured by the control yoke. Video views from the camera trained on the overall instrument panel of the attitude indicator and slip-skid ball were from almost twice the normal eye distance, and the instruments were obstructed by arms and elbows during the later stages of these maneuvers.

Test Conditions: Flaps up, landing gear up, 20 percent torque, trim airspeed 150 KIAS: stick shaker (stall warning) 105 KIAS. Slip-skid ball moved one ball diameter left, and even with full left lateral control yoke, the aircraft rolled 80° right, with the longitudinal control held on the aft stop for no more than 2 seconds, then moved forward. Subsequent stalls in this configuration were characterized by the slip-skid ball moving up to 2 ball diameters left, with right rolls up to 45°, indicative of "roll due to yaw".

Test Conditions: Flaps up, landing gear up, 50 percent torque, trim airspeed 150 KIAS. By anticipating the requirement for left rudder, the ball moved only ½ diameter left; but even with rapid full left yoke, the aircraft still rolled 32° right.

Test Conditions: Flaps 5°, landing gear up, 50 percent torque, trim airspeed 141 KIAS. Attempting to react to the slip-skid ball and bank angle, with rudder and lateral controls, the ball moved 2 diameters left, and aircraft rolled 85° right.

Test Conditions: Flaps 5°, landing gear up, 20 percent torque, trim airspeed 141 KIAS. Held ball near center, aircraft rolled to 20° right.

Test Conditions: Flaps 20°, landing gear down, 50 percent torque, trim airspeed 123 KIAS, stick shaker at 85 KIAS. Held roll to 10° right.

Test Conditions: Flaps 20°, landing gear down, 20 percent torque, trim airspeed 123 KIAS. Did not anticipate left rudder, ball 2 diameters left, roll 80° right.

Test Conditions: Flaps up, landing gear up, 20 percent torque, trim airspeed 150 KIAS, turning stall 30° left bank, one knot per second deceleration. Slip-skid ball moved 2 diameters left, aircraft rolled right to 30° right bank. Repeated test from 30°

right bank. Again, ball moved 2 diameters left and aircraft rolled to 90° right. Both of these tests meet certification criteria.

Test Conditions: Flaps up, landing gear up, 50 percent torque, trim airspeed 150 KIAS, turning stall 30° left bank, one knot per second deceleration. Ball held near center with anticipated left rudder. Aircraft rolled wings level.

Test Conditions: Flaps 20°, landing gear down, 20 percent torque, trim airspeed 123 KIAS, left turning stall from 30° bank. Ball moved one diameter left, but was brought back to center with left rudder; then ball moved 2 diameters left, and aircraft rolled right to a bank angle of 85°. This met certification criteria.

Test Conditions: At 18,000 feet Hp, flaps up, landing gear up, 20 percent torque, trim airspeed 150 KIAS. Anticipating left rudder, the ball was centered when the aircraft started a right roll to 30°, and during the recovery, the ball moved 2 diameters right, indicative of the left rudder input. This high altitude test seemed no different than the previous stalls at around 8,000 feet Hp.

<u>Autopilot approach mode evaluation:</u>

An ILS approach to runway 36R at Tulsa International Airport was performed with the autopilot coupled in the approach mode. Again, the autopilot control authority was very positive, tracking the glide slope and localizer quite accurately. When the autopilot was disconnected at 600 feet above ground level, the aircraft was in trim and a circling procedure to land on runway 26 was made.

ICING TANKER TESTS

Simulated icing testing was conducted behind the USAF NKC-135A Icing Tanker at the AFFTC, Edwards Air Force Base (AFB), California. The tests at Edwards AFB were conducted at the request of, and sponsored by the FAA, and consisted of four flights between April 26 through 28, 1996. All costs associated with these tests were borne by MHI.

The test airplane was an MU-2B-60 (Marquise), Registration Number N794MA, Serial Number 794 SA. The airplane was a conformed article with the addition of audio and video recording equipment, and black painted stripes to show extent of ice accretion. The video recording equipment was to show the extent of ice accretion located inside the fuselage with external cameras or ports located on the leading edge of the vertical stabilizer mounted in a small blister, a viewing port on the underside of the right hand wing tip, and a viewing port on the right side of the fuselage looking aft to the right hand stabilizer. The black paint stripes were one-inch wide and one-inch apart on the upper and lower wing surfaces aft of the boots. Each propeller spinner was also painted with two reference stripes at approximately 25 and 50 percent chord.

The airplane was flown by a USAF Reserve Test Pilot, Lieutenant Colonel Eric P. Hansen, and the MHI pilot, Tommie E. Batchelor. Other crewmembers on the MU-2B were an instrumentation operator and a photographer/observer. The tests were supported by the 452d Test Squadron with its NKC-135A equipped with a water icing spray rig. A Learjet was contracted from Aeromet Inc. to provide a calibration of the spray cloud and in-flight photographs during the tests. The FFFSCR Team members aboard the NKC-135A witnessing the tests were Jon Hannan, Tim Smyth, John Dow and Joe Brownlee.

Below is a chronology of the events that transpired during the four flights:

1. April 26, 1996. First Flight, icing conditions within 14 CFR part 25, Appendix C, envelope.

The USAF icing tanker takeoff was at 0720 Pacific Daylight (Saving) Time (PDT).

Initially, with tanker flaps 10°, 11,500 feet Hp, 220 knots KIAS, the MU-2B was engine power limited and had difficulty in maintaining position behind the tanker. At 11,500 feet Hp, 210 KIAS, the MU-2B was able to hold a stable position with left tip tank behind the water spray array (a large "shower head" device made up of nozzles for both water spray and air emissions). The required MU-2B positions behind the tanker and the array were evaluated for aircraft controllability before testing commenced. With the MU-2B's right engine and inboard wing behind the array, turbulence caused by airflow from the array and downwash from the tanker resulted in some buffeting on the MU-2B. With the nose of the MU-2B directly behind the array, turbulence caused by the array buffeted the tail resulting in a lateral sidestep translation. If the pilot was active on the rudder, position could be maintained precisely. With the tanker slowing to 200 KIAS, there seemed to be no difference in aircraft control requirements to maintain position from the 210 KIAS case.

Upon reaching the proper test conditions, the tanker was set up for testing. The tanker engines 2 and 3 were set to 85 percent to provide proper bleed air pressure to the icing array for atomization of the water at the nozzles, and to prevent water from freezing inside the boom. Engines 1 and 4 were adjusted as necessary to maintain airspeed and altitude. At 18,000 feet Hp, 200 KIAS, 0.1 °C Total Air Temperature (TAT), the Aeromet Learjet calibrated the cloud, 75 feet aft of the array, at 0.15 to 0.20 g/m^3 LWC and 25 to 40 μm MVD drops at 30 percent Relative Humidity (RH) (quick look at data). These values (data where there is documentation from on-board instrumentation in the chase Learjet such as Indicated Airspeed (IAS), ALT, RH, TAT, LWC, and MVD) vary somewhat during the conduct of the tests. The values given are representative of the test point, however, the results of the data taken from the chase airplane and appropriately processed are considered the official values. That data can be found in a separate MHI document. The rationale is that some of the parameters varied during the test and, in the case of some of the FSSP data, there were some problems found later, and have been resolved.

The MU-2B was able to get into position with the nose accreting ice, but was unable to hold the position at 200 KIAS. The formation then slowed to 180 KIAS. Outside the tanker wake, the MU-2B required 500 pounds per hour (PPH) fuel flow, and at 75 feet aft of array, the fuel flow required was 600 PPH. The Learjet then made cloud calibrations at 17,500 feet Hp, -0.7 °C TAT, 100 feet aft of the array, tanker engines 2 and 3 at 89 percent. Quick look data indicated conditions at 27 percent ambient RH, 0.15 g/m^3 LWC with 40 μm MVD drops (larger drops near bottom of cloud).

Testing commenced with the MU-2B flying 100 feet aft of the array, with the nose and left fuselage in the icing cloud produced by the array (hereinafter referred to as the "cloud"), at a temperature of -0.2 °C TAT. Ice accreted on nose, landing gear sponsons, horizontal stabilizer to fuselage fairing, and the lower part of left windshield. The longer the MU-2B remained in the cloud, more engine power was required to maintain position. After 6.5 minutes in the cloud, the MU-2B exited to shed the accreted ice.

After the ice was cleared, the MU-2B was set up with the right inboard wing in the cloud. At -0.3 °C TAT, ice accretion was immediate on wing to fuselage fairing, beneath right wing, dorsal fin, horizontal stabilizer to fuselage fairing, and leading edge of horizontal stabilizer extending about 1-inch aft of the stagnation point. Little ice accreted on the right engine propeller spinner. Full power was now required to stay in position. Ice also accreted on the right inboard wing boot aft of the propeller arc. Full power was not enough to hold position and the airplane began to lose position after 11 minutes in the cloud. The airplane exited the cloud down and to the left for pictures from the Learjet, and the boom operator's position. Ice accretions were observed on the horizontal stabilizer outboard of the elevator balance horn and the leading edge boot, on the right engine nacelle, the right wing boot aft of stagnation point with no ice on the area around stagnation point. To maintain position, 10 to 12° of left control yoke deflection was required. A single boot activation shed ice from the horizontal stabilizer and most of the wing, but all of the ice from the right inboard wing near the leading edge did not shed. The Learjet performed a post-test point calibration at 17,500 feet Hp, 0.00 °C TAT, 180 KIAS, and the liquid water content increased the closer the airplane was to the array.

The MU-2B was then set up to ice the left outboard wing, just inboard of tip tank, at 22 percent ambient RH. Immediate accretion was noted on the tip tank nose and tip tank to wing fairings. Three and a half minutes later, ice was observed on the wing boot. A comment was made from Learjet – ice on wing boots was accreting still within active portion of boot. After a boot cycle where all the boots cleared their ice, the MU-2B returned to Edwards AFB for landing. At 17,500 feet Hp, 0.9 °C TAT, and 28.4 percent ambient RH as measured by the tanker, a final Learjet calibration measured the cloud at 0.5 to 0.6 g/m^3 LWC and 30 μm MVD drops. The tanker landed 1012 PDT yielding 2 hours and 52 minutes of flight time.

The following are some of the observations from the USAF Test Pilot flying the MU-2B:

With ice accretion on the right inboard wing between the right engine and the fuselage, to maintain wings level in the cloud required approximately 20° of left control yoke (left spoiler up). Clear of the cloud and the tanker wake, it still required some left spoiler to maintain wings level. As the ice melted and/or sublimated, the requirement for left control yoke decreased. However, for ice accretion on left outboard wing, no real need for right lateral control displacement was noted to maintain wings level. (Since the propellers rotate in the same direction, the flow fields aft of the propellers was not symmetrical, nor was the ice that formed symmetrical.)

2. April 26, 1996. Second Flight, icing conditions beyond 14 CFR part 25, Appendix C, (SLD).

The USAF icing tanker takeoff was at 1329 PDT.

The first test point Learjet calibration at 17,600 feet Hp, 180 KIAS, measured -0.5 °C TAT, 0.3 to 0.35 g/m^3 LWC, 25 to 30 μm MVD drops, and 23 percent ambient RH.

The MU-2B left outboard wing was positioned so that the tip tank was in the cloud at 18,000 feet Hp, and -0.5 to -0.6 °C TAT. Some ice accretion was noted on the wing boots. However, the outside air temperature was not stable. The decision was to hold altitude and monitor the ambient temperature fluctuations. The tanker required maximum power at maximum engine temperature on the inboard engines to hold airspeed and altitude. The formation slowed to 175 KIAS. The tanker had to reduce power on the inboard engines after a time limit was reached at maximum power. There was some difficulty in adjusting the cloud characteristics with the engine power limitations on the tanker, and a communication failure at the boom operator's station. Therefore, the decision was made to abort the test (holding 18,000 feet Hp, TAT fluctuating ±1.9 °C). A Learjet cloud calibration was performed before departing at 17,500 feet Hp, 175 KIAS, 75 feet aft of array, 1.2 to 0.9 °C TAT, tanker engines 2 and 3 set to 92 percent, water flow 2.6 gallons per minute (GPM), that measured LWC 0.2 g/m^3 and MVD 50 μm. The tanker landed at 1659 PDT after 1 hour and 30 minutes of flight time.

Note. A comment from the USAF Test Pilot flying the MU-2B – flying in downwash from the tanker is equivalent to climbing, requiring 100 °C more EGT than in still air. 10 ° right control yoke was required with the left outboard wing immersed in the icing cloud. A comment from the observer in the Learjet – all ice accretion was on the boots, with the ice limit moving aft along span toward wing tip (a logical result from wing twist (washout)).

3. April 27, 1996. Third flight, icing conditions beyond 14 CFR part 25, Appendix C, (SLD).

The MU-2B took off before the tanker to reduce the gross weight with fuel burn. The USAF icing tanker takeoff was at 0732 PDT.

For the first test point, the Learjet cloud calibration at 16,850 feet Hp, 180 KIAS, tanker flaps 20°, +0.6 °C TAT, engines 2 and 3 set at 94.5 percent, water flow 3.1 GPM, 50 feet behind array, measured LWC 0.2 to 0.3 g/m^3 and MVD 100 μm. The MU-2B positioned the left outer wing in the cloud and had power to spare due to the lower altitude and lighter gross weight. The tanker water flow rate had changed to 4 GPM. Tanker engines 2 and 3 were reset to 93 percent and the flow rate decreased to 3.1 GPM, as in the previous calibration. Ice accretion was noted on the tip tank nose, the tip tank to wing fairing, and aft of the wing boots. The formation climbed to 17,050 feet Hp to maintain TAT at -0.6 °C. As before, the accretion impingement line followed the outboard wing twist and airfoil section change.

The temperature noted was -1.2 °C TAT and ambient RH was 12.4 percent when ice accretions were noted back to the third black stripe on the bottom of the left wing (aft of the boots). Increased requirement for right control yoke displacement to 15° was observed, with excursions to 20 to 25°. Ice on the leading edge was beginning to self-shed in the area aft of the propeller tips. To completely de-ice the boots above the stagnation point required two boot cycles. It was reported that it appeared as if the boot inflation tubes below the stagnation point were not inflating. The test pilot commented that there was less control yoke deflection required after the boot cycles. Three minutes after the previous boot cycle, ice self-shed from below the stagnation point. When the MU-2B moved out of the tanker wake, the pilot noted a centered control yoke. The MU-2B then descended to melt and sublimate the accreted ice, while the Learjet performed another cloud calibration. The Learjet calibration at 17,200 feet Hp and -0.6 °C TAT was LWC 0.3 to 0.4 g/m^3 and MVD 40 ±10 μm. The tanker had 15° of flaps extended.

For the next point, the MU-2B positioned the left inboard wing in the cloud. Immediate ice accretions were noted on the horizontal stabilizer to fuselage strake (a rather sharp leading edge). After a minute and a half, ice accretions were observed on the wing boots, the left propeller spinner, and the inboard engine nacelle. The propeller spinner accretions were back to the propeller blade roots. The appearance of "ice fingers" was observed under the wing. Frost to the back edge of the boot on the upper surface of the horizontal stabilizer was also noted. This point required control yoke movements that were centered around the neutral position. An ice ridge started to build on the engine inlet, even though the engine inlet heater was in the ON position. A ½ inch of ice was noted on the horizontal stabilizer leading edge below the stagnation point. A boot cycle was initiated when the double-horn ice reached ¾ inch on the wing leading edge. The MU-2B crew felt the shed ice as it hit the horizontal tail. The horizontal stabilizer boot shed completely clean. Ice remained aft of the boot on the lower surface of the wing. The ice was 6 inches aft of the second stripe on the spinner, near the propeller blade root. The Learjet performed another post-point calibration. The calibration at 17,200 feet Hp, 175 KIAS, -0.6 °C TAT, 3.1 GPM water flow, and 22.4 percent ambient RH was measured by the tanker. RH measured by the Learjet in the cloud was 78 percent and 0.3 to 0.5 g/m^3 LWC with 30 μm MVD. The mission was complete and the tanker landed at 0944 PDT for 2 hours and 12 minutes of flight time.

Note. Comments were recorded during the flight debriefing – the MU-2B pitch attitude at 180 KIAS away from the tanker wake was 3½°, and within the tanker wake was 6½°. The observed engine inlet ice was a safety concern. The AFM/Pilot Operating Handbook recommends allowing ¼ inch of ice to accrete on the wing boots before initiating a boot cycle. When the boots were cycled with 1-inch accretion, the wing outer boots did not completely clear. Approximately 1/8 inch of ice remained at the stagnation point. Ice also accreted below the stagnation point and back to the third paint stripe on the underside of the wing, aft of the boot. There was 3/8 inch of ice on the tip tank light shield (a sharp medal shroud around the light) and a large ice shape on the inboard engine oil cooler inlet. (There are two electrically heated semicircular protruding air inlet scoops on both sides of the aft portion of the engine nacelle providing ram air to the engine oil cooler.)

4. April 28, 1997. Fourth flight, icing conditions beyond 14 CFR part 25, Appendix C, (SLD).

The USAF icing tanker takeoff was at 0709 PDT.

Initial Learjet cloud calibration at 14,750 feet Hp, 180 KIAS, +1.1 °C TAT, with tanker engines 2 and 3 at idle, water flow rate 4.8 GPM, 14 percent RH, measured LWC 0.7 to 0.85 g/m^3 and MVD 110 to 130 μm. During the calibration, the Learjet T-tail upper surface accreted ice almost immediately to 30 to 50 percent chord, and its right engine spinner also collected ice. Tanker water flow rate was so high that the estimated time till water exhaustion was 1 hour and 45 minutes.

The MU-2B was positioned with the left outer wing in the cloud. Ice was noted accreting near the tip tank to near the aft extent of the wing boot. After 6 minutes, the boots were cycled. An ice ridge was observed aft of the boot. After the boot cycle, the power required to hold position was a little less. After 9 minutes, some ice self-shedding was observed. An observer in the Learjet reported ice ¼ inch thick, ¼ inch aft of the boot (between the boot and the first black paint stripe) on the top of wing. Ice "nodules and feathers" were noted to extend aft to the first black stripe. It was observed that flap mechanism fairings and underwing surfaces collected ice nodules back to half of the wing chord. The boots were cycled 7 minutes after the previous boot cycle and resulted in less right control yoke displacement, and again less engine power was required to hold position. Ice accretion was observed back to the first black stripe on the top of the wing, and ice ridges accreted past the third paint stripe beneath the wing. Three minutes after the previous boot cycle, the boots were cycled again. There was an immediate 5° reduction in roll control required, and a 20 °C engine EGT reduction in power required to hold position. Ice 1-inch thick was noted back to 30 percent chord on the underside of the wing. As ice accreted, the control yoke was displaced up to 25° right and a 15 °C EGT increase in engine power was required to hold position. The boots were cycled 3 minutes after the previous cycle. The ice aft of the boot remained on the wing. The MU-2B exited the cloud at the conclusion of this test point. Clear of the tanker wake, the lateral control displacement was still the same and resulted in ½ ball out of trim to hold wings level. As the ice melted or sublimated, the roll control requirement decreased. The post-test point Learjet calibration at 14,950 feet Hp, 180 KIAS, +2.3 °C TAT, with the tanker engines 2 and 3 at idle, 4.46 gal/min water flow rate, measured LWC 0.7 to 0.985 g/m^3 and MVD 100 to 115 μm.

