MISHAP INVESTIGATION REPORT 01-07

1. **THIS IS THE FINAL INVESTIGATION REPORT OF AN INCIDENT (WITH POTENTIAL).**

2. **SUBJECT: MULTIPLE ENGINE FAILURES DUE TO SALT INGESTION AT LOW ALTITUDE OVER NORTH ATLANTIC AT NIGHT**

3. **EQUIPMENT:**
   a. Aircraft: Lockheed WP-3D
   b. Registration: N42RF

4. **PILOT-IN-COMMAND:**
   LCDR, Airline Transport Pilot, FAA Class I medical; total hours 3500.9; model hours 2909.5; within last 30 days 53.2 hours; 60 days 54.8 hours; 90 days 62.3 hours.

5. **ENVIRONMENT OF MISHAP:**
   a. Date: 9 February, 2007
   b. Time: 2020 Z
   c. Location: 540 miles east of St John’s Newfoundland
   d. Radar (absolute) Altitude: 2725 feet AGL
   e. Weather:
      Wind direction and speed: approximately 250 at 85-95 knots
      Visibility: event occurred at night in low pressure storm environment
      Ceiling: N/A
      Temperature: at or below freezing (-3 to -1.5 deg C)
      Dew Point: -5 deg C
      Pressure at flight level: 880 millibars

6. **CIRCUMSTANCES:**
   a. Origin of aircraft: St John’s Newfoundland, CYYT
   b. Mission: Ocean Winds data collection (task code PND)
   c. Destination: St John’s Newfoundland, CYYT
   d. Damage: No actual physical damage occurred

7. **PILOT-AT-CONTROLS:**
   LCDR, Airline Transport Pilot, FAA Class I medical; total hours 3500.9; model hours 2909.5; within last 30 days 53.2 hours; 60 days 54.8 hours; 90 days 62.3 hours.
   PILOT-NOT-AT-CONTROLS:

LCDR, NOAA WP-3D designated co-pilot, FAA Class II medical; total hours 1950; model hours 660; within last 30 days 53.2 hours; 60 days 57.7 hours; 90 days 62.3 hours.

FLIGHT ENGINEER:

Civ, NOAA WP-3D designated flight engineer, FAA Class II medical; total hours 6978; model hours 6978; within last 30 days 27.6 hours; 60 days 30.9 hours; 90 days 32.8 hours.

8. IF VEHICULAR MISHAP: (Not Applicable)

9. AOC MISHAP BOARD:

CAPT Ed McNerney, PHS – Safety Department Head AOC

CDR Tom Strong, NOAA – Chief Operations Division; P-3 Aircraft Commander

Mark Sweeney LCDR 13Aug07

LCDR Mark Sweeney, NOAA – Operations/Aviation Safety Officer; graduate of Naval Aviation Safety School

Albert M. Girimonte LCDR NOAA 13AUG2007

LCDR Al Girimonte, NOAA – Training Officer; P-3 Aircraft Commander

13 Aug 2007

Jim Roles – Science and Engineering Division; Electronics Engineer

Dewie K Floyd 13 AUG, 2007

Dewie Floyd – Flight Engineer; Maintenance Branch

Marty Mayeaux – Flight Director/Meteorologist

Richard J. McNamara

Richard McNamara – Science and Engineering Division; Electronics Engineer

A. Barry Damiano 8/13/07

Barry Damiano – Flight Director/Meteorologist

10. SUMMARY OF EVIDENCE

During January and February of 2007, N42RF, one of NOAA's WP-3D research aircraft, was assigned to support the Ocean Winds Winter Experiment based in St. John's, Newfoundland. The project is intended to calibrate satellite readings of surface or near surface wind speeds with aircraft mounted sensors in remote regions of the North

Atlantic. On February 9, N42RF was scheduled to launch at 1500 local (1830Z) from St. John's to investigate a low pressure system located approximately 450 to 500 nautical miles east of St. John's.

The previous night's flight had been completed by 2200 local and the crew was well rested and nourished when they arrived at the airport for preflight at 1200 local (1530Z) on the 9th. The preflight brief contained nothing unusual for the missions they had been conducting, though the crew noted that the system appeared to contain less moisture than they had seen on previous missions. The flight was scheduled for 7 hours with the potential to extend to 8 hours and fuel sufficient for an 8 hour flight was loaded. No discrepancies were noted with the aircraft and deicing was not required prior to flight. Weather forecast for scheduled time of return to St. John's was good.

Takeoff occurred 7 minutes early at 1453 local (1823Z). Engine efficiencies were not specifically tested prior to flight, but all engines reached shaft horsepower (SHP) of 4600 at 80 knots with lower than forecast Turbine Inlet Temperature (TIT) of 998 degrees C, indicating that they were all operating at a minimum of 100% efficiency. No degradation in performance of engines had been noted during any of the previous flights of this project. (It may be noted that P-3 engine efficiencies often test at greater than 100%, so it is possible to have an engine drop in performance yet still indicate 100% efficiency on takeoff.) The departure was flown under VMC conditions at 3000 feet. The majority of the transit to the operations area was conducted at 3000 feet. Approximately 40 minutes into the flight, the crew turned on engine anti-ice due to low outside air temperature (~-10 deg C), periodic clouds, and oncoming darkness. Darkness inhibited the ability to determine levels of atmospheric moisture so the crew left engine anti-ice on until well into their transit home. Despite largely VMC conditions, a moderate chop (turbulence) was experienced for the majority of the flight.

Approximately an hour into the flight, the crew observed that the windshield was excessively dirty with a white film and attempted to clean it with the windshield washer system. The effort was unsuccessful due to the inoperability of the windshield washer pump. The crew described the substance as looking "like snowflakes, but not melting." The Flight Engineer reached up to feel the windshield and confirm that the windshield heat was working, which in fact it was. At 1953Z the crew descended to 2500 ft to calibrate the scientific gear with a "roll maneuver" which lasted for 30 minutes and involved slipping the aircraft. For the next few hours the flight progressed normally. The crew did not observe any degradation in performance of the engines or problems with the operation of the aircraft. Flight station crew confirmed that, qualitatively, the engines were performing normally. Gradual reductions in power were required to maintain a set airspeed as aircraft weight decreased. All members of the crew did note that there was much less liquid precipitation during this flight than there had been on previous flights. That is to say, they were not flying through as much rain as they normally did. Additionally, the winds noted during this flight were of exceptionally high speed. Most wind readings were in the range of 85 to 95 knots in the onstation area.

At 2204Z the aircraft made a left turn from a heading of 205 to 013 and shortly thereafter released the last dropsonde of the mission. The winds at this time were at 260-270 degrees at 90-95 knots. At 2212Z the aircraft made a heading correction to 002 for winds to fly a ground track of 022. The mission was essentially over at this time and the crew was collecting the data from the last dropsonde. The aircraft was flying at 3000 feet, 210 knots with approximately 1700-1800 SHP set on each engine. Moments later, aft crew members' attention was drawn by flashes of light outside the starboard windows and they observed flames coming from the #3 engine tailpipe accompanied by audible "popping." Crew members immediately notified the flight station by declaring "fire on #3, flames, flames, flames" over the ICS. Simultaneously, the Copilot (CP) and Flight Engineer (FE) observed the illumination of the #3 Turbine Inlet Temperature (TIT) over temperature warning light, an indication of 1110 TIT, and SHP dropping rapidly on the #3 engine with no fire warning light or horn. The flight station crew also confirms hearing "popping" sounds. The aircraft commander (AC) directed the FE, "E-handle #3, HRD discharge, emergency shutdown checklist." (Note: the P-3 NATOPS operating manual dictates, "Execute the Emergency Shutdown Procedure when advisable and when any of the following occurs:…2. excessive or uncontrollable power loss;…5. TIT increases and cannot be controlled;…7. actuation of the fire warning system." Although the engine fire warning system was not activated, there was a confirmed fire reported by the crew.) The AC advanced power slightly on engines 1, 2, and 4 to approximately 2500 SHP. The CP began to read the emergency shutdown checklist but had not completed it when the aft crew members observed flames coming from the tailpipe of the #4 engine and announced "fire on #4". The flight station crew saw the #4 engine TIT over temperature light illuminated, TIT indicating 1175 degrees C, SHP dropping rapidly, but again no fire warning light or horn. Specific readings of SHP, RPM, or fuel flow were not noted. At 2221Z, the AC directed the FE, "E-handle #4, HRD discharge, emergency shutdown checklist." The CP began to very carefully and methodically read the emergency shutdown checklist declaring, "This is for #3 and #4 now." The AC advanced power cautiously on the #1 and #2 engines and after turning to a westerly heading attempted to climb maintaining 200 knots or more. With the loss of the #4 engine, scientific power was automatically shed and data recording was terminated. Emergency shutdown checklists were completed for #3 and #4 engines, oil tank shutoff valve circuit breakers were set, the auxiliary power unit (APU) was started, and the boost handles were uncovered. The AC gradually advanced the power levers as far as approximately 3000 SHP on #1 and #2 while climbing to 3200 feet and observed that the airspeed had dropped to 180 knots. Uncomfortable with the possibility of inducing a fire warning on #1 or #2 through high angle of attack, low airspeed, and high power setting, the AC leveled the plane to regain airspeed but was unable to maintain 200 knots at 3200 feet. The AC began a descent back to 3000 feet and subsequently 2800, then 2600 feet in an attempt to maintain 200 knots indicated airspeed. The AC ultimately stabilized the aircraft at 2600 feet and 200 knots with approximately 1000 degrees TIT on the #1 and #2 engines. The CP announced to the crew that the #3 and #4 engines had been shutdown and directed the crew to review their ditching placards. The CP also directed the off duty navigator to contact Gander radio on the satellite phone to inform the ground station of their emergency.