The MU-2B was positioned with the right inboard wing in the cloud. The crew noted an immediate ice buildup on the windshield wiper blades and on the unheated portions of the windshield. The propeller spinner was entirely covered with ice. The crew commented that ice was building faster than they had ever seen it build. The ice impingement line on top of the right inboard wing formed an elliptical pattern, further forward near the fuselage and the engine nacelle, and further aft on the wing boot between the fuselage and the nacelle. Some ice self-shed aft of the prop tip. After 3 minutes in the cloud, there was a 15° left roll control requirement to hold position. Ice had accreted on the upper surface around the engine inlet. The boots were cycled after 4 minutes in the cloud. This reduced the required roll control displacement by ½. The crew commented that the ice accumulation on the side of the engine nacelle could be a visual cue for large drop (SLD) accretion. They also expressed a safety concern about the ice around the engine inlet (potential for flameout). Soon after the boot cycle, the controls reverted back to the 15° of left roll control displacement. The ice detector appeared to function properly. Very little ice accretion was noted on the side window. Ice was observed to form on the right-hand side of the leading edge of the vertical stabilizer. The roll control requirement increased up to 25 to 30° control position. The boots were cycled 3 minutes and 40 seconds after the previous boot cycle. Roll control again reverted back to 30° in only 46 seconds after the boot cycle. Thirty four more seconds and the roll control had reached the pre-briefed limit of 35°. The MU-2B exited the cloud after 9 minutes and 25 seconds to de-ice the boots. The boot activation out of the cloud did not remove all of the ice on the boots. Ice was noted ¾ to 1-inch thick aft of the boot on the underside of the wing that extended back to the third paint stripe. While the MU-2B descended to a lower altitude to de-ice the airplane, the Learjet performed a calibration at 15,000 feet Hp, +2.8 °C TAT, 4.4 gal/min water flow, tanker engines 2 and 3 at idle, and measured the MVD at 110 to 130 µm.

The MU-2B was positioned with the left inboard wing in the cloud. Ice accretion was very rapid and very quickly required a 10 to 15° right roll control input. The sides of the engine nacelle accreted ice within one minute. Again, this was noted as a good visual cue for large drop (SLD) recognition. Generally, the same comments prevailed about the power and roll control required during ice accretion and boot cycles, as were seen in the previous test point. Large drops (SLD) anywhere on one wing section affects the roll control requirements. However, SLD has a more significant effect on the inboard sections. After 12 minutes in the cloud, ice accumulation was noted back to 3 inches aft of the third paint stripe on the underside of the wing. After 13 minutes, a small ice ridge aft of the boot was observed on the underside of the horizontal stabilizer. After 14 minutes, the propeller spinner had accreted a cone of ½ to 1-inch thick ice. The ice cone on the spinner appeared to wobble and vibrate causing a safety concern. The MU-2B exited the cloud and descended to de-ice the airplane. The post-point calibration was performed at 15,400 feet Hp, +2.3 °C TAT, 4.5 gal/min water flow, tanker engines 2 and 3 at idle, and the tanker measured RH at 16 percent. The Learjet measured RH of 40 percent in the cloud, but this is not considered an accurate value, with LWC and MVD values about the same as the previous point.

The MU-2B was positioned with the right inboard wing in the cloud at 200 KIAS for a lower AOA evaluation. Again, immediate ice accretion was noted on the inboard surface of the engine nacelle, confirming that this is a reliable visual cue for large drop (SLD) recognition. Wing ice accretion again appeared to be aft of the boot. Some ice self-shedding was noted from the boot. Ice accretion was observed on the upper wing surface to the aft part of the third black stripe. The ice built up rapidly within 1 minute and 40 seconds. This ice formation was not attributed to runback ice, since there was no substantial light green coloration on the leading edge of the wing forward of the ice accretion. The aft chordwise coverage was consistent with decreased AOA and the left/right wing asymmetry was due to propeller airflow effects. This test point was terminated in less than 2 minutes.

The Learjet post-point calibration was at 15,400 feet Hp, 200 KIAS, +2.8 °C TAT, 5.44 gal/min water flow, LWC about the same, and the MVD was 100 µm.

The tanker landed at 0952 PDT after 2 hours and 43 minutes of flight time.

Note. Comments were recorded from the flight debriefing – the MU-2B USAF Test Pilot stated that the inboard wing ice had the greatest effect on roll control requirements. Regarding visual cues, the tip tank is the easiest to see as the engine nacelle is too far aft to be easily observed. De-ice boot cycles cause an almost instantaneous reduction in the roll control required. The cloud terminating criteria for roll control, 35°, was established relative to a clean airplane by the control yoke displacement required to maintain wings level with full trim ailerons. It was also stated that Appendix C ice accretion looked like frost, and drizzle size drops looked liked wet "Grapenuts." The copilot of the MU-2B was impressed with the rapidity of SLD ice accretion on windshields and spinners. It was also observed that SLD ice accumulated on the upper corner of the engine “smile” shaped inlet, aft of the spinner. The crew reported they felt unusual vibrations with the thick ice accretion on the spinner. All immersions into the cloud were flown with the engine continuous ignition in the ON position. Ice on the inboard engine oil cooler inlet scoop formed a ridge that started to close off the inlet, but no increase in engine oil temperature was noted (there is an identical oil cooler inlet scoop in the outboard side of the nacelle).

An observer in the Learjet said that the ice ridge on top of the right wing extended aft to the leading edge of the first paint stripe. Ice accreted aft on the underside of the wing to 25 percent chord with distributed roughness elements back to 40 to 50 percent chord. Also, little nodules of ice were noted on the underside of the horizontal stabilizer. Another observer in the Learjet said that the ice on the undersurface of the wing seemed to be related to the paint stripes (paint stripes created surface discontinuities, which served as a collection site for droplets).

An observer in the MU-2B said that the underwing ice extended 2 to 3 inches aft of the third paint stripe, including a ridge of ice on the boots. The FAA Test Pilot stated a concern about the increase in drag observed with small accretions of SLD ice and what total immersion of the aircraft in an ice cloud would do to drag and power required. The Aeromet Learjet meteorologist stated that the target LWC of 0.7 and MVD of 120 μm were met with only deviations of a little more LWC and a little less MVD; basically the same conditions as a previous large droplet icing tanker campaign (SAAB 2000).

STALL CHARACTERISTICS EVALUATION

On April 29, 1996, after completion of the MU-2B icing tanker tests, a flight was made from the AFFTC, at Edwards AFB, to demonstrate the test aircraft to the Commander of the 452d Test Squadron. The project FAA Test Pilot, Joe Brownlee, accompanied the Commander, Lt. Colonel David Eichhorn; the MHI Pilot, Tommie Batchelor; and Video Operator, Michael Barnes, of Visual Productions. The FAA Test Pilot evaluated stall characteristics, with the airplane in the same test conditions flown in the initial aircraft evaluation. The aircraft weight and c.g. were 10,500 pounds and 94.2 inches, but stall characteristics were much better than those evaluated at Tulsa, Oklahoma, on April 18 and 19, 1996, and met the criteria in FAR § 23.201 – wings level stalls.

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HANDLING QUALITIES EVALUATION WITH ARTIFICIAL ICE SHAPES AND ROUGHNESS

August 5, 1996, Clinton-Sherman Airport, Oklahoma (CSM)

MU-2B-60 (Marquise) Registration Number N794MA, Serial Number 794 SA

Ramp weight – 10,524 Lbs. Center of Gravity – 192.97 inches aft of datum (near forward c.g.)

FAA Test Pilot – Joe Brownlee; MHI Pilot – Tommie Batchelor
FAA Test Pilot – Jon Hannan; MHI Flight Test Engineer – Larry Timmons
Video Operator – Michael Barnes, Visual Productions.

Flight FAA-4 – Takeoff 1809 Central Daylight Time, Land 1848, 0.5 hour flight.

Evaluation of the susceptibility to ice contaminated tailplane stall:

The horizontal stabilizer leading edge was fitted from span to span, with 60 grit sandpaper covering the de-icing boot on the top surface, and extending much further aft of the boot on the bottom surface.

Test Conditions: Pushover maneuvers were performed at flaps 20°, landing gear down, engine power for level flight at 105 KIAS (1.3 V_{S1}), and flaps 40°, gear down, power for level flight at 99 KIAS (1.3 V_{S0}). Normal load factors for the target airspeeds were approximately 0.0 g's (no g meter installed). There were no perceptible longitudinal control force lightening and no force reversals throughout these maneuvers; i.e., an increasing push force was required to achieve and hold 0.0 g. It was not necessary to reach the longitudinal control forward stop to generate the pitch rates to achieve the target load factors. The maneuvers were repeated in the approach configuration, with the slip-skid indicator held ½ ball diameter and one full ball diameter from center, with no perceptible change in longitudinal control force.

Flight FAA-5 – August 6, 1996. Takeoff 0948 Central Daylight Time, Land at 1122, 1.6 hour flight.

Ramp weight – 11,520 Lbs. Center of Gravity – 195.8 inches aft of datum (near aft c.g.)

Same aircraft, same crew.

The aircraft was clean of any artificial ice shapes.

Baseline handling qualities test:

Windup turns, rapid rolls, and wings level stall characteristics were evaluated in the following configurations (turns and rolls were evaluated with power for level flight and boots not inflated).

TEST CONDITIONS

Flaps up, landing gear up, engine power at idle and 75 percent torque (torques matched), trim airspeed 134 KIAS.

Flaps up, landing gear up, engine power at idle and 75 percent torque, trim airspeed 134 KIAS, boots inflated.

Flaps 5°, landing gear up, engine power at idle and 75 percent torque, trim airspeed 125 KIAS.

Flaps 5°, landing gear up, engine power at idle and 75 percent torque, trim airspeed 125 KIAS, boots inflated.

Flaps 20°, landing gear down, engine power at idle and 75 percent torque, trim airspeed 110 KIAS.

Flaps 20°, landing gear down, engine power at idle and 75 percent torque, trim airspeed 110 KIAS, boots inflated.

Flaps 40°, landing gear down, engine power at idle and 75 percent torque, trim airspeed 103 KIAS.

Flaps 40°, landing gear down, engine power idle and 75 percent torque, trim airspeed 103 KIAS, boots inflated.

Windup turn to approximately 1.2 to 1.3 g's revealed virtually constant lateral control forces to achieve and maintain bank angles. Timed rolls from 30° through 30° using full control wheel throw, rudder fixed, revealed no lateral control force changes. Roll rates with flaps full down (40°) were noticeably faster than in other configurations.

Stall definition was the attainment of full aft longitudinal control. There was no nose down pitching moment, which could not be arrested by movement of the longitudinal control. Generally, if the airspeed deceleration rate was maintained at one knot per second for as long as possible, roll attitude could be maintained by aggressive lateral control, usually to full left travel, and the slip-skid ball could be maintained in the center by aggressive yaw control, the aircraft would pass FAR § 23.201 roll and yaw angle criteria.

Stall warning margins between stick shaker and the minimum speed in these stall characteristics evaluation maneuvers were in the range of 5 to 10 knots, but with boots inflated, the stick shaker (stall warning) either did not activate or activated just before the minimum speed. Airframe buffet to minimum speed margin, boots inflated or conformed, was around 10 knots with flaps up, but with flaps extended, the margin decreased to very near the minimum speed. Power on stall minimum speeds were seen as low as 50 KIAS, due probably to airspeed position errors.

Baseline autopilot control tests:

With flaps up, landing gear up at 12,000 feet mean sea level (MSL), the autopilot/yaw damper was engaged in ALT hold and heading hold. At 180 KIAS, the power levers were retarded to idle and the torques were matched. During the airspeed deceleration, longitudinal trim moved nose up at a rate which increased with decreasing airspeed, and rudder trim was minimal. Roll control moved slowly left to approximately 15° angle. The autopilot was manually disconnected near the airplane stall with a 2,500 ft/min descent rate. There was no automatic disconnect feature in this autopilot installation. Aircraft control forces, after autopilot disconnect, were actually lighter in pitch than the previous stall characteristic maneuvers because the autopilot longitudinal trim continued to input nose up trim throughout the deceleration. A normal stall recovery maneuver was made.

From 12,000 feet, the autopilot was engaged with landing gear down, flaps 20°, the engine power was retarded to idle, and at 125 KIAS, the autopilot pitch control was moved nose down to establish a 2,000 ft/min descent rate. The ALT pre-selector was set to 9,000 feet and ALT select mode was entered. At approximately 9,200 feet, the autopilot started to pitch the nose up and the longitudinal trim started to move nose up. At 9,000 feet MSL, the altitude was captured and the airspeed decelerated. Similar roll control movement to the constant altitude airspeed deceleration was observed, and autopilot disconnection and maneuver recovery was made at 80 KIAS.

This descent was repeated by setting the ALT pre-selector below 9,000 feet, and at 9,000 feet selecting ALT capture mode. The autopilot immediately started to pitch the nose up and the longitudinal trim started to move nose up. The aircraft descended below 9,000 feet and the autopilot tried to climb back to the target altitude, therefore, airspeed deceleration rate was quite fast and the stick shaker activated at 85 KIAS. The autopilot induced control movement was essentially the same as the previous test.

Baseline directional stability tests:

With flaps up, landing gear up at 6,300 feet MSL, 150 KIAS, wings level sideslips were established with one slip-skid ball displacement in both directions. Lateral control displacement to maintain wings level was measured at approximately 10° both left and right.

Flight FAA-6 – August 6, 1996. Takeoff 1502 Central Daylight Time, Land at 1627, 1.4 hour flight.

Ramp weight – 11,507 Lbs. Center of Gravity – 198.5 inches aft of datum (near aft c.g.)

Same aircraft, same crew.

The wing was covered with artificial ice shapes, emulating ice formation during icing tanker testing with ice beyond 14 CFR part 25, Appendix C, envelope, in the form of "roughness elements" from aft of the de-ice boot to approximately 13 percent chord (see photographs in the Icing Section). Also, the right side of the vertical stabilizer was similarly treated with these "roughness elements."

Handling qualities tests:

Lateral control forces were approximately the same in windup turns and rapid rolls. Roll rates with flaps full down (40°) were again noticeably faster than in other configurations.

Stall characteristics with this ice shape were not evaluated with boots inflated because parts of the artificial ice shape were affixed to the wing leading edge with metal straps around the boots. Stall definition was again the attainment of full aft longitudinal control and, as before, there was no nose down pitching moment which could not be arrested by movement of the longitudinal control. The same comments as in the clean configuration apply, although there was a noticeable softness in the lateral control, as if roll spoiler hinge moments were lower. Stall warning (stick shaker) was either nonexistent or occurred near stall definition, similar to stall warning with de-ice boots inflated on previous flight with no ice shapes. Light to moderate buffet was felt near the normal stall warning airspeeds.

Stall warning margins between stick shaker and the minimum speed in these stall characteristics evaluation maneuvers were in the range of 4 to 13 knots, but the stick shaker would not activate during all stalls. Airframe buffet to minimum speed margin was 6 knots with flaps up, but with flaps extended, buffet and shaker were near coincident. Power on stall minimum speeds were seen as low as 49 KIAS, due probably to airspeed position errors.

Autopilot control tests:

With autopilot engaged as on the previous flight, during the airspeed deceleration, roll control moved progressively left until the full control stop was reached at near 90° of control yoke travel near the stall. The autopilot was manually disconnected and a normal stall recovery maneuver was made with quite low control forces.

From 12,000 feet, the autopilot was engaged, the power was retarded to idle, and at 125 KIAS, the autopilot pitch control was moved nose down to establish a 2,000 ft/min descent rate. The ALT pre-selector was set below 9,000 feet and at 9,000 feet altitude, the capture mode was selected. The autopilot immediately started to pitch the nose up and the longitudinal trim started to move nose up. The aircraft descended below 9,000 feet and the autopilot tried to climb back to the target altitude, therefore, airspeed deceleration rate was quite fast. In this case, roll control moved right to approximately 50°, then the autopilot was disconnected and the recovery maneuver was made.

Directional stability tests:

As before, with flaps up, landing gear up at 6,300 feet MSL, 150 KIAS, wings level sideslips were established with one slip-skid ball displacement in both directions. Lateral control displacement to maintain wings level required slightly more right displacement with left rudder than left displacement with right rudder.

Flight FAA-7 – August 7, 1996. Takeoff 0852 Central Daylight Time, Land at 1017, 1.5 hour flight.

Ramp weight – 10,924 Lbs. Center of Gravity – 196.0 inches aft of datum (near aft c.g.)

Same aircraft, same crew.

The wing was covered with artificial ice shapes, emulating ice formation during SLD icing tanker testing. Ice shapes were duplicated in the form of an irregular ridge with peaks up to ¾ inches just aft of the de-ice boots with "roughness elements" from aft of the ridge to approximately 13 percent chord (see photographs in Icing Section). Also, the right side of the vertical stabilizer retained the previous "roughness elements."

Handling qualities tests:

Lateral control forces were approximately the same as in the previous flights in wind-up turns and rapid rolls, but stall buffet occurred at higher speeds. With flaps 20°, the feel of the aircraft was as if it were in the flaps 40° configuration. With flaps full down (40°), there was a perceptible lateral control "dead band" where little roll moment was generated with control movement, but roll rates with flaps 40° were again noticeably faster than in other configurations.

As before, stall characteristics with this ice shape were not evaluated with boots inflated because parts of the artificial ice shape were affixed to the wing leading edge with metal straps around the boots. Stall definition was again the attainment of full aft longitudinal control and, as before, there was no nose down pitching moment which could not be arrested by movement of the longitudinal control. The same comments as in the clean configuration apply, although there was again a noticeable softness in the lateral control, as if roll spoiler hinge moments were lower.

A landing gear up, flaps up stall maneuver was performed with two of the crewmembers seated in seats further aft than before, causing the c.g. to be 199.1 inches near the aft limit. Generally, with due regard to maintaining coordinated flight, the characteristics were the same as all other maneuvers.

In this configuration, the stick shaker (stall warning) did not activate in stalls with landing gear up, flaps up; the landing gear up, flaps up aft c.g. stall; and landing gear down, flaps 40° idle power stall. Stall warning margins between stick shaker and the minimum speed in the rest of the stall characteristics evaluation maneuvers were in the range of 4 to 15 knots. Airframe buffet to minimum speed margin was from 14 to 33 knots. Power on stall minimum speeds was seen as low as 60 KIAS, due probably to airspeed position errors.

Autopilot control tests:

With autopilot engaged as on the previous flight during the airspeed deceleration, roll control moved initially right, then progressively left, until 90° of control yoke traveled at 110 KIAS in moderate buffet. The autopilot was manually disconnected and a normal stall recovery maneuver was made with quite low control forces.

Again, the autopilot was engaged in ALT hold and heading hold, and the power was retarded to idle. The autopilot was manually disconnected at 130 KIAS and a brief handling quality assessment was made to assess the feasibility of limiting autopilot use to not less than 130 KIAS in icing conditions. With the autopilot disconnected, approximately 20° of right control yoke was required to hold the wings level. There is no autopilot actuated roll trim, but the roll forces were around 10 pounds.

This maneuver was repeated with the engine torques retarded to 25 percent. With the autopilot disconnected at 130 KIAS, there was a slight roll rate to the left with controls free.

Directional stability tests:

As before, with flaps up, landing gear up at 6,300 feet MSL, 150 KIAS, wings level sideslips were established with one slip-skid ball displacement in both directions. Lateral control displacement to maintain wings level required approximately 20° of right displacement with left rudder, and approximately the same left displacement with right rudder – about twice the control displacement as the uncontaminated airplane.

Stall warning concern:

The artificial stall warning (stick shaker) system did not perform its intended function and could be erroneously misleading with SLD ice shapes applied to this aircraft.

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III. SYSTEMS

Service Difficulties

Discussion:

Service Difficulty Reports and Accident/Incident Data System (AIDS) Selected Brief Reports were reviewed on the MU-2B for the period from 1981 through 1995. There were no reports on de-ice or anti-ice systems, which indicated that repairs to these systems were considered as normal maintenance actions rather than systems failures.

The review did find three reports on acrylic windshields, fifteen on cabin windows, five on cabin door windows, one on cockpit side windows, one on crew emergency windows, and two on windows. These reports included a few cases of entire windows or parts of windows departing the airplane, but most were cracks or delaminations. The Maintenance Manual contains inspection criteria for the windows that may not be observed consistently.

The review also found five failures of autopilot servo actuators that affected roll or pitch control. AD 81-01-06 was issued against the autopilot servo actuators. This review did not find additional service problems following the AD.

There was some concern with the maintenance state of the fleet of 442 U.S. registered MU-2B airplanes, as two of the accident airplanes had or were suspected to have had anti/de-ice systems inoperative prior to a flight into forecasted icing conditions. The Team contacted the Flight Standards Service, AFS-300, and requested a directed safety investigation or special emphasis inspection of all known MU-2B aircraft operating in the United States. They were requested to pay close attention to the number of patches, holes, and deterioration of the boots. After more than 12 months, only four reports have been received. Of these four reports, three were unfavorable, however, due to the small sample size, it is impossible to determine if an AD is warranted to inspect the anti/de-ice systems.

Recommendation:

Considering the time span and number of aircraft, the Team finds no service problems that require an AD as corrective action, but the Team recommends that MHI establish a new section in the MU-2B Maintenance Manuals. Include in this section mandatory compliance for the service bulletins issued for acrylic windows, including acrylic window/windshield inspections, and anti/de-ice system inspection.

Anti/De-Ice Systems Review

Discussion:

Flight into known icing was approved based on analyses in Mitsubishi Report MR-0144, and pilot testimonials/icing encounter reports, in Mitsubishi Report MR-0149, taken from extensive operational experience on A2PC airplanes. Testing of the anti/de-ice equipment was limited to operational testing of the systems, and stability and control with the boots inflated.

The 1984 SCR team found the original certification was correctly done, but the final SCR Report did mention the possibility of latent failures in the airframe de-ice system. This review has found two such failure modes in the de-ice boot system:

1. The distributor valve has two independent solenoid valves. The "A" valve supplies bleed air to the wing de-icing boots and the "B" valve supplies bleed air to the tailplane de-icing boots. Thus, failure of the "B" side will prevent inflation of the vertical and horizontal tail boots. This is a latent failure mode because the system includes one pressure switch in the "A" side that operates a cockpit light when the pressure in the "A" manifold is 10 plus or minus 2 psi. There is no pressure switch in the "B" side and the tailplane boots are not visible from the cockpit.

2. The "B" manifold from the distributor valve to the tailplane boots must bypass the cooling turbine (air conditioning system) inlet air duct. This is accomplished by bending the manifold into a "U" shape at the inlet air duct. Thus, a water trap is formed. Freezing of this water could prevent operation of the tailplane boots while the pressure switch would be unaffected (see item "1" above).

The certification basis in both Type Certificates, A2PC and A10SW, is CAR 3, amendments 3-1 through 3-8. CAR 3, paragraph 3.690, amendment 3-7, requires the following: "Not more than one circuit, which is essential to safety in flight, shall be protected by a single protective device." The Left-Hand Overhead Switch Panel (see figure III.1) contains four essential systems: Propeller De-Ice, Engine Intake Anti-Ice, Oil Cooler Inlet Anti-Ice, and Pitot-Static Anti-Ice, all receiving power from CB2107 (left-hand side) and CB2108 (right-hand side) (see figure III.2). In addition, the ON/OFF switch for each of these systems is a combination switch/circuit breaker. Therefore, these four systems are protected by two circuit breakers and if either CB2107 or CB2108 fails to open, all four of the downstream essential systems would be inoperative. While the FFFSCR Team believes this design does not meet the requirement in CAR 3, paragraph 3.690, amendment 3-7, this configuration was FAA approved in the original certification and reaffirmed in the 1984 SCR. The 1984 SCR accepted this configuration based on both the low probability of a circuit breaker failing in the open position after a preflight check had verified it closed, and the power monitoring capability of the system. This situation has been discussed with the FFFSCR Team and while MHI points out this configuration was twice found acceptable previously, they have agreed to modify the anti/de-ice system circuit protection by eliminating CB2107 and CB2108.

This review included a visit to a repair station, Intercontinental Jets of Tulsa, Oklahoma, with extensive experience in the maintenance of MU-2B airplanes. The Team spoke to managers, the lead inspector, and various inspectors and technicians. They said they knew of no failure modes in "long" models that are not present in the "short" models. Maintenance personnel did find tailplane boot failures that had not been reported by the flight crew, and they stated they had no method of removing water from the airframe boot system.

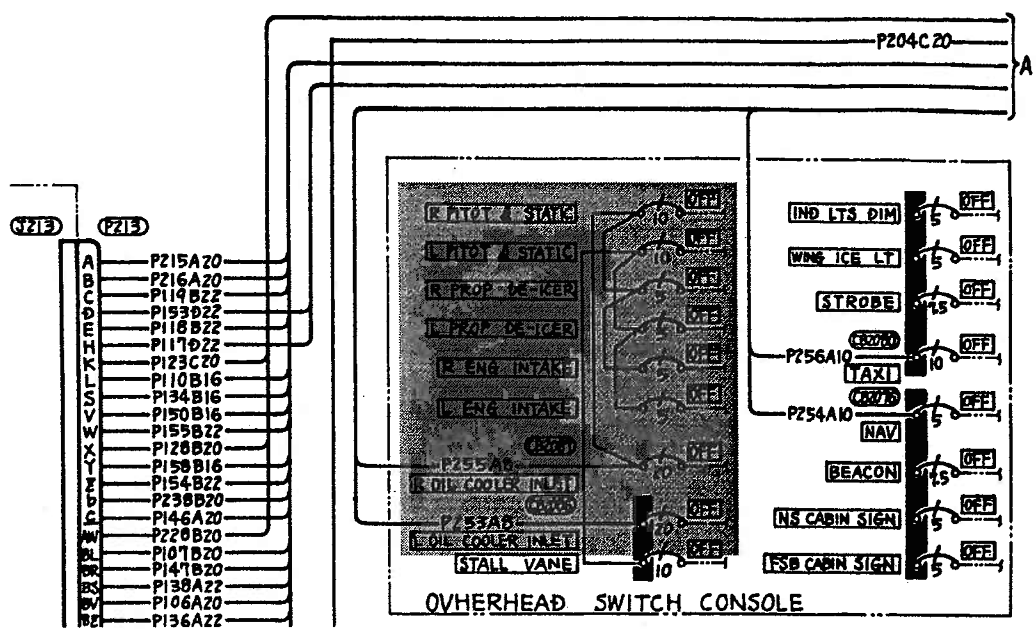

Figure III-1
Left-hand overhead switch panel.

Recommendations:

1. Recommend a service bulletin be issued by MHI to require the installation of a water trap/drain valve in the tail de-ice manifold pressure line, and require that the system be drained during each 100 hour inspection. If the line accumulates water through condensation or flight through rain, the line may freeze and render the tail boots inoperative.

2. An open failure of a single circuit breaker for icing systems results in loss of capability of four essential anti/de-ice systems and should be corrected. Issue an AD to remove Circuit Breakers CB2107 and CB2108 for the essential systems that are protected by combination switch/circuit breakers.

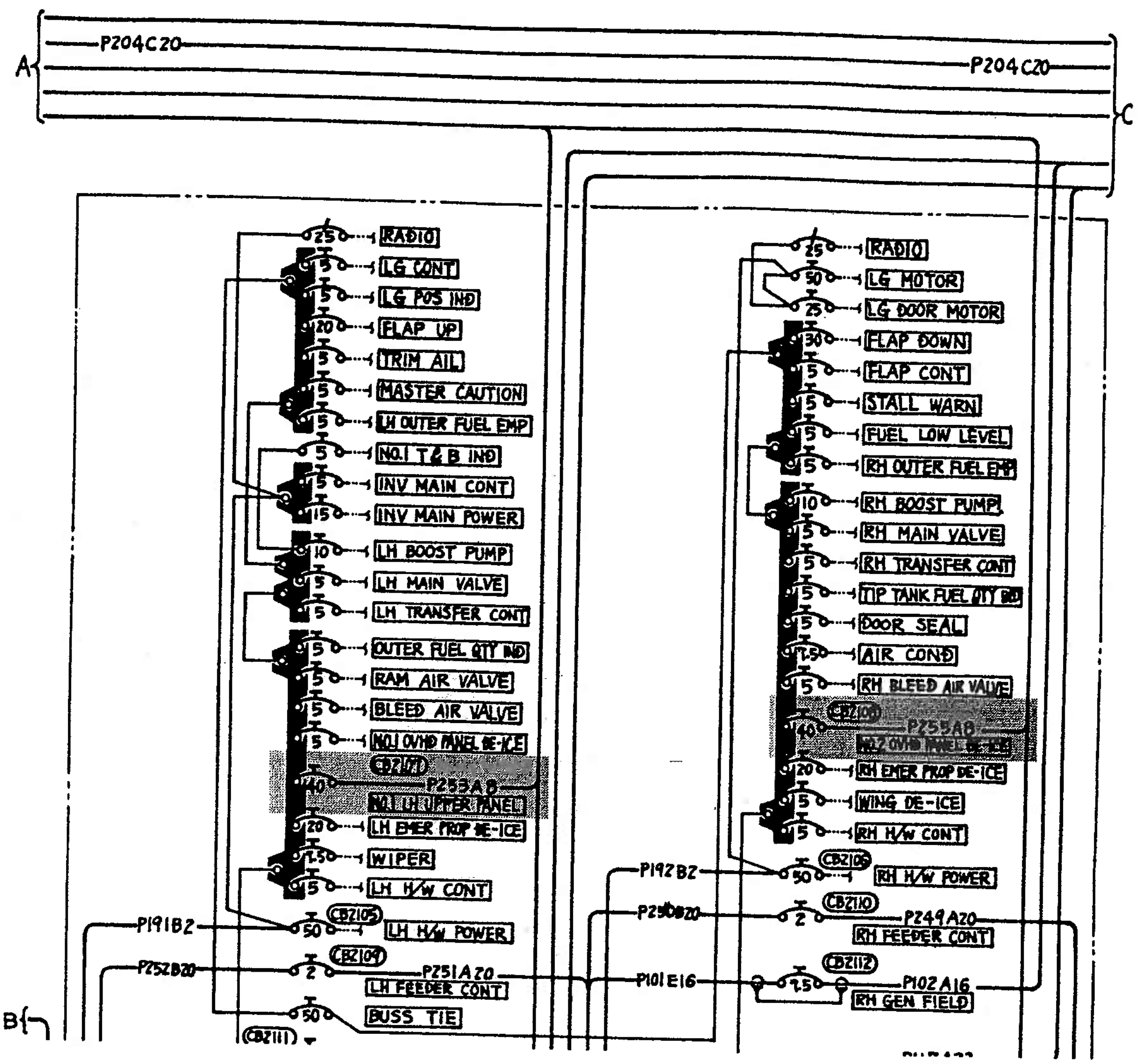

Figure III-2
Circuit breaker panel.

3. By means of an AD, modify the airframe de-ice system by installing a pressure switch in the tail de-ice boot pressure line, and revise the circuitry so the cockpit light will illuminate only when both pressure switches read the required pressure, and both pressure switches must have a minimum set point, such that illumination of the light annunciates to the pilot that both wing and tail systems are operating at a pressure that ensures all boots are at least 90 percent of full inflation.

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IV. PROPULSION SYSTEM

During the investigation, the MU-2B propulsion system was extensively reviewed for elements that may have contributed to the scenario of the MU-2B accidents where icing conditions were forecasted or present prior to the accident. These included:

A. In-flight engine failures.

B. Partial engine power loss.

C. Engine flameouts.

D. Loss of engine power control.

E. Propeller pitch control failures.

F. Improper propeller rigging.

G. Engine performance with inlet ice formation.

H. Propeller performance with ice formations.

I. Engine fuel control settings.

J. Engine torque instrument readings.

K. Engine negative torque sensing (NTS) system.

L. Garrett TPE-331 series engine power rollback in-flight.

M. Malad City, Idaho, accident investigation. Engine and propulsion teardown reports, and accident analyses.

A. In-flight engine failures.

During a review of the FAA Service Difficulty Report (SDR) System for Garrett TPE-331 engine failures installed on MU-2B series airplanes over the last 17 years, the Team found that 12 engine failures have been reported. These reported engine failures have occurred for a number of different reasons. The Engine Fuel Control System can be identified to explain the majority of these failures. It is considered that the failure rate for this installation is no different from any other Garrett TPE-331 engine installation. No direct evidence was found to indicate that engine failures appear to be a significant factor that contributes to the MU-2B icing accident scenarios that were reviewed. However, several system improvements have been identified that can increase safety and are described in the recommendation sections of this report.

B. Partial engine power loss.

A review of the comparable accident data, FAA SDR System, and interviews with operator and maintenance personnel indicate that partial engine power loss is a condition that the Garrett TPE-331 engine rarely experiences. No evidence was found to indicate that this was a factor in the MU-2B icing accident scenarios that were reviewed.

C. Engine flameouts.

Five engine flameouts have been reported in the FAA SDR System. Several of these reports occurred in weather where possible icing conditions were present. This can be a significant factor in one of the elements identified in the accident scenario, although the Team's investigation has not found that this condition is a direct cause of the MU-2B airspeed slowdown prior to departure from controlled flight in the majority of accidents. At least one accident, Putnam, Texas, can be linked to an engine flameout, although we cannot determine from the reported physical evidence whether the flameout occurred before or after the departure from controlled flight. During the USAF icing tanker tests conducted at the AFFTC in April 1996, the Team found that a 6-inch diameter by a ¼ inch thick ice shape can be formed in front of the engine inlet especially when flying in (SLD) conditions. During one of the icing tests, a significant chunk of ice broke loose from the area identified and was ingested into one of the engines. With the continuous ignition on, the engine power was not interrupted and the airplane flew normally. No engine damage was found during the post-visual inspection following this occurrence. However, as previously stated, the review of the FAA SDR System did indicate that several engines had experienced a flameout in severe weather including icing conditions. Because of this data, the Team asked AlliedSignal Inc. (Aerospace) to conduct an analysis on the time to restart the engine at altitude if an engine flameout was to occur. Based on their analyses, the engine can be brought back to rated torque (time to rated speed and torque) in as little as 3.8 seconds from a flameout, if the pilot recognizes the engine condition and reacts to restart the engine in the proper sequence, and does not allow the engine speed to decay below 90 percent RPM. If the pilot was in a high workload situation, such as severe weather including icing conditions, it is conceivable that the engine speed could decay below 90 percent RPM during an engine flameout before corrective action could be taken. If the engine is allowed to decay to 80 percent RPM, the engine requires 6 seconds to recover to rated speed and torque. If the engine is allowed to decay to 48 percent RPM, the engine requires approximately 23 seconds to recover to rated speed and torque. All times are based on a typical cruise speed and 15,000 feet altitude. Using the available Auto Re-light system, the time to recover to rated speed and torque can be as little as 2 seconds under similar scenarios described above to a maximum of 3.8 seconds. This improvement and associated workload reduction has significant safety benefits since the pilot does not have to initiate corrective action to restart the engine. This can also improve the handling characteristics of the airplane since an asymmetric power condition would be minimized, thereby allowing the pilot time to fly (control) the airplane and exit icing conditions, and/or severe weather.

One potential safety flight problem was identified, based on discussions with field personnel, that many operators do not like the continuous ignition system used on the Garrett TPE-331 engine. This system causes an increase in potential maintenance for the ignition system igniters and capacitance discharge box. These components need to be replaced at periodic intervals to maintain the ignition system integrity and airworthiness. This can increase the continued airworthiness costs to operate the airplane engine. This is also true on other airplanes that use the Garrett TPE-331 engine with this ignition system, not just on the MU-2B airplane. Because of this situation, many operators manually turnoff the continuous ignition system after the engine is started and operating normally. There is a possibility that pilots have the continuous ignition turned off and encounter weather conditions that can cause an engine flameout. An airplane, other than the MU-2B that uses the Garrett TPE-331 series engine installation, experienced several engine flameouts over a short period of service experience. The FAA issued 10 AD's to require an Auto Re-light ignition system installation, or require the use of manually controlled ignition in certain environmental conditions. The Auto Re-light ignition system automatically activates the igniters to relight the engine fuel air mixture, which can almost immediately restore the power of the engine.

One of the benefits of the Auto Re-light ignition system is that it is inactive until the NTS system senses a reduction in engine torque. When loss of engine torque is sensed, the ignition system is activated to ensure that engine fuel combustion is occurring. Once the Auto Re-light ignition system was incorporated on the affected airplane, reports of engine flameouts were virtually eliminated. Another benefit of this system is that the ignition system components have a greater service life, which reduces periodic maintenance costs. The Auto Re-light ignition system only activates the engine igniters when needed, thereby leaving the igniters and associated ignition components inactive until operation is required.

Recommendation:

Require an AD to incorporate the Auto Re-light ignition system per the manufacturer's service bulletin, and require both engines to be modified with the Auto Re-light ignition system on all MU-2B airplanes. The engine Auto Re-light ignition system has significant safety benefits for Garrett TPE-331 powered turboprop airplanes, including the MU-2B airplanes.

D. Loss of engine power control.

The Team's investigation identified a Garrett TPE-331 engine service bulletin that defines a condition where the pilot can lose control of engine power settings. An investigation by

AlliedSignal Inc., the manufacturer of the Garrett TPE-331 engines, revealed that the P_2T_2 atmospheric pressure and temperature inlet sensor can freeze up and affect the pilot's ability to change engine power output. This condition does not occur very frequently and certain weather conditions need to be present to have the P_2T_2 engine inlet sensor "freeze up." In addition, there must be moisture present in the P_2T_2 sensor line. The weather conditions identified are similar to conditions that create airframe icing. The inlet pressure and temperature sensor provides a means to trim the fuel control to deliver proper fuel flow and pressure to the engine's combustion chamber. Based on airplane service reports submitted by airplane operators that use the Garrett TPE-331 engine, several engines were found during cruise flight to have frozen power settings. No matter what the pilot commanded with the power control, the engine would not respond and remained at approximately 40 percent torque. This is a potential safety of flight conditions. Garrett determined that the engine power control could be regained if the pilot selected the engine inlet anti-ice function. A period of several minutes is needed to warm the frozen inlet sensor and allow it to function. This time period was determined to be too long by the Team and could potentially cause an unsafe condition. No direct evidence was found to link this safety problem with the investigated MU-2B accident scenarios. However, this scenario may help explain the observed condition where a pilot does not appear to take action to change power settings in-flight when in severe icing conditions, and the MU-2B airplane is experiencing a slow, steady reduction in airspeed.

AlliedSignal Inc. (Garrett Division) has developed a modification to the P_2T_2 inlet sensor line system that will prevent a loss in power control. This modification is relatively inexpensive and will provide engine power control to the pilot, even if the sensor "freezes up." Service bulletin information has been released by the company and has been distributed to the field. The pilot can select the engine inlet anti-ice system to wait for the P_2T_2 sensor to thaw and still control the engine power settings.

Recommendation:

The Team requested an AD be created to incorporate the recommended Garrett P_2T_2 sensor modification. The Los Angeles, California, Aircraft Certification Office (LA-ACO) subsequently drafted an AD, and the Engine and Propeller Directorate will issue a Notice of Proposed Rulemaking which is in the final stages of coordination.

E. Propeller pitch control failures.

A review of the Hartzell propeller pitch control history was conducted including field service interviews. No evidence was found indicating that the propeller pitch control is a factor in the accident scenario. A review of the propeller pitch control system did not reveal any component failures that could be associated with the accident scenario. No reported evidence of in-flight beta selection by the pilot was found. During the preliminary investigation of the Malad City accident, it was determined that the propeller was in a pitch setting that indicates the propeller was being controlled by the governing system.

F. Improper propeller rigging.

The Team did find evidence that some MU-2B airplanes have had improper propeller rigging after maintenance. At least one accident has been identified where the pilot lost control of the airplane during a maintenance flight checkout of the propeller operating system. The beta light system was mis-rigged and the indicator light did not function properly to warn the pilot. According to the accident report, the propeller feathering system was misrigged and would not allow the pilot to restart the engine after the pilot performed an engine shutdown. Improper propeller rigging can have catastrophic effects on the controllability of the airplane in flight.

MHI investigated this situation and issued a manufacturer's service bulletin to the field. This service bulletin requires a check of the propeller rigging and associated beta light system after any engine or propeller maintenance. In addition, the bulletin details a daily system check of the propeller feathering system and propeller beta indicator lights by the pilot.

Recommendation:

The Team recommends that the manufacturer's propeller rigging service bulletin be incorporated into the appropriate manufacturer's maintenance manual sections. The Team recommends that an AD be issued to incorporate a limitation in the AFM that requires a propeller NTS and feather valve check prior to the first flight of the day.

G. Engine performance with inlet ice formation.

The Team reviewed engine service history information and did not find any evidence of engine performance degradation due to ice formation in the inlet. Extensive icing tanker testing did not indicate any reduction in engine power output. The engine performed properly even in simulated SLD conditions. The engine had continuous ignition and engine anti-ice systems ON during the tests. Significant testing was accomplished during the USAF icing tanker tests. During SLD testing, two small areas of ice formation were observed in the engine inlet. Post-test visual inspection of the engine inlet revealed traces of dye that indicated ice accumulation. The residual icing dye indicated that ice had formed in front of and on the P_2T_2 inlet sensor. The other area noted was just behind the propeller on the bottom side of the engine fairing in front of the engine inlet. If the continuous ignition was not on, or the engine anti-ice system was not activated, then the engine could experience a power degradation or a flameout.

During the icing tanker testing, the Team did discover that the oil cooler inlet would buildup a significant amount of ice. The inlet is heated with an anti-ice system, but does not appear to be adequate for large Appendix C droplet sizes, or for simulated SLD icing criteria. However, even with the oil cooler inlet ice buildup, no change in engine oil temperature was noted during the tests. The engine operated within normal temperature limitations.

After the icing tanker testing using Appendix C and SLD icing conditions, MHI had the MU-2B test airplane engines examined. The TPE-331 engines required maintenance to bring the engines back into overhaul service limits. This indicated that the simulated icing conditions created by the tanker was a rigorous environment.

H. Propeller performance with ice formations.

The Team conducted an extensive review of the propeller performance characteristics with ice shapes present. A literature search indicates that a reduction in propeller thrust can be expected in icing conditions. Up to a 15 percent loss in thrust has been recorded by researchers. This area was of particular interest to the Team to try to explain the gradual loss in airspeed during cruise as one of the events identified in the MU-2B accident scenario. During the icing tanker testing, power required data was being monitored and collected to determine the amount of change in power required, while the airframe and propulsion system were accumulating ice. Several different icing conditions were explored including simulated SLD (severe) icing criteria. SLD is outside the current 14 CFR part 25, Appendix C, requirements. Because of the research that has been conducted both nationally and internationally, the change in power required to maintain a set flying condition was considered an important factor in our investigation. Results from the tanker testing, which included SLD criteria, indicated that the change in power required was not significant (approximately 10 percent), which is mostly attributed to induced and parasite drag as reported by Mitsubishi engineering representatives.

The engine anti-ice and propeller de-ice systems performed satisfactorily in all 14 CFR part 25, Appendix C, conditions tested. The engine anti-ice and propeller de-ice systems performed less effectively in SLD conditions; however, the buildup of ice near the inlet area was noted previously and when ingested into the engine in flight during one test condition, it did not affect the power output. The propeller operated satisfactorily, however, post-flight inspection did show a small ice buildup outboard of the de-ice boot and along the very leading edge of the propeller blade. These buildups did not measurably affect the propeller thrust output or seem to affect blade angle. This is noted since power was monitored (trimmed) throughout the test condition. The propeller is a constant speed propeller and no significant change was noted between the two engines. (Note. Icing testing was conducted on one section of the airplane only during a particular test.)

Photographs were taken in flight during icing tanker tests and on the ground during post-flight visual inspections. Traces of icing dye were observed on the propeller that confirmed the observations during the flight testing. The Hartzell Propeller Company reviewed the photographs from the icing tests, and indicated that the propeller would likely perform within approximately 3 percent of nominal performance predictions based on the ice shapes formed during testing. This conclusion reasonably agrees with the actual observed performance of the airplane during the icing tanker tests.

It should be noted that if an appreciable change in power output was needed to make up the difference in propulsion efficiency due to ice buildup on one section of the airplane, the power output readings would have reflected this need. An estimate was made to account for the ice buildups noted during testing as applied to the entire airplane. Based on the testing conducted, Mitsubishi engineering representatives calculated that an 8 to 15 percent increase in power is necessary to maintain a given airspeed when comparing a clean airplane to one that has significant ice buildups, including ice shapes created in simulated SLD conditions. It should be noted that this calculated increase is based on the SLD conditions created as part of the icing tanker testing. This is not the most severe SLD icing conditions that have been experienced in actual service. Pilot reports of flying the MU-2B and atmospheric research using other airplanes indicate that there are more severe SLD icing conditions present at times. If a pilot flies into a severe SLD icing situation, additional power would be necessary. Severe SLD icing conditions may overcome the airplane's ability to maintain level flight with the remaining power available. Severe SLD conditions may also overcome the engine anti-ice and propeller de-ice capabilities.

In summary, the propeller de-ice systems performed adequately for 14 CFR part 25, Appendix C, requirements tested. The propeller de-ice systems were somewhat less effective in simulated SLD testing conditions, however, the change in power output requirements did not reflect a significant reduction in propulsion efficiency. No changes are recommended for the engine anti-ice and propeller de-ice systems.

Recommendation:

The Team recommends that additional government and industry research into severe SLD conditions be performed to better understand its affect on engine and propeller anti/de-icing performance, and capabilities for turbopropeller airplanes with pneumatic boots.

I. Engine fuel control settings.

During the review of the propulsion system, it was discovered that some operators of the MU-2B airplanes may modify the manufacturer's minimum fuel flow setting on the engine fuel control. Interviews with field personnel indicated that this is done to change the airplane's landing approach and touchdown procedures. Changing the engine minimum fuel control settings of the MU-2B airplane provide the ability for the pilot to approach at a slightly higher speed than is specified in the AFM. The fuel control revisions also allow the MU-2B airplane to slowdown faster when the pilot reduces the power for landing. These revisions have the potential to significantly affect the airplane's low speed handling characteristics. The minimum fuel control settings were developed by the manufacturer to maintain a certain level of residual thrust during approach, and to maintain a rate of descent and controllability in compliance with the certification requirements.

Changing the residual thrust output of the propulsion system can affect the airplane's rate of descent and, potentially, the stall speed and handling characteristics. No testing has been done to determine the effects on airplane handling or the acceptability of these revised settings. The Team could not identify any accident caused by this specific issue, however, a potential safety problem may be created by these changes, and the Team will recommend that the manufacturer release service information to warn of the hazardous airplane handling effects of these unauthorized changes if made by the operator.

Recommendation:

Require the manufacturer to release information/service bulletin to the maintenance community to inform them that changes to the fuel control can affect the airplane's low speed handling characteristics, which affects safety. A video is in development for informing the pilots of this condition.

J. Engine torque instrument readings.

During the Team's investigation, field service interviews were conducted. It was discovered that the torque instrument calibrations can be altered by field service personnel. This was accomplished at times when a pilot reports that engines torque readings were significantly different. This is not uncommon with engines that may be at different points in their respective service lives. As an engine time-in-service builds, performance may slowly deteriorate to a point that a higher cockpit power lever setting is required to produce rated torque for takeoff or cruise. If the two engines installed on the MU-2B are producing different power outputs, the power levers may be at different positions (offset) on the cockpit throttle quadrant to produce the same rated power. The pilot normally likes to have the power levers positioned together, he/she may ask the mechanic to "trim the engines" to produce the same power output. At times, the mechanic may adjust the torque sensor to change the torque instrument meter to read the same torque outputs. This adjustment does not change the power output of the engine, only the instrument reading. Because of this, the pilot thinks he has equal power outputs from the engines, but in reality the engines may be producing different power output levels. This will affect the way the airplane will handle on takeoff, in cruise, and during landing. Many pilots will trim the airplane with the rudder or aileron trim to adjust the out-of-balance (trim) condition created by the engines that are producing different power levels, even though the torque instruments indicate equal power outputs. This condition can be especially aggravated during high power and low airspeed flight. In icing conditions, this unbalanced condition may help explain why some MU-2B airplanes when approaching or encountering a stall may depart into a spin or spiral. However, this is not the only reason, a wing stalling at a higher than published stall speed in an asymmetric aerodynamic condition is the most likely explanation for an airplane departing controlled flight in severe icing conditions. It is likely that if the engines are producing different power outputs, the airplane would have a tendency to roll or yaw into the side with the weaker engine. This is not unique to the MU-2B model airplane. Any conventional twin-engine propeller airplane could experience the same condition.

Recommendation:

The Team recommends a service bulletin that requires a calibration check on the engine's torque sensing systems be developed. Also, inform pilots through the training video on the pitfalls of changes to the torque sensing calibrations and its affect on airplane handling characteristics.

K. Engine negative torque sensing (NTS) system.

A review of the accident history used in this investigation and discussion with field personnel revealed no service difficulties of this system as a contributing factor in the accident scenarios.

Recommendation:

No changes to this system are recommended.

L. Garrett TPE-331 series engine power rollback in-flight.

During the Team's investigation, a report was received that indicated that Garrett TPE-331 series engine can experience a power rollback on the ground during a takeoff roll. According to the report, several pilots have seen this condition occur over the years and reported it to maintenance facilities. The report indicated that the pilot commands full power with the power lever, and the engine begins to "stumble" and "bog down" losing power during a takeoff roll. The Team investigated this report and was interested to determine if this type of condition could occur in-flight. The Team felt this might help explain why the MU-2B airplane experiences a fairly rapid slowdown prior to departure from controlled flight when in severe icing conditions.

Several telephone discussions were organized with the FAA, a field technician, MHI representatives, and AlliedSignal Inc. (Garrett) engineers to explore the variables that might cause this condition. It was generally agreed that the engine fuel control and prop governing system would have to be out of rig, and the compressor section performance of the engine would need to be deteriorated to the point where the fuel control scheduling becomes affected. The group agreed this is not a normal condition and the engine performance "health" would likely be out of the manufacturer's maintenance limits. At power settings on the ground in a static condition, the group indicated that it might be possible to reach a fuel limited condition (maximum fuel flow) in the fuel control and, with the engine control systems out of rig, have movement in the power level where the propeller governing system is overcome by the beta sleeve follow-up causing the propeller (with higher blade angle) to command more power from the engine than it can produce. This is the most likely scenario that would need to exist to experience a power rollback on the ground. AlliedSignal Inc. representatives indicated that they have never received a report of this condition occurring and did not find it likely. It was concluded the possibility of a power rollback in-flight has not and could not occur.

During the discussions, other subjects were presented in detail. They were: (1) TPE-331 series engine fuel control maximum fuel flow parameters, and (2) power assurance information for maintaining rated power of the engine during its service life.

1. In recent years, AlliedSignal Inc., in response to airplane operators using the Garrett TPE-331 series engine, has revised the maximum fuel flow settings for certain fuel controls to help the engine maintain rated takeoff power throughout its service life. The Team determined that this information should be disseminated to all airplane operators that use the TPE-331 series engine. Currently, this information is only available to the fuel control manufacturer, and the maximum fuel flow rates are revised during routine fuel control overhauls. The Team determined that airplane operators should be made aware of the revised settings, and this may provide a safety benefit to the airplane fleet using TPE-331 engines.

2. During the telephone conversations, a condition was brought up that some airplane operators will operate an airplane with an engine that may not be producing rated takeoff power in accordance with the approved type design performance data. All telephone conference representatives agreed that this was a bad idea. It was stated that some operators will do this since there may not be Power Assurance Charts in the AFM in the Limitations Section that mandate the requirements. The condition described was that an operator may be able to reach the engine temperature limitation during a pre-takeoff power check, but may not be able to reach rated torque at this temperature limitation. The AlliedSignal Inc. engineering representatives indicated this is a sign of an engine that is not healthy and would likely need maintenance and/or repairs to bring it back into a serviceable condition. After some discussion, it was agreed that airplanes that do not have Power Assurance Charts should have them. The FFFSCR Team determined that this can provide a safety benefit since operating an airplane with engines that do not produce rated power can be potentially hazardous, especially in severe icing conditions where maximum available power may be needed. MHI agreed that any MU-2B airplanes that do not have power assurance charts will receive information to have that data added to the AFM. The Team agreed to notify other airframe manufacturers that use TPE-331 model series of this situation and may mandate changes by an AD.

Recommendations:

1. The Team recommends that service information be published and made available to the airplane operators about the revised maximum fuel control fuel flow settings.

2. The Team recommends that MHI provide AFM Power Assurance Charts on all models of the MU-2B airplanes that use the TPE-331 series engines.

M. Malad City, Idaho, accident investigation. Engine and propulsion teardown reports, and accident analyses.

Following the Malad City, Idaho, accident that occurred on January 15, 1996, an engine and propeller teardown was conducted on the recovered propulsion systems components from the accident site.

Engine teardown report

The teardown inspection of the recovered engines was conducted on March 5 and 6, 1996, at AlliedSignal Inc. (Garrett Division), Phoenix, Arizona. Both engines were found to have severe impact damage. The initial inspection of both engines revealed that they were rotating at the time of impact. At the request of the FAA, the right engine third stage turbine stator was analyzed for foreign object damage and metal flame spray deposits.

The foreign object damage and metal flame spray patterns appeared to be less intense on the right engine than on the left engine. Because of this observation, a metallurgical examination was conducted on the right engine's third stage turbine stator. Based on the laboratory analysis, it was determined that typical rotational damage was found to be consistent with an engine operating. Aluminum particles were found on the third stage turbine stator vanes. It was determined that the aluminum particles passed through the engine as a result of the compressor wheels rubbing against the compressor housing by the airplane accident impact forces, and were deposited on the turbine hot section components. It has been concluded that both engines were producing power at the time of impact. It has not been verified that both engines were producing the same amount of power at the time of impact. Refer to AlliedSignal Inc. Aerospace Teardown Report of two Model TPE-331-5-252M Turboprop Engines, Serial Numbers P-20517C and P-20547C, dated May 24, 1996, for details of the findings.

Propeller teardown report

The Hartzell HC-B4TN-5GL four bladed propeller assemblies teardown was accomplished on March 7, 1996, at Ottosen Propeller and Accessories, Inc., located in Phoenix, Arizona. From the examination of the left and right propeller assemblies, it was determined that the propellers showed no signs of premature malfunction or pre-existing conditions that would have prevented proper engine or propeller operation. The propeller cylinders displayed witness marks that indicated both propellers assemblies had relatively high propeller blade angles of approximately 47 to 47.5°. This is consistent with a normal MU-2B airplane cruise power configuration at altitude. This is also consistent with the engines producing similar power outputs.

Accident analyses

An attempt has been made to try to determine the impact speed of the airplane using propulsion system examination and analysis. Preliminary NTSB analysis, based on accident site evidence, indicates that the airplane may have impacted the ground at a speed in excess of 400 knots (460 mph).

The FAA questions that impact speed based on the following evidence and analyses:

1. Propeller Blade Angles – At high speed, it typically requires a small blade angle change to absorb a significant change in RPM or H_P. At the speed proposed by the NTSB, the propeller blade angle would more likely be at 53 to 54°. This angle is based on data and analyses provided by Hartzell Propeller, Inc., and the Team. Based on the blade angle measured during the propeller teardown (which is considered a minimum blade angle), a speed of approximately 290 to 300 knots (334 mph to 345 mph) has been estimated. V_{mo} of the MU-2B airplane is 250 knots.

2. Propeller Pitch Control – Many constant speed propeller pitch control systems use hydraulic oil pressure and mechanical spring force to control a blade angle. The Hartzell HC-B4TN-5GL propeller is a single acting pitch control propeller where oil pressure acts on one side of the propeller piston, and spring force counteracts that pressure on the other side. The propeller pitch control system is designed to adequately control the propeller blade angle through a specified range of angles within the performance envelope of the airplane. In the case of the MU-2B airplane, the propeller control system is designed to adequately control the propeller blade angle to V_D (dive speed) according to CAR 03. Hartzell Propeller provided a pitch control hydraulic pressure margin at that speed and so it can be shown that the propeller may properly control propeller blade angle slightly above V_D. The Team found eyewitness accounts where an MU-2B model airplane with the Hartzell HC-B4TN-5GL propeller installed was dive tested during company tests at speeds approaching 360 knots (414 mph). This is well in excess of the CAR 03 certification requirements. The test pilot noted that the propeller operated properly and maintained a constant RPM throughout the test. Hartzell Propeller, Inc., conducted an analysis for the Team to determine if the propeller pitch control system could control propeller blade angle at speeds in excess of 360 knots. The analysis shows that the hydraulic pressure margin to control the propeller blade drops steadily to a point where slightly above 360 knots, the propeller pitch control is within the range of the propeller pitch control frictional forces. To understand the relationship as the airplane speed builds, the aerodynamic twisting moment that tries to twist the propeller blade to a lower pitch increases steadily. At some point, the hydraulic pressure, which has a maximum psi limitation (up to 340 psi), can be overcome by the aerodynamic forces created as the speed is increased. Although there is some residual positive hydraulic pressure calculated at speeds approaching 400 knots, it is likely that the propeller would not act normally and the possibility of a propeller overspeed is high.

3. Engine Operation at High Speed – The engine manufacturer was consulted about the engine operation at high airspeeds beyond the certification requirements. Based on the propeller analysis and the likelihood of a propeller overspeed, the Team asked Garrett to analyze and inspect the engines for possible overspeed. AlliedSignal Inc. (Garrett Engine Division) advised the Team that if an engine overspeed was experienced on either engine, it would most likely show up in the growth of the turbine wheel (disc) inner bore diameter. Based on the measurements and analyses conducted, the left engine may have experienced a slight overspeed condition up to approximately 115 percent at some point in its service life. This is based on several left engine turbine wheel (disc) inner bore diameter measurements. The investigation was unable to determine when the overspeed condition occurred.

The right engine turbine wheel (disc) inner bore diameters were measured and the data indicates the engine has inner bore diameter growth considered normal based on nominal engine operating service experience. No evidence exists to show that this engine has ever experienced an overspeed condition.

4. Engine Flameout Investigation – One of the scenarios that was reviewed in the FFFSCR investigation was an engine flameout condition causing the airplane to rapidly lose airspeed to the point of stall and then depart controlled flight. The Team could not find any direct evidence that the Malad City MU-2B airplane accident experienced a flameout on either one or both engines.

Conclusion:

Based on the propeller analyses and calculations, and the engine measurements, it is reasonable to conclude that an overspeed condition was not experienced during the high speed descent that occurred prior to the airplane impact. The calculated speed of 290 to 300 knots reasonably agrees with the evidence and propulsion system analyses. It is more likely that the airplane impacted the ground at that speed.

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V. ACCIDENT REVIEW

This section of the report deals with the similarities in the eight long body MU-2B accidents, not associated with approach and landing, where ice was a possible factor or a potential contributing cause of the accident. A review of all available MU-2B accident reports from the NTSB and foreign authorities was made and the list below includes icing related MU-2B accidents since 1983. The accident reports were studied and examined for common traits that could contribute to an accident scenario and were useful in determining corrective action recommendations (items 4 and 5 from the Charter).

01/15/96 - MALAD CITY, ID - CRUISE, DECREASE IN AIRSPEED, THEN SPIN/ HIGH SPEED DIVE/SPIRAL, NEUTRAL ELEVATOR TRIM

01/22/93 - BEUCHERLING, GERMANY - CLIMB WITH LANDING GEAR STUCK DOWN, CRUISE, STALL/SPIN, NOSE UP ELEVATOR TRIM

02/14/90 - PUTNAM, TX - CRUISE, DECREASE IN AIRSPEED, THEN HIGH SPEED DIVE/SPIRAL, NOSE UP ELEVATOR TRIM

01/25/90 - MEEKATHARRA, AUSTRALIA - CLIMB, CRUISE, STALL/SPIN, NOSE UP ELEVATOR TRIM

12/16/88 - LEONORA, AUSTRALIA - CLIMB IN STORM, THEN STALL/SPIN, NOSE UP ELEVATOR TRIM

12/09/88 - CORAL SEA, AUSTRALIA - CRUISE IN ICE, DESCEND TO CLEAR ICE, CLIMB, THEN UNCONTROLLED DESCENT, LOST AT SEA

04/16/88 - ST. ETEINNE, FRANCE - CLIMB, THEN STALL/SPIN, NOSE UP ELEVATOR TRIM

05/24/83 - BARGO, NEW SOUTH WALES, AUSTRALIA - CLIMB, THEN HIGH SPEED DIVE/SPIRAL, FULL NOSE UP TRIM

From the above list and other MU-2B icing related accidents, a spreadsheet was constructed from the accident data using the similarities common to most of the accidents. Approximately half of the accidents occurred during climb and the remainder during cruise in icing conditions. There were no Cockpit Voice Recorder or Flight Data Recorder devices installed in any of the accident aircraft (none required by regulations), so the exact circumstances can never be determined. Radar data, pilot experience levels, elevator trim settings at impact, time of day including general weather conditions, and witness testimony were available to some degree in most cases. Radio transmissions just prior to the accident were also recorded in some of the accidents. Other factual information was provided by the manufacturer and NTSB/FAA/Foreign Civil Airworthiness Authorities accident reports.

Effectively using all this information requires making some suppositions as to the conditions and pilot actions in each accident. From the information obtained from the spreadsheet and these suppositions, a scenario was constructed for each accident. Through analyses of all this information, several possible factors that may have contributed to the cause of the accidents were identified, including the perception of a hazardous condition that the Team felt should be addressed through appropriate corrective action. The hazardous condition found was that the pilots of the accident airplanes appeared to have relied on the autopilot to the extent of unknowingly allowing the airspeed to deteriorate well below normal operating speeds for the existing flight conditions. It was determined that this deceleration can be attributed to drag from ice accretion on the airplane in most of the accidents. It is plausible for an engine to fail resulting in a slowdown, and during the engine restart sequence the speed is allowed to decrease to a critical point just as the engine is restarted. So it would be operating properly at impact. However, engine and propeller service difficulties were reviewed and no engine power loss incidents were reported that could confirm this as a possible cause. All of the accidents, where radar altitude/airspeed time histories were available, showed either a gradual slowdown well below the 180 knots minimum airspeed specified for cruise in icing conditions in the AFM, or a gradual slowdown well below the normal climb airspeed for this airplane. The exact airspeed at which the aircraft departed a normal flight regime cannot be determined from the existing radar data, but it was always above normal stall speed. Stall warning characteristics may have been reduced or nonexistent depending on the amount of ice accretion. During the stall tests with SLD ice shapes, a 7 to 14 knot increase above normal stall speed was observed. The artificial stall warning device (stick shaker) failed to warn of an impending stall during these tests, but some natural airframe buffet was noted. Several reports of stalling with no warning were reviewed. The reports varied depending on ice accretion and de-ice system use.

As a result of the analyses described above, the Team determined the following scenario attributes that were common to all of the accidents with the qualifying and exclusionary statements:

A. Icing conditions were reported or forecasted.

B. There was insufficient engine power monitoring by the pilot.

C. The autopilot was engaged, probably in heading and altitude hold, or an attitude hold mode.

D. There was an uncommanded and unobserved airspeed decrease.

E. The pilot was not aware or failed to understand the significance of the airspeed reduction.

F. The pilot did not increase the power setting when the airspeed loss reached a critical point or did not decrease the AOA by reducing the aircraft pitch angle.

G. The pilot did not take steps to exit the hazardous icing conditions.

H. The airplane may have experienced a systems malfunction.

I. An airspeed reduction due to ice accretion will be rapid using an altitude hold mode when flying on the backside of the power curve, or if climbing in an attitude hold mode without a power increase made by the pilot.

J. An airplane with ice contamination on the wings usually will stall at a higher than normal airspeed.

K. The airplane departed controlled flight with incorrect or no pilot flight control inputs.

L. The airplane entered a spin mode or a near vertical spiral mode, until ground impact.

Below is a discussion of each element with recommendations as appropriate:

A. Icing conditions were reported or forecasted.

Weather forecasting and reporting of icing conditions, including location, extent, and severity are inexact and incomplete at best. Pilot reports of icing conditions encountered are not always forwarded to other pilots flying in the same vicinity. In some cases, there was no assurance that other flights transited the intended route and altitude, so there may not have been an opportunity for other pilots to observe and report icing conditions. Also, some severe icing conditions may have developed in a relatively short time. Finally, ice detection from ground and airborne sensors leaves much to be desired, especially in the SLD range.

Currently, available ice detection sensors installed on aircraft do not allow precise measurement of the icing environment surrounding the airplane, nor do they provide a warning to alert the pilot to conditions beyond the airplane's ice protection system capability. Existing ice detectors provide only one bit of data to the pilot – ice is present. This is insufficient data for the pilot to make proper decisions regarding exiting the icing conditions. Once ice is detected, the pilot must monitor physical cues on the airplane, airplane response through flight instruments, and make a judgment as to when the severity warrants a change in altitude or heading. Using visual icing cues available from the airplane's external features is not an exact science, and requires almost constant vigilance and judgment as icing conditions can and do change very quickly. In some cases, the cues may not be readily detectable because of the formation of clear ice, or there may be ice accretion on parts of the airfoil, and little on the leading edge. It appears that the pilots of the accident airplanes either ignored the cues, did not understand and interpret the indications properly, or were distracted from vigilantly monitoring the severity of the icing.

RECOMMENDATIONS:

1. Recommend continued government research, and encourage the aerospace industry to develop and certify airplane ice detector sensors that quantify ice accretion with appropriate pilot notification, and with automatic anti/de-ice capability, and provide annunciation when icing conditions are beyond the capability of the airplane's protection systems.

2. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

3. By means of an AD, require an ice detector to be installed on all MU-2B airplanes.

4. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

B. There was insufficient engine power monitoring by the pilot.

Climb and cruise at a constant power setting are normal conditions; however, the pilot must not forget to monitor what is happening to the airplane. The pilot must stay aware of the airplane's airspeed and altitude, as well as the OAT, and watch for the presence of ice and its effect on the airplane, even with the autopilot engaged. The autopilot is an aid to the pilot and cannot be considered as another pilot flying the airplane – the autopilot cannot think. The pilot must continue to monitor the airplane's performance and the environment when flying in possible icing conditions.

Once icing has been encountered, the pilot must monitor the conditions and performance of the airplane. If the airplane is decelerating at a constant power setting, the problem must be immediately investigated, especially if climbing at the Best Rate of Climb (BROC) airspeed (defined as V_y) with an autopilot hold mode engaged (see figure V-1, in appendix 3, for an explanation of the significance of BROC). When the airspeed loss is greater than 20 knots, the de-ice system must be operated. If the airspeed is not regained after de-ice boot operation, an immediate exit of the icing conditions is warranted, as ice may have accumulated aft of the protected areas, or incompletely shed from protected areas. If the airspeed loss is not attributed to ice accretion, it must also be investigated and corrective steps taken prior to reaching 180 knots. The Team was not able to find any evidence of another reason for the slow airspeed loss, other than an engine failure. The Team is also recommending the engine Auto Re-light ignition system to prevent ice induced engine failures due to inlet blockage from shedding ice. Only a couple of the accidents showed evidence of an engine failure prior to impact. It is always possible to have suffered an engine flameout with the pilot becoming so focused on the restart that the airspeed loss went undetected until the airplane stalled, just as the engine was re-started. The Team concluded that the pilots flying the accident airplanes did not adequately monitor the conditions, or the airplane's performance, prior to departure from controlled flight. This apparent lack of pilot awareness can be corrected through training, and should lead to a better understanding of the effects and consequences of flight in icing conditions. The flying experience level of the accident pilots shows evidence of high total flying time, but low amounts of MU-2B flying time, leading to the Team's decision that the training should be recurring on a biennial basis.

RECOMMENDATIONS:

1. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

2. By means of an AD, incorporate the manufacturer's engine Auto Re-light Ignition System Service Bulletin, and require both engines to be modified with the Auto Re-light ignition system on all MU-2B airplanes.

C. The autopilot was engaged, probably in heading and altitude hold, or an attitude hold mode.

Two autopilots have been approved by type certificate for use in the MU-2B: the Sperry SPZ-500 and the Bendix M4 Series. The Sperry SPZ-500 autopilot has three hold modes, plus Touch Control Steering (TCS), that are of primary interest: Altitude (ALT) Hold, Vertical Speed (VS) Hold, and Indicated Airspeed (IAS) Hold. The Bendix M4 autopilot has fewer, but similar, modes: Autopilot (AP), Altitude (ALT) Hold, and Pitch (PITCH) Command. An understanding of these basic modes and TCS is vital to know the autopilot selection possibilities and their significance in the accident scenarios (see appendix 4 for an explanation of the approved autopilots).

From the altitude and airspeed data available from the approach/enroute radar printouts in several accidents, the stability of the flight path traces shows that it is highly probable autopilots were engaged and flying the airplanes prior to the accidents. The longitudinal trim servo was found in most of the accident aircraft to be 12 to 30° nose up, indicative of the autopilot trimming into the stall. It is our belief that the pilot would not normally and knowingly manually trim into the stall, but should have noticed a dangerous trim requirement building prior to the airplane actually stalling.

RECOMMENDATIONS:

1. Recommend continued government research, and encourage the aerospace industry to develop and certify airplane ice detector sensors that quantify ice accretion with appropriate pilot notification, and with automatic anti/de-ice capability, and provide annunciation when icing conditions are beyond the capability of the airplane's protection systems.

2. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

3. By means of an AD, require an ice detector to be installed.

4. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

5. By means of an AD, require a trim in motion aural notification system be installed on all MU-2B airplanes with an autopilot installed.

D. There was an uncommanded and unobserved airspeed decrease.

Regardless of the rate of decrease, any decrease in airspeed must be noted by the pilot and evaluated prior to reaching a hazardous condition. The AFM includes a WARNING that has now been changed to a limitation by an AD to not allow the airspeed to decrease below 180 knots in cruise flight when flying in icing conditions. Despite the warning and specified procedures, the pilots of the accident airplanes have allowed their airplanes to decelerate to below 150 knots without any pilot action. Ice accumulation on and aft of the de-icing boots on the wing, and other unprotected areas on the airplane, results in a loss of airspeed due to an increase in drag and a loss of lift, which is compensated for by the pilot or autopilot increasing the AOA. The loss in lift, from tripping portions of the boundary layer across the top of the wing, must be compensated for (in order to hold altitude or attitude constant) by an increase in AOA on the wings, which increases the induced drag and slows the airplane. The increase in parasite drag, due to ice accumulating on unprotected areas and aft of the boots, slows the airplane, and must be further compensated by another increase in the wings AOA. The ice accumulation characteristics on an airplane are an infinite spectrum. The ice roughness, especially in the SLD environment, may affect the lift and drag more than the depth and shape of the ice accumulation. Each icing encounter is different, and therefore must be evaluated almost continuously, as the icing conditions and resulting effects can change rapidly.

One of the easiest recognized cues to hazardous icing conditions is a loss in airspeed. This cue can be complimented by an aural trim in motion cue. If the airplane is being operated on autopilot in the ALT Hold mode, the longitudinal trim will automatically trim nose up to hold the altitude as the airspeed decreases. The MU-2B does not have an audible trim in motion system, and must rely on the pilot's knee resting against the trim wheel for tactile perception. If the pilot does not rest the knee against the trim wheel, only visual cues warn that trim motion is occurring. The trim system has sufficient authority to trim the airplane into a stall. In a nominal gross weight and c.g. configuration, the basic airplane with no ice will give a stall warning (stick shaker) at approximately 12° nose up trim, and most of the accident airplanes were found with the trim set between 12 and 30° nose up. The nose up elevator trim at stall warning is a function of gross weight and c.g. location, and can also require as much as 18° nose up trim at the forward c.g. limit. However, the nose up trim required with ice accumulation will be less than required for a clean wing. The trim system will continue to trim nose up after a stall if the autopilot is not disconnected at stall. This appears to be the case in some of the accidents, and in some of the accidents, the autopilots appear to have been disconnected at the stall.

The stall speed can be elevated due to ice accumulation to as high as 14 to 45 knots above normal. Ice accumulations of 1 to 3 inches without boot activation have been reported (see the testimonial given by Charles Priester as part of the icing flight test substantiation report submitted in the MHI Engineering Report MR-0149, Revision A, dated 2-23-76). This stall speed increase may be insidious as the normal stall warning (stick shaker) may not function. The airplane's normal accompanying pre-stall buffet may be of greater magnitude, but shorter in duration, or may be absent entirely. Flight tests in dry air, with the artificial ice shapes determined from the AFFTC icing tanker tests, have shown higher than normal stall speeds with no stick shaker, and higher than normal buffet levels, but closer to stall. Pilots have also reported that they sensed changes to handling characteristics with ice accretion.

If the airspeed reduction goes undetected and decreases below the minimum power required point without pilot action, the stall is guaranteed as the airplane is now operating on the backside of the power curve. From the discussion in appendix 3, it can be seen that the trim system will attempt to trim nose up to hold altitude, and that an increase in power is required to fly in this regime. The autopilot will now trim at a faster rate, then continuously, until the stall occurs as the selected altitude cannot be maintained with longitudinal trim alone, needing more engine power.

RECOMMENDATIONS:

1. By means of an AD, require a trim in motion aural notification system be installed on all MU-2B airplanes with an autopilot installed.

2. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

3. By means of an AD, require an ice detector to be installed.

4. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

E. The pilot was not aware or failed to understand the significance of the airspeed reduction.

Although the autopilot may be controlling the airplane, the pilot must not allow distractions to divert attention from the flight instruments. Even an emergency condition as serious as the loss of a cabin window should not focus pilot attention away from flight instruments for an extended period of time. From the discussion above, it should be noted that a hazardous condition can occur in a very short period of time if an airspeed loss goes undetected/uncorrected. Actual research flight tests of a Beechcraft King Air flying in SLD icing conditions have shown airspeed losses from a low cruise speed to stall in 4 minutes. The King Air was attempting to hold 150 KIAS in icing conditions by adding power to compensate for any loss in airspeed and was monitoring the drag rise. The drag rise for the first 10 to 15 minutes was fairly constant until the ice seemed to change its surface texture in the SLD encounter. The next 4 minutes saw an exponential rise in drag and the airplane could not climb or accelerate at full power. The airplane was in pre-stall buffet and something had to be done. The wing stalled as the aileron was put in to start the turn to exit the conditions. The Team did not see conditions this bad during the tanker tests, but understands that they can occur in rare instances in nature. Some of the accident airplanes could have encountered conditions of this magnitude that are well beyond the de-ice capability of the airplane and failed to exit the conditions prior to stall. These severe conditions provide cues to warn the pilot that the conditions are beyond the capability of the airplane, as noted during the tanker tests. The Team felt that these cues and appropriate AFM limitations must be mandated as mandatory compliance items by an immediately adopted AD (AD 96-25-02 dated 12/05/96). The other AD recommendations will be published as the fixes become available.

The basic aerodynamic design of this airplane requires a trim change (rudder and trim aileron) be made by the pilot when the airspeed is changed by approximately 20 knots. This is a trim intensive airplane, and it must be learned early in the training for the MU-2B. Some pilots may not have learned this requirement very well. One of the problems associated with this characteristic is that when the airplane slows down due to a power reduction or due to ice accretion, the pilot must manually re-trim the rudder and aileron. If the airplane is being controlled by the autopilot, the pilot must still make the aileron trim changes. This was simulated during the FFFSCR flight tests by engaging the autopilot with ALT and heading hold modes engaged, and reducing the engine power to flight idle. The test conditions (test altitude, gross weight, c.g., engine propeller, and engine rigging) may have been different each time, but the airplane response was essentially the same. The response did not differ from what one might expect on any other twin-engine airplane with propellers that turn in the same direction.

Indeed, the reduction in power to promote a deceleration causes a lesser P-Factor effect. As the airplane slows down, an unbalance in the aerodynamic forces gradually occurs. A control change will be required in the roll spoiler, elevator, and rudder. The autopilot uses the elevator and the rudder trim tabs to reduce surface control forces, but does not use the trim ailerons. The autopilot maintains heading with bank angle and to do this it uses the spoilers. The autopilot uses the rudder to maintain coordinated flight by nulling the side forces on the airplane measured by an accelerometer. The Sperry autopilot also has a turn rate sensor input. As the airplane decelerates, pitch attitude increases, P-Factor causes a yaw and roll, which is countered by the spoilers (with roll control yoke movement), and rudder (with assistance from the rudder trim) to maintain constant heading and coordinated flight until full control travel is reached. If these conditions are allowed to continue, an uncoordinated stall will occur. An uncoordinated stall (stall with sideslip present) will usually result in a departure from controlled flight, culminating in a spin or near vertical spiral mode.

The rudder trim that was added by the autopilot during these events was not consistent. Opposite rudder from spoiler was added on some occasions and rudder with the bank was added on others. The rudder trim added by the autopilot to maintain balanced flight may not have been consistent, due to engine/propeller idle settings and other drag differentials. The constant factor was the spoilers were driven to the maximum deflection and wings level could not be maintained as the stall was approached. During the tests, the autopilot was disconnected at stall warning, and recovery was initiated because a departure from controlled flight may occur if the airplane is allowed to stall in this condition.

This is not to say that the autopilot response is unsafe, novel, or unusual, but that the pilot must be aware of what is happening, and take appropriate action before reaching the point of departing controlled flight. It is the Team's perception that the pilots of the accident airplanes did not understand the criticality of their situations, and allowed the airplane to stall with the autopilot engaged. The same response may occur on other airplanes, but the pilots in the MU-2B were allowing it to take place with no corrective action. In a recent accident, the pilot of a Beechcraft King Air C-90 did not realize his airplane was iced up with freezing drizzle and crashed straight ahead while maintaining airspeed above stall, rather than allowing the airplane to stall and depart controlled flight. However, the MU-2B accident pilots did not take the appropriate actions, and the Team agrees that the MU-2B crews should be told what may occur in severe icing conditions, what causes it to occur, and how to recognize and exit the dangerous conditions.

This autopilot response should not be construed as an autopilot malfunction, but the problem is really pilot inattention or dereliction of pilot duty, including failure to trim and control the airplane. An effective pilot training program that includes autopilot modes familiarization and recommended mode use may prevent the pilot from falling into the traps discussed above.

RECOMMENDATIONS:

1. By means of an AD, require a trim in motion aural notification system be installed on all MU-2B airplanes with an autopilot installed.

2. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

3. By means of an AD, require an ice detector to be installed.

4. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

F. The pilot did not increase the power setting when the airspeed loss reached a critical point or did not decrease the AOA by reducing the aircraft pitch angle.

The relationship between power required and power available must be thoroughly understood, as well as what it really means to fly on the backside of the power curve. The airspeed must be closely monitored, especially with the autopilot engaged, and power must be added when flying at speeds below the point for minimum power required.

RECOMMENDATIONS:

1. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus of appendix 2.

2. By means of an AD, require an ice detector to be installed.

3. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

G. The pilot did not take steps to exit the hazardous icing conditions.

It must be understood that icing conditions can exist beyond the anti/de-ice capability of any airplane (i.e., SLD). If the icing condition is beyond the airplane's anti/de-ice capability, the pilot must be able to recognize it and take appropriate action. The pilot must, therefore, have some criteria for deciding to seek a change in heading or another altitude prior to the environment creating an unsafe condition. One commonly used criterion is watching for an airspeed reduction of some number. The Team recommends approximately 20 knots and, if the ice cannot be shed and airspeed regained, exit the conditions. If the pilot fails to monitor the airplane's condition in ice, there should be another cue before a hazardous condition occurs. With only a 20 knot loss, the airplane could easily descend, or still have sufficient power to climb to higher altitudes and colder temperatures (less likely for SLD ice to occur), but the pilot must take the action, and not rely on the autopilot and icing certification to protect the airplane. The MU-2B AFM had a WARNING containing a minimum airspeed in icing conditions, but a limitation is more appropriate, and became mandatory by an AD recommended by the Team. The pilot notification and automatic disconnect of the autopilot at 130 to 140 knots is a second chance, and is intended to prevent the autopilot from trimming into a potentially catastrophic stall situation. The disconnect requires the pilot to manually fly the airplane. The pilot should add power to regain the airspeed and hold altitude, re-trim the airplane, and note that dangerous ice has accreted on the airplane requiring a descent/climb out of the severe icing conditions.

If an engine flameout occurs in this severe icing environment, the engine should NTS (NTS system drives the propeller pitch to a low drag position) and allow the pilot to cope with the emergency. However, the ice must be removed by the de-ice system, or the airplane may not be able to maintain altitude and airspeed above stall during the attempt to start the flameout engine. This may have occurred in some of the accidents where an engine was inoperative at impact. To ensure the emergency propeller systems are operative, the propeller NTS system and feather valve checks should be performed on the ground before the first flight of the day. The importance of SLD recognition and exit criteria was so exigent that the Team has already issued an immediately adopted AD similar to the AD issued for commuter airplanes with unpowered flight controls and pneumatic de-icing boots.

If the engine flameout was due to ice ingestion blockage of the engine inlet, the engine would be able to be restarted, as no damage is likely. However, if an Auto Re-light ignition system had been installed, the engine would not fully lose power before the engine ignition automatically restores power in a matter of seconds.

RECOMMENDATIONS:

1. By means of an AD, require an ice detector to be installed.

2. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

3. By means of an AD, incorporate the manufacturer's engine Auto Re-light Ignition System Service Bulletin, and require both engines to be modified with the Auto Re-light ignition system on all MU-2B airplanes.

4. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

5. An immediately adopted AD was issued (AD 96-25-02, dated 12/5/96) to require changes to the AFM to include: Limitations on minimum speed in icing conditions – 180 knots in level flight; prohibit use of flaps for sustained operations in icing conditions, except for approach and landing; provide cues to allow pilot recognition of SLD conditions; and provide an exit criteria.

H. The airplane may have experienced a systems malfunction.

See the Propulsion and Systems sections of this report for a complete discussion and recommendations.

I. An airspeed reduction due to ice accretion will be rapid using an ALT hold mode when flying on the backside of the power curve, or if climbing in an attitude hold mode without a power increase made by the pilot.

Half of the accidents occurred from a climb, and half from cruise flight. Without a flight data recorder, the use or non-use of the autopilot cannot be positively determined. However, from the longitudinal trim setting if it could be determined at the accident site, it was deduced that the autopilot was controlling the airplane in five of the eight accidents, and probably in two of the other three. The Team reasons that the pilot would not intentionally trim into a stall, but could be distracted and not note a slow deceleration, and not take the appropriate action without proper stall warning. A longitudinal trim setting of 12° or higher is an indication of the trim range where a stall can occur with a higher than normal stall speed due to ice accumulation. In this range, the airplane is operating on the backside of the power curve if in level flight and well below climb airspeed if in a climb. The pilot must have a clear understanding of operations on the backside of the power curve and where that occurs on the airspeed indicator. When flying in level flight at any airspeed lower than V_y, a potential hazard exists and additional power must be applied. Most pilots have been exposed to this simple principle, but may tend to forget the full implication of operating in this regime. Therefore, recurrent training becomes necessary. Also, pilot awareness of problems associated with flight in icing conditions and the effects on V_y of ice accumulation must be fully understood. The high wing loading of the MU-2B may make operations in these environments more significant than with other airplanes of lesser wing loading (see appendix 3 for discussion on the significance of V_y). Without recurrent training, pilots may tend to forget the relationships between ice accretion and power required curves. If power must be added to maintain airspeed and additional power is not available, airspeed must be maintained by a reduction in altitude. This must occur prior to reaching stall speed, otherwise, an altitude reduction may become uncontrollable.

RECOMMENDATIONS:

1. By means of an AD, require an ice detector to be installed.

2. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

3. An immediately adopted AD was issued (AD 96-25-02, dated 12/5/96) to require changes to the AFM to include: Limitations on minimum speed in icing conditions – 180 knots in level flight; prohibit use of flaps for sustained operations in icing conditions, except for approach and landing; provide cues to allow pilot recognition of SLD conditions; and provide an exit criteria.

4. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

J. An airplane with ice contamination on the wings usually will stall at a higher than normal airspeed.

Stall speed increases when the wing is contaminated with ice. The amount of increase depends on the amount, shape, extent, and texture of the ice. Ice accumulation on the upper surface of the wing may have a significant effect on stall speed, and this area may not be visible from the cockpit on high wing airplanes such as the MU-2B. Every icing encounter is different and the icing continuum is infinite, but certain qualities remain constant, and the pilot must understand this. Training and recurrent training are the only means of providing the pilot with this understanding. The pilot must understand that no airplane can cope with every possible icing encounter. The pilot must have established some decision-making criteria within his/her own mind prior to encountering ice. The pilot must pay close attention to what is happening to the airplane, and must exit the icing conditions when the criteria are reached. There is no accurate way to predict stall speed once the wing is contaminated with unshed ice. As soon as this condition occurs, the pilot must exit the icing if 180 KIAS cannot be maintained.

Awareness of the hazards involved can be accomplished only through training. If the pilot does not come to this airplane with the training, the pilot must be trained through an FAA mandate of some kind. The Team's review of the accident reports indicated that pilots flying the accident airplanes did not possess sufficient knowledge, or the knowledge was not current enough to be remembered as applicable to the situation. MHI, in concert with the FAA, is preparing a training videotape (program) to make the pilots flying the MU-2B aware of the icing hazards and icing lessons learned during this review. This tape will be required training initially and on a biennial basis thereafter for all MU-2B pilots that act as pilot in command. Current schools that are airplane specific for the MU-2B (Flight Safety and Reese Howell) are used by most corporate pilots and, if the training program is adopted by these schools, it will satisfy the training requirement. Other pilots can acquire the necessary training by attending an MHI PROP Seminar, or making other arrangements through MHI.

RECOMMENDATION:

By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix-2.

K. The airplane departed controlled flight with incorrect or no pilot flight control inputs.

The pilot must understand that the autopilot has sufficient authority to trim the airplane into a stall, and it will do just that if the power required for flight is less than the power set. The airplane will decelerate due to drag when ice is accreted if nothing is done to de-ice the airplane. If this process is allowed to continue, or if ice forms on the boots and is not shed, or forms aft of the boots and cannot be de-iced, the process will speed up, and the effects on airplane performance degradation will be made more severe. When airspeed becomes less than the minimum power required speed, the airplane will soon stall. When the stall occurs, the aerodynamic conditions present will probably not be force balanced and some sideslip may occur. Then the airplane may not stall straight ahead, but may depart controlled flight. The pilot may not identify correctly what is happening and aggravate the situation by making incorrect flight control and power inputs. If the stall occurs well above normal stall speed, the pilot may not get any artificial or natural warning. The stall might occur with no pilot inputs to power or flight controls and the engine power may still be set at cruise. Airplane response at stall may be very disorienting in instrument flight conditions.

RECOMMENDATION:

By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

L. The airplane entered a spin mode or a near vertical spiral mode, until ground impact.

At least two modes are probable after a departure from controlled flight. The spin mode may be unrecoverable – it has not been investigated because it is beyond FAA's certification requirements. The spin mode may deteriorate into the near vertical spiral mode, as it frequently occurs in single-engine airplanes and gliders. The spiral mode may be recoverable if the proper control inputs are made, but this mode may be confused with a spin, and therefore is frequently unrecoverable.

RECOMMENDATIONS:

1. Recommend continued government research, and encourage the aerospace industry to develop and certify airplane ice detector sensors that quantify ice accretion with appropriate pilot notification, and with automatic anti/de-ice capability, and provide annunciation when icing conditions are beyond the capability of the airplane's protection systems.

2. By means of an AD, require all MU-2B pilots (PIC) to attend biennial training to include icing awareness, anti/de-icing system operation, icing severity cues, and exit criteria. This training should include, as a minimum, the items in the training syllabus in appendix 2.

3. By means of an AD, require an ice detector to be installed.

4. By means of an AD, require installation of an autopilot disconnect system. The system will disconnect the autopilot, with suitable annunciation, at a suitable airspeed, during an uncommanded deceleration, with the aircraft in a clean configuration (the system

will incorporate a cue to notify the pilot that the autopilot will disconnect in 2½ seconds prior to disconnect).

5. By means of an AD, require a trim in motion aural notification system be installed on all MU-2B airplanes with an autopilot installed.

6. Recommend the FAA provide funds for NASA to conduct a near vertical spiral mode investigation to determine if the mode is probable following a departure in the MU-2B, and, if probable, determine the recovery procedure. If software is available for similar studies, in lieu of spin tunnel testing, recommend NASA procure and make available to the FAA and NTSB use of the software programs, and assist in analyses.

Appendix 2 — Training Syllabus Requirements

Pilot Recurrent Training Course Outline

1. Define potential MU-2B accident condition scenarios
   - Define and discuss accident analyses and factors that contribute to the accidents.

2. Discuss MU-2B icing certification
   - What does FAA icing certification mean?
   - What is 14 CFR part 25, Appendix "C"?
   - What are the MU-2B limits?
   - What are Supercooled Large Droplets (SLD) icing conditions?

3. Discuss MU-2B operational requirements in icing conditions
   - Appendix "C" icing conditions
   - SLD icing conditions
   - Discuss engine operating characteristics
     * Engine ice buildups
     * Engine rigging
     * Engine performance
   - Discuss propeller operating characteristics
     * Propeller ice buildups
     * Propeller rigging
     * Propeller performance

4. Discuss how MU-2B airplane performance can be affected by icing conditions including SLD icing
   - Airspeed minimum airspeed
   - Stall speed and characteristic changes
   - Handling
   - Climb performance

5. Identify physical airplane cues that the pilot can monitor to evaluate the MU-2B airplane conditions
   - These include but are not limited to:
     - Weather conditions
     - Airspeed degradation
     - Ice buildups on airframe
     - Trim changes (autopilot)
     - Rate of climb changes

6. Discuss pilot decision process to exit icing conditions
   - Air Traffic Control priority
   - Airplane handling procedures

7. Discuss the backside of the power curve

Appendix 3 — Power Required Curve

Figure V-1 is a power required for level flight curve that should be familiar to most pilots. For those not familiar, the curve is a plot of the actual engine torque required to fly level at a constant given airspeed, at a given altitude (density altitude as defined by pressure and temperature), at a given gross weight and c.g. The curve shown is a typical curve of power required versus power available, such as in a commonly used Aerodynamics textbook by Perkins and Hage, page 189. The curve was generated by actually flying at a sufficient number of separate airspeeds to gather the data, correcting the data for known errors, and then plotting the curve. The lowest point on the curve is, by definition, the Minimum Power Required to fly level at the conditions tested. This point is also the point where the maximum power differential occurs between the curve and the maximum power available line (maximum engine power available from the engines expressed in percent torque, 100 percent in this case). This excess power available can be used for power to climb, and if the airspeed is maintained, this will be the maximum rate of climb possible under these conditions. This airspeed can also be called the BROC airspeed and is referred to as V_y. The V_y airspeed will change due to changes in the atmosphere, pressure and temperature, changes in gross weight (c.g. effects are minimal for the MU-2B), and propeller speed (charts are available in the AFM to predict the V_y airspeed and climb rate). The actual V_y airspeed will have been validated through a series of climb performance tests and may vary slightly from the minimum power required curve determination.

If the airplane is in cruise flight at point A on the curve and icing conditions are now encountered that are beyond the capability of the de-ice systems, the ice accumulation will cause a loss of lift and an increase in drag. Both of these conditions will cause the airplane to sink or lose altitude and slow it down. If the autopilot is engaged and in the ALT Hold mode, the autopilot will not let the airplane sink, but will increase the elevator nose up trim to maintain the altitude (increases the AOA on the wing). This will result in a new airspeed, lower than the original airspeed, at a new nose up trim position (point B on the curve). As more ice is accumulated, the airspeed will decrease as before, but if the airplane sustains a power loss for whatever reason, the slowdown occurs much faster, and can result in a case where the power is just below the minimum power required for level flight, point B'. If no power loss is sustained, a very large increase in drag is required to reach the minimum power required, point B'' on the curve. If these airspeeds are reached, different things start to happen. As can be seen on the curve, the slower the airplane flies, the more power is required to hold altitude until stall is reached, and the airplane can no longer stay at this altitude (point C on each curve). Note. Additional power is available for the pilot to use to accelerate or climb. However, if the pilot does not add power, the nose up trim will run almost continuously until stall occurs.

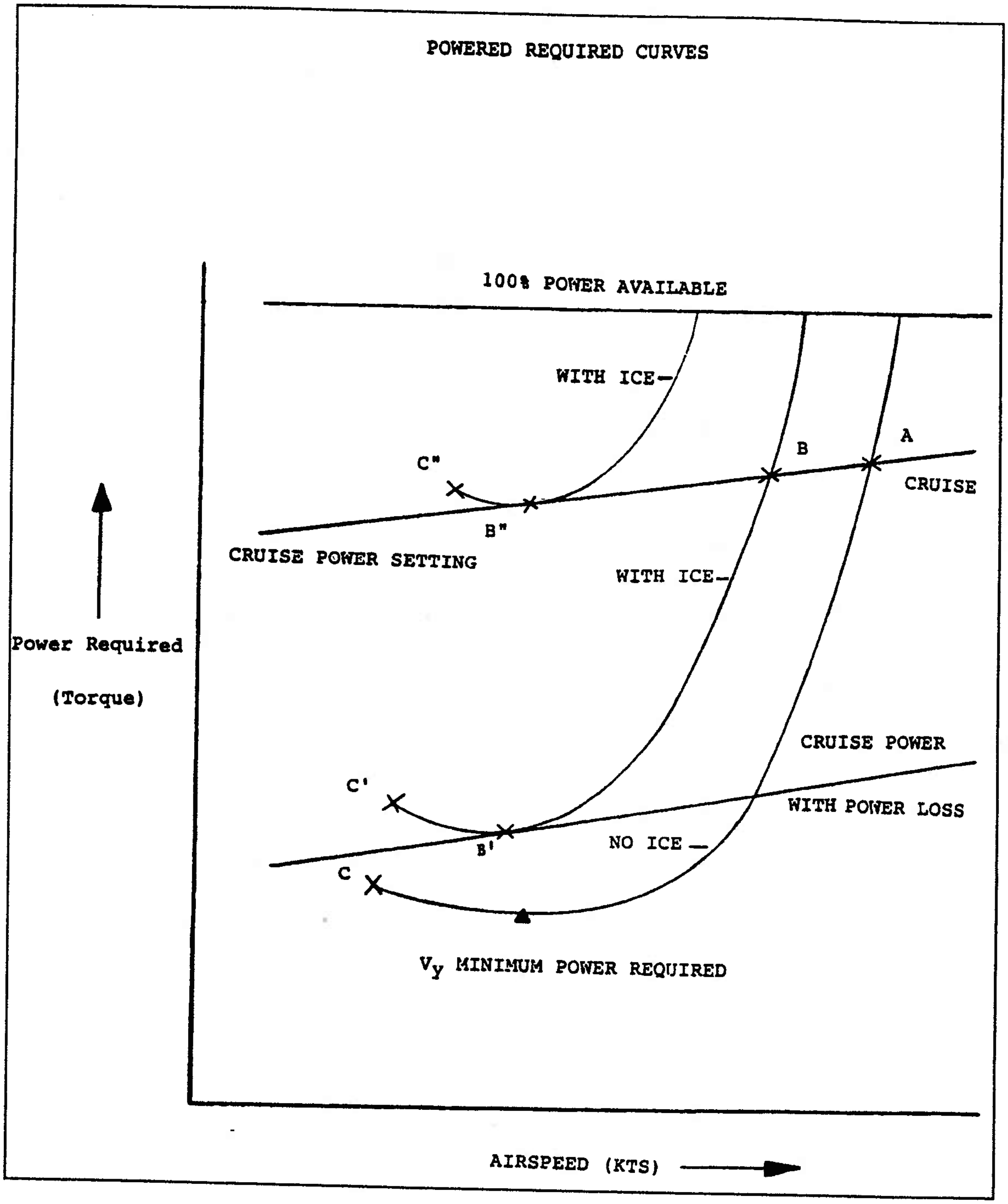

Figure V-1, Power Curve

In actual flight operation, the ice accumulation will change the shape of the curve and raise the curve as shown by the dashed lines. The ice will cause an elevated stall airspeed depending on the shape, roughness, and extent of the ice, as well as the use or non-use of the de-ice boots. Stall airspeeds, as high as 45 knots above normal have been reported (FAA certification data without de-ice boot activation) with a large ice accumulation. Stall speeds with wing SLD ice shapes determined from the FFFSCR tanker testing resulted in an increase of only 14 knots.

What happens to the airplane at stall if the autopilot is controlling the airplane with no pilot intervention? If the airplane is in trim and does not have ice contamination, the airplane will stall straight ahead. However, the airplane in this example has ice accumulation on the wing and tail surfaces, and the airplane may not be in perfect trim, so as the stall occurs, there may be some sideslip present. The stall may occur with no stick shaker to warn of the approaching stall and the natural pre-stall buffet may be less than normal. The sideslip present will cause the airplane to yaw and a roll will develop due to this sideslip. The roll control and spoilers may not have sufficient authority to arrest the roll rate, and the airplane may depart controlled flight.

The departure roll will be rather abrupt and may get the pilot's attention if the pilot was distracted. However, the pilot must immediately recognize a stall has occurred and push the control yoke forward to break the stall, regain flying speed, and then roll the wings level during the pull-up to level flight.

The above analysis is not the only possible one, but it is the best available with the known flight characteristics of the MU-2B. This does not mean that the airplane does not meet the certification requirements, but rather that icing conditions beyond the certificated capability of the anti/de-ice systems must be avoided. There are currently several commercially available icing detectors in the process of certification that will indicate or warn when the ice is beyond Appendix C limits. Until such devices have been shown to be effective and reliable, some method or criteria must be established to allow recognition of the conditions, and ensure sufficient respect for these conditions for the pilot to exit them prior to a hazardous condition developing. This can only be accomplished by the proper use of maximum power available, recognition of icing cues that indicates the icing conditions are beyond the system capabilities, and exiting the conditions before a hazardous condition occurs. The following cues were seen or derived from the MU-2B FFFSCR icing tanker tests and may indicate the presence of SLD conditions:

1. Unusually extensive ice accreted on the airframe in areas not normally observed to collect ice:

- Accumulation of ice on the propeller spinner farther aft than normally observed (more than halfway back to the propeller cutouts).

- Accumulation of ice on the lower surface of the wing aft of the de-icing boots, and visible from the pilot's position that is not removed by the de-ice boot operation; and
- Accumulation of ice on the upper surface of the wing aft of the de-icing boots visible from the pilot's position that is not removed by the de-ice boot operation. (Note. Ice accretion beyond the limit of the boots on the upper surface may be visible from the pilot's position as a solid or partial ridge of ice.)

2. Airspeed losses greater than 20 knots that are not regained after a boot de-ice cycle;
3. Decrease in rate of climb during a constant airspeed climb to 300 feet per minute; and
4. When unusual lateral/yaw trim requirements are encountered.

Appendix 4 — Autopilot Descriptions

Several autopilots have been approved for the MU-2B – the vast majority of the airplanes are equipped with either the Sperry SPZ-500 or the Bendix M4 series autopilot. The Sperry SPZ-500 autopilot has three hold modes plus Touch Control Steering (TCS) that are of primary interest: Altitude (ALT) Hold, Vertical Speed (VS) Hold, and Indicated Airspeed (IAS) Hold. The Bendix M4 autopilot has fewer, but similar modes: Autopilot (AP), Altitude (ALT) Hold, and Pitch (PITCH) Command. An understanding of these basic modes and TCS are vital to understanding the autopilot selection possibilities and their significance in the accident scenarios as explained below:

The ALT Hold modes of the Sperry SPZ-500 or of the Bendix M4 Series will maintain the altitude at the time the mode is engaged. It maintains the altitude solely by the use of the longitudinal flight control (the elevator and its trim tab). Once the ALT Hold mode is engaged, any change in altitude is corrected by the autopilot trimming the elevator up or down. In a possible accident scenario as ice accretes on the wings, it creates drag that slows the airplane. The airplane would normally descend with this decrease in airspeed, as the tail has been trimmed to hold the wing at a given AOA. However, the autopilot senses this descent and trims the elevator to pull the nose up (nose up trim) to hold the original altitude. A new airspeed, lower than the original trim speed and at a higher AOA, is now maintained (equilibrium). As more ice is accumulated, this same procedure is repeated – the rate of deceleration is directly proportional to the drag increase due to ice accumulation. This is essentially true until the airspeed slows below V_y, (approximately 155 knots, decreasing 1 knot per 1,000 feet above 13,000 feet in the MU-2B, see the AFM Performance Chart, Figure V-2, in this appendix). At this point, the autopilot cannot reach a state of equilibrium (in airspeed and altitude) because more power is required to fly at a slower speed in this regime, and the autopilot cannot add more power. This undesirable situation is referred to as operating on the Backside of the Power Curve (see figure V-1 in appendix 3). Therefore, the rate of airspeed decrease is more rapid because the autopilot is now almost continuously trimming nose up (autopilot trims in increments) in a hopeless attempt to stop the airplane's descent.

The MU-2B trim system has sufficient authority to trim the aircraft into a stall. Artificial stall warning (stick shaker) in a clean configuration with no ice contamination occurs about 12° (dependent on gross weight and c.g.) nose up on the trim indicator. In all the accidents except Malad City, Idaho, (trim in neutral), where the trim motor was recovered, the trim servo was found to be from 12 to 30° nose up (30° is full nose up trim). If the autopilot is not disconnected at stall, the trim system will continue to trim until it stops at full nose up.

BEST RATE OF CLIMB - MAXIMUM CONTINUOUS POWER

ENGINE POWER:	MAXIMUM CONTINUOUS POWER (EGT = 650°C OR TORQUE 100%) (BLEED AIR IS ON BOTH)
ENGINE SPEED:	100% RPM
GEAR AND FLAPS:	UP
CLIMB SPEED:	BEST RATE OF CLIMB SPEED

EXAMPLE:

OAT	-8°C = ISA +15°C
PRESSURE ALTITUDE	19,000 FT.
WEIGHT	10,350 LBS.
RATE OF CLIMB	1,190 FT/MIN
CLIMB SPEED	147 KCAS

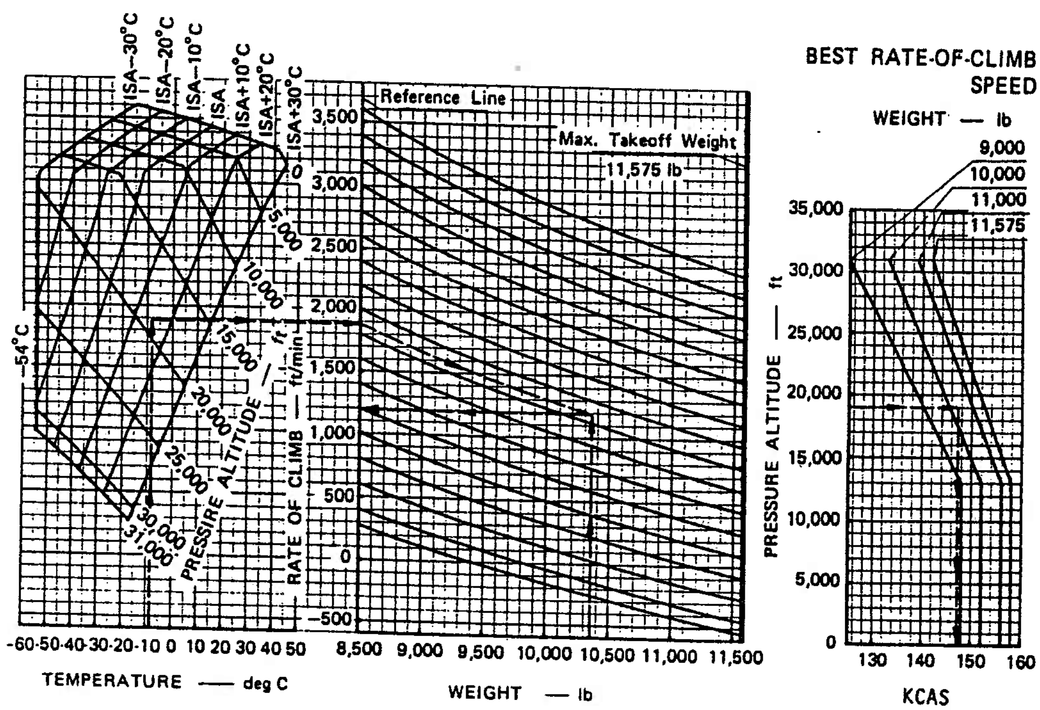

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Figure V-2, AFM Performance Chart

The VS Hold mode of the Sperry SPZ-500 can be used in the climb, but may not be the best choice, as this mode maintains the vertical speed at the time of VS mode engagement. The autopilot increases the pitch angle, or trims nose up, to maintain the climb rate when the rate tends to decrease, due to drag from ice accumulation, and power decreases due to altitude affects. Thus, if the ice causes a large increase in drag, the autopilot will trim nose up. The airplane may stall if power is not added or the vertical climb rate is not manually decreased. In SLD conditions, stall speed may be increased significantly and stall may occur before the pilot notices the seriousness of the situation.

The IAS Hold mode functions in a manner very similar to the VS Hold mode, except it maintains constant airspeed instead of constant climb rate. Thus, if the airplane tends to slow due to ice accumulation or engine power loss, the autopilot will trim nose down away from stall to maintain the airspeed. This mode is a desirable mode to use in a climb, as it leads away from attempting to hold a climb rate that is unachievable. However, if this mode is not monitored, it can trim the airplane into a descent. This mode was apparently not the mode of choice in the accident cases.

The TCS mode of the Sperry SPZ-500 and the AP/PITCH mode of the Bendix M4 Series differ from the foregoing modes. Both the TCS and the AP/PITCH modes maintain airplane attitude, pitch, and roll when the control switch is released with the autopilot engaged, but no vertical mode is engaged (ALT Hold, VS or IAS). Either of these modes can be used during climb to hold the climb attitude, but can be dangerous if the airplane is not monitored carefully when climbing in icing conditions. If the airplane is climbing in one of these modes and the pilot releases the control button at V_y, continuous deceleration may occur. Any accumulation of ice during the climb (and sometimes an almost transparent, rough coating of ice can form on the boot, and can be more adverse to drag and stall characteristics than large ice shapes) may cause a speed reduction at the same time power is being reduced due to altitude affects. Thus, if the pilot does not increase the power, or manually decrease the pitch attitude as the airspeed decreases, the autopilot will make an adjustment by the only method it has – a change in longitudinal trim. The autopilot will add nose up trim to compensate for the decrease in airspeed and, if the airplane is already trimmed at the V_y airspeed, the nose up trim will continue until the airplane stalls. Because of the absence of onboard flight data/voice recorders, the Team was unable to determine which AP modes were being used in the fatal accidents. But, the mode selected is critical because the autopilot has sufficient authority to quickly stall the airplane if airspeed and altitude are not closely monitored when flying in icing conditions.

Following a careful review of all available data, the Team concluded that the basic cause of the accidents was pilot unawareness of the criticality of the condition that exists just prior to departure from controlled flight. In some cases, the pilot knows that a hazardous condition exists, but is unwilling or unable to take the required action prior to departing controlled flight.

Listed below are possible reasons for unawareness of a critical situation:

Pilot is distracted from instrument scan and observing ice accumulation by:

- Radio communication with air traffic control.
- Conversing with passengers and/or copilot.
- Coping with an emergency situation or system malfunction.
- Filling out paperwork with no cross-check of instruments.
- Poor instrument scan training.
- Complete reliance on the autopilot with no cross-check.

Other reasons that may have contributed to the accident scenarios, some of which are listed below, were brought to light after reviewing all of the accident reports:

- Icing environments were different for each encounter, and the pilot believed that the airplane could handle the ice with no concern for ice beyond the system capability.

- Sideslip was present at stall, due to out of trim condition in flight controls and/or engine/propeller rigging.

- Pilot observed decreasing performance, but did not associate the loss with ice and became involved in attempting to troubleshoot the problem by focusing on engine power setting, engine power instruments, air data instruments, flight instruments, or automatic flight control system.

- Full aft stick stalls were not taught in airplane checkout, so the pilot was not familiar with a sideslip induced roll as the autopilot trims into stall.

- Pilot was not familiar with wing drop at stall, so he/she confused recovery technique, and used recovery from roll upset technique, which had no affect.

- Optimistic pilot thought conditions would improve in a short time, since it always had in the past.

- Optimistic pilot thought the airplane would handle the ice for a few more minutes until it would be time to start down to a lower altitude where the ice would melt or sublimate prior to landing.

- Optimistic pilot took off into forecasted ice with de-ice system inoperative thinking airplane would handle it as it had in the past, and a climb or descent was always possible if it got too bad.

- Pilot habit pattern was to reduce power first when starting a descent, and forgot that a large accumulation of ice could raise stall speed to the point that a reduction in power precipitates a stall.

- Pilot lacked training to allow correlation of airspeed decrease with ice accumulation on wing and tail surfaces to critical situation in a stall.

- Lack of training in the copilot (if a crew of two) to assist in decision making, and recognition of critical situation due to airspeed loss and stall speed increase.

- Lack of understanding of the concept of trimming into a stall, as airspeed decreases due to ice, stall will occur at an elevated airspeed.

- Pilot operated at airspeeds, knowingly or unknowingly, below the minimum airspeed for flight in icing conditions limitation (180 knots) in the AFM.

- Pilot operated at airspeeds below flap extension speed without lowering flaps.

- Lack of respect for icing conditions leads to belief that the airplane could handle any ice, so the pilot was not concerned with airspeed loss due to ice accumulation.

- Pilot had high expectations on mission completion due to financial, employment pressures, or personal reasons that clouds judgment.

- Pilot had macho image to maintain and would not turn back or exit icing conditions.

- Pilot got behind the airplane due to unfamiliarity with approach procedure, and/or the airplane systems and procedures.

- Pilot judgment impaired due to alcohol, or high anxiety, due to low fuel state during extended overwater ferry flight.

The above reasons were possible contributing causes for the accidents and, after much deliberation, it was not possible to arrive at a single mechanical remedy that would have prevented the accidents from occurring. However, the accidents may all have been prevented by proper training that is successful, in that complete understanding takes place, and is remembered when encountering the conditions that were covered in training. This means that effective training must take place and be reinforced biennially to assure proper pilot actions. The Team is therefore recommending a series of mechanical fixes, systems changes, AFM limitations, and a training program to correct the unsafe condition. A summary of the accident data has been compiled in a spread sheet for easy review and comparison in appendix 5, figure V-3.

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VI. Response

MITSUBISHI HEAVY INDUSTRIES, LTD.
NAGOYA AEROSPACE SYSTEMS WORKS
10, OYE-CHO, MINATO-KU
NAGOYA, 455 JAPAN

June 9, 1997

Mr. Michael Gallagher
Manager, Small Airplane Directorate
Federal Aviation Administration
ACE-111
601 E. 12th Street
Kansas City, MO 64106

Dear Mr. Gallagher,

MHI has received a copy of the" Final Report-Fact Finding Focused Special Certification Review of the Mitsubishi Heavy Industries MU-2B Series Airplane" from Mr. Ochi of the JCAB and he has advised us to submit our response directly to the FAA. We have now had the opportunity to review the report and we wish to provide you with this response for incorporation in Section VI.

MHI first wants to thank the FAA Team members for their professionalism and cooperation throughout this extensive and thorough review. MHI is in substantial agreement with the report, its recommendations, and its conclusions. While MHI substantially agrees with the report, there are a few statements that appear to be unsupported by the facts.

Based upon the conclusions reached by the FAA in its review of MU-2B accidents, it is clear that some pilots do not pay sufficient attention to their environment and do not follow recommended procedures when operating in icing conditions. While implementation of the report's recommendations should improve the pilot's awareness of the presence of potential icing conditions and should reduce the possibility of pilot error causing an accident, only the pilot's full appreciation of the hazards of in-flight icing and a cautious approach to operating in such conditions will assure safe operations.

As a general comment, MHI is concerned that readers of this report, may conclude that the recommendations and conclusions only apply to MU-2B airplanes and only when operating in supercooled large droplet(SLD) icing conditions. MHI understands that most of the recommendations and conclusions apply to virtually all airplanes that are certified for flight into known icing conditions and the FAA intends to determine the applicability of its recommendations to many other airplanes. It should also be emphasized that, although the MU-2B was found to have been properly certified and in full compliance with all applicable certification requirements, pilots should not interpret this report to constitute approval by the FAA or the manufacturer to indefinitely operate their airplanes in icing conditions, whether within or beyond the certification parameters. Icing conditions are potentially dangerous for all airplanes.

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In accordance with the charter of the FFFSCR Team set forth on page vii of the report MHI agrees with the following conclusions from the report.

(1) Original Icing Certification - That the MU-2B was certificated properly in full compliance with the applicable icing certification requirements (Section I.A);

(2) Characteristics in Appendix "C" Conditions - That all testing and analysis demonstrated that the MU-2B had acceptable handling and impingement characteristics in Appendix C conditions (Section I.B.);

(3) Characteristics in Freezing Drizzle Icing (SLD) Conditions - That flight tests confirmed that the MU-2B remained controllable for a sufficient time to safely exit even SLD conditions, beyond the certification requirements (Section I.C.);

(4) Determine if Above Could Contribute to an Accident Scenario - That for various reasons, unrelated to the design of the airplane, the basic cause of the accidents reviewed appears to be an unawareness by the pilot of the critical nature of the icing conditions (Section V);

(5) Corrective Actions - That requiring biennial pilot training to include icing awareness, anti/de-icing system operation, icing severity cues, and icing environment exit criteria will improve safety of operations when icing conditions are encountered (Section V). MHI further agrees that, although no service problems were discovered that require an AD as corrective action, certain de-ice system modifications could reduce the possibility that a de-ice system would fail in the future (Section III). In addition, the engine auto-relight, trim-in-motion and autopilot disconnect modifications, plus enforcement of the ice detector service bulletin by AD, should reduce the possibility of pilot inattention causing an accident.

With regard to areas investigated by the FFFSCR Team that were not specifically covered by the charter, MHI agrees that, in the tailplane stall evaluation, the MU-2B demonstrated no tendency to tailstall and no unsafe handling characteristics (Section I.D.). Similarly, there has been no adverse service history and the temperature survey showed no problem related to the engine exhaust on the tailplane (Section I.E.).

With regard to stall warning , MHI disagrees with the implication that the artificial stall warning (stick shaker) did not perform its intended function with SLD ice shapes applied to the aircraft (Section II). As with most airplanes of this type, the stick shaker is not expected to perform accurately in SLD conditions and the Airplane Flight Manual contains clear warning against relying on the stick shaker in icing conditions. Nevertheless, natural airframe buffet provided stall warning in tests conducted with ice shapes.

MHI agrees with the conclusion in Section V that all MU-2 accidents in icing conditions may have been prevented by proper training, if the pilots understood the training, remembered it when encountering such conditions and implemented it. A clear example of a preventable accident is the one that precipitated this FFFSCR which occurred on January 15, 1996 (Malad City) and resulted in the tragic and unnecessary loss of eight lives. At that time, the National Transportation Safety Board (NTSB) was still investigated the cause of the accident. On April 29, 1997, the NTSB released their probable cause determination for the Malad City mishap.

The NTSB determined that the probable cause of the accident was:

" continued flight by the flight crew into icing conditions with known faulty deice equipment; structural (airframe) ice; and failure of the flightcrew to maintain adequate airspeed, which resulted in the loss of aircraft control and collision with terrain.

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A factor relating to the accident was: the en route weather (icing) condition, which was not forecast (inaccurate forecast)."

MHI has worked closely with the FAA Team to meet the challenges presented regarding all aspects of this FFFSCR program. MHI believes that the FAA and the JCAB share our view that this was completely and satisfactorily accomplished. The MU-2B-60 was exposed to severe icing conditions as set forth by the FAA during the Icing Tanker flight tests. Subsequently, dry air simulated ice shape flight tests were conducted by FAA pilots. These flight test shapes were conservatively based on actual inflight ice buildup as observed during the Tanker SLD flights. Throughout the tests, the MU-2B proved that it remained controllable and prov ided ample time for the pilot to recognize and exit the SLD conditions. These flight tested conditions exceeded all documented cases of SLD encounters regarding Liquid Water Content and Median Volume Diameter and represented the most severe conditions believed to exist in the environment. We know of no other general aviation aircraft that has ever been exposed to icing flight test conditions that were this severe. In fact, the MU-2B was subjected to the same icing conditions, recreated by the U.S. Air Force Icing Tanker, which resulted in an uncommanded roll of the ATR-72 airplane during similar flight testing. The MU-2B flight control systems proved to be satisfactory in SLD conditions as did the anti/de-ice systems.

MHI shares the goal of the FAA and NTSB, to reduce the aircraft accident rate to zero. Unsafe operations in adverse flight conditions and improper maintenance/ operational practices combined with little or no recent training can produce a tragic "Malad City" type accident for any airplane. Until flightcrews dedicate themselves to professional flying and operational habits, there will continue to be some accidents that neither the FAA, NTSB nor aircraft manufacturers can prevent.

MHI will support the FAA's efforts to implement the recommendations in the report. Moreover, MHI is particularly interested in leaning the results of FAA, NASA and industry research and developments in the area of SLD icing conditions.

Thank you for your assistance and cooperation in this worthwhile endeavor.

Sincerely,

H. Kawachi

Hidekazu Kawachi
Deputy General Manager
Nagoya Aerospace Systems

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VII. List of Appendixes and Reports on File

These Appendixes are not contained in this report, but are maintained in the Small Airplane Directorate files. The appendixes are divided into two categories. The appendixes noted with a "P" designation contain information that has been determined to be manufacturer's proprietary data and, as such, is not releasable to the public. The appendixes without the "P" designation contain no proprietary information and are subject to release.

APPENDIX/BINDER

1P/1	MHI Results of MU-2B Evaluation in Icing Conditions
2P/2	MHI Initial Meeting Briefing Notes
3P/2	MHI Tulsa Baseline Configuration Flight Test Proposal and Test Cards
4P/2	MHI Test Proposal: MU-2B Simulated SLD Ice Test
5/2	MHI MU-2B-60 Airplane Flight Manual
6P/2	MHI AFFTC Icing Tanker Test Proposal and Test Cards
7P/2	Cloud Conditions During the MU-2B/USAF NKC-135 Icing Test, August 1996
8P/2	MHI Clinton-Sherman Artificial Ice Shapes Test Proposal and Test Cards
9P/2	MHI AES 9680 Simulated Ice Shape Tests
10P/2	MHI Horizontal Tail Temperature Survey
11P/3	MHI Review of MU-2 Accidents
12P/4	MHI MU-2 Systems Review 97 Program
13P/5	Cloud Conditions During Natural Icing Tests of the MU-2B-40 and MU-2B-60 Aircraft, February 24, 1993
14P/5	BFGoodrich Aerospace Letter with Report 75-223-011A Icing Impingement Analysis for the Mitsubishi Model MU-2 Series, Report No. 75-23-011A, July 23, 1975
15P/5	Addendum A to the Airworthiness Group Chairman's Factual Report De-icer Boot Timer Component Examination, June 25, 1996
16P/5	MHI MU-2B -25 -26, -35 -36 Ice Protection System Report MR0144, Revision A, 2-23-76
17P/5	MHI Icing Flight Test Report MR0149, Revision A, 2-23-76
18P/5	MHI Letters on Propeller De-icer Certification for MU-2B-26 and -36 Four Bladed Propellers
19P/5	AlliedSignal Operating Information Letter on TPE 331 Turboprop Engine
20P/5	AlliedSignal Service Bulletin on P_2T_2 Sensor Freeze-up
21P/5	MHI Service Bulletin on Ice Detector System Installation
22P/5	Hartzell Propeller Inc. Performance Map for MU-2B Propeller.

23P/5	BFGoodrich Report, Survey of Ice Accretions Formed in Freezing Drizzle Under Natural Icing Simulated Icing Behind the USAF Tanker and in NASA-Lewis Icing Research Tunnel
24/5	Controllability Evaluation Process - Lateral Control (Jim Ashley's Slides)
25/5	Copy of the 1984 FAA SCR Report on the MU-2B
26/6	NTSB Accident Reports on MU-2B (with ice present or forecast, available from NTSB)
27/7	NTSB Accident Reports on MU-2B (with ice present or forecast, available from NTSB)
28/10	FSDO Ramp Inspection Reports
29/10	Type Certificate Data Sheets (MU-2B TCDS for A10SW and A2PC)
30P/5	Engine Teardown Report (Malad City Accident)
31P/5	Garrett Turbine Wheel Analysis (Malad City Accident)
32P/5	Garrett Overspeed Analysis (Malad City Accident)
33P/5	Garrett Engine Re-light Analysis
34P/5	Manufacturer's Service Bulletins
35P/5	Hartzell Propeller Teardown Report (Malad City Accident)

MU-2B Accident Data Date	A/C	S/N	Location	Accident Profile	Weather	ElevtrTrim	AutoPilot	Pilot Qual.	*MU2 Hrs	#TOT Hrs	Other Info	Fatalities	Day/Night
1/15/96 N693PA	36A Lg	693	Malad City, ID. (RADAR data)	Emergency declared at FL 16, decel f/b rapid dscnt	Severe icing reported S	Neutral L	Bendix M4-D	Former Mrktg Exp. at MHI	H	H	Suspect A/C had Inop. de-ice Engines OK	8	N
4/6/93 N96JP	-35 Shrt	556	Casper WY	Fast Approach	Icing Cond. Possibly L	Nose up A 15 deg.	Bendix M4-D	12,360 hrs Tot. 205 hrs MU-2	L	H	Air Ambulence, Pilot Fatigue	8	N 0435
1/22/93 407MA	-60 Lg	1503 SA	Beucherling GR (RADAR data)	Gear stuck down, climb to FL 17, cruise, spins	Icing Mod to severe ICT S	Nose up L 28 deg.	SPZ-500 Sperry/HW	1120 Ttl Time 65hrs MU-2	L	M	Nose gear stuck down, scissors left dis-connected, departed ~ 150knts	1	N 2000
2/14/90 N300CW	-60 Lg	795	Putnam, TX. (RADAR data)	A/C slows and accelerates slows in icing conditions.	Severe icing reported S	Nose up L 17 deg.	SPZ-500 Sperry/HW	Simulator & Flight Safety	L	H	45 deg. descent, R wing first impact pilot asked for descent. (R. Eng. Inop)	5	0753 Dawn
1/25/90 VH-MUA	-60 Lg	746	Meekatharra Australia	Cruise @ 21, turn, stalls, left spin 90-95 deg.ND	Rime, Glaze ice reported M	Nose Up C 17 deg.	Bendix M4-D	First Solo Flt 51.7 hrs MU-2	L	H	Overweight T.O., speed chges FL15 engs ok, radio'd lost cntrl, no yaw chnl	1	N 0105 AM
1/2/89 N500V	-26 Shrt	3795A	Mansfield, OH	Dive> 30deg. 12' into ground NAV reception prob. on ILS	Light frzg L drizzle & snow	Nose up A 10 dg. (20/GD)	Bendix M4-D	2860 hrs MU-2 (Instr. 8800)	H	H	3 mi/ SE of LOM, AP AD not complied grnd schl at Howell Entr., Med Prblm	4	D 1505
12/16/88 VH-BBA	-60 Lg	782 SA	Leonora Australia	Pilot lost control flying over storm, exited clouds, Lft spin	Big storm S ISA +15 deg.C	Nose up C 13.4 deg.	SPZ-500 Sperry/HW	No Training 134 hrs MU-2	L	H	Climb to FL 210 in big clouds, engines OK, 40 to 50 deg. ND impact.	10	D 1015
12/9/88 N296MA	-35 Lg	592	Coral Sea Australia	A/C disappeared on ferry flight during thunderstorm.	Tndr strm S act. on route	UNK. C No Wreckage	Bendix M4-C	No Training 1000 hrs MU-2	M	H	Descent FL190 to FL120 to de-ice clmbd FL20, Mayday, unctrld descnt	1	N 2221
4/16/88 F-GERA	36A Lg	701 SA	ST. Eteine France	Scant experience, high blood alcohol content	Pilot reprts M icing in area	Nose up C	Bendix M4-D	13 hrs, 40 min. Time in MU-2	L	?	Witness out of control, A/C departs decel. in 16,000 from climb.	6	D
3/5/86 N513DC	-60 Lg	1513 SA	Eola, IL. Air Hi Ho	Low altitude spin on ILS approach at 4000 ft. Hit level	Rime ice & M moderate turb.	Nose up A 12 dg.(17 MHI)	SPZ-500 Sperry	Low Tim e 180hrs MU-2	L	H	Mayday, reported spin, decel 181 knts to 123 kts in 1.3 min. impct 10 deg. ND	5	D 1706
3/24/83 N72B	-60 Lg	735	Jeffersonville GA.	Lost contrl for unkn reason exceeded load limit of A/C	Lt rain, 5 mi. L Vis. 2000 Clng	Nose Up L	Bendix M4-D	Crt. 7/82 Recrmt 12/82	M	H	Last report @ FL180, inflt breakup 547 hrs in MU-2 (Bad Habit Patterns)	4	N 0236 AM
9/6/81 N3ED	-10 Shrt	101	Riverton, WY. (RADAR data)	Dive near vertical high speed 80 deg ND, boots bad	Frez. rain S mod. ice FCT	Nose up C Full (MHI?)	Bendix M4-C	15hrs MU-2 1500 hrs TOT.	L	M	4 descrep. in de-ice sys. lost at FL140 clmbg to FL170, Nervous Pilot at RF	5	D 0900 AM
9/2/81 N273MA	-25 Shrt	251	McLoed, TX.	Spin right (obsrvd) decel from 198 knts to 145 knts in 4.5 min.	Modrte Ice S Twr Cum Clds	Nose up	Bendix M4-C	155 hrs MU-2 FSI no IFR	L	H	Clrd to clmb 210 to 230, A/C slowed to 126knts frm 198knts, trainning w/FSI	5	D 1645
12/6/80 N969MA	-40 Shrt	408 SA	Ramsey, MINN.	Spin obs near vert. R spiral/ spin, frez. rain FCST	Icing reprtd by other A/C L	Neutral	Bendix M4-D	875hrs MU-2 4949 Total.	M	H	On VOR apprch, engines, OK 140knts at 3000ft 121 knts grnd spd.	5	D 1617

*MU-2 Pilot Hrs - L=Low<300,M=Medium>300<1000, H=High>1000
Pilots Total Time Hrs - L=<1000, M=>1000<3000, H>3000
Accident Summary: 7 day, 5 night, 1 Dawn; Auto pilots: 10 Bendix, 4 SPZ-500; Trim: 11 noseup, 2 neutral, 1 unk.
Wx: 7 Severe, 3 Moderate, 4 Light; Relatively Low Time Pilots:
MU-2B Time - 7 Low Time,5 Med. Time, 2 High Time

Total Number of MU-2 A/C - 703 Produced, 478 active (+ 50 JDA Operates)
Long Body - US Reg (9 accidents) 220
Short Body - US Reg (5 accidents) 222
Total Time - No Low Time, 2 Med. Time,11 High Time (+1Unk.)
5 Accident In Climbs, 4 On Approach, 5 In Cruise, all in IFR conditions

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