Approximately 3 to 5 minutes after stabilization from the shutdown of the #4 engine, the aft crew observed flames from the tailpipe of the #1 engine and announced to the flight station, “fire on #1.” Again, simultaneously, the AC and FE noted a power loss and TIT over temperature on the #1 engine, also with no fire warning system activation. The AC directed the FE to pull back power on the #1 engine in an attempt to extinguish the flames without shutting down the engine. The FE retarded the #1 power lever to approximately the flight start position. The drop in SHP continued as did the flames from the tailpipe. Watching the engine RPM drop below 70% and believing he heard a direction to shut down #1, the FE pulled the Emergency shutdown handle for the #1 engine. Roughly 10-15 seconds passed between the initial indications of failure of the #1 engine and the time the E-handle was pulled. The HRD was not discharged for #1 and the emergency shutdown checklist was not executed. The aircraft began a descent at about 700 feet per minute, unable to hold altitude on the power of one engine. The CP directed the navigator to broadcast an emergency message to Gander via the HF radio and instructed the crew to don their anti-exposure suits. Failing other options, the AC called for an immediate restart of the #1 engine. The CP opened the checklist but was delayed for a moment looking for the appropriate section of the page. AC directed the FE to skip the checklist and start the #1 engine immediately. The AC also instructed the CP to lower the flaps to the “maneuver” setting and CP complied. The FE pushed in the #1 E-handle, noted a residual TIT of 458 and, after wind milling the engine to bring the TIT within limits, successfully restarted the engine. During the descent and restart of the #1 engine, the aircraft briefly (less than 60 seconds) passed through an area of liquid precipitation. The aircraft reached a minimum altitude and airspeed of 800 feet and 140 knots prior to beginning a slow climb on two engines. Following the successful restart of #1, the AC directed the FE to restart #3. The initial attempt to unfeather the #3 engine resulted in neither blade angle decrease nor rotation of the propeller. The FE then attempted to restart #4 also resulting in no blade angle or rotation. The FE and AC noted that the E-handles for #3 and #4 engines were still out and the FE reset both handles. Subsequent attempts to restart were successful on both engines. The flight station crew very gingerly advanced the power levers on #3 and #4 engines to approximately 1700 SHP at 710 TIT and began a climb in earnest. At 180 knots and climbing, the AC directed the retraction of the flaps, securing of the APU, and covering of the boost handles. The CP informed the crew that all engines were back on line but that there was no explanation for the failures.

The aircraft climbed to an altitude of 14,000 feet for the transit home with a power setting of 2500 SHP and 810 TIT. The flight station crew began a careful in depth discussion of what happened. The FE shined his flashlight on the windscreen and observed that it was extremely dirty, to the point of obscuring vision. Flight station crew discussed the potential for another loss of engines and steps to be taken in that event. The crew repeatedly called for updated weather in both St John’s and Gander. Flight station discussions focused on concerns that advancing of power levers for a weather induced missed approach could cause a low altitude failure of multiple engines. Fuel quantity was not an issue and flight station crew agreed that if weather at their time of arrival in St John’s would be marginal, the better choice would be to continue to Gander. Weather in St John’s was predicted to be above 2000 ft broken, but had a 40% probability line of low ceilings and marginal visibility. As the flight proceeded, the navigator continued to update ATC on their status and position, and ATC provided headings to oil platforms, primarily Hibernia, in case a ditch became necessary. Crew elected to pull oil tank shutoff valve circuit breakers on #3 and #4 engines, which had been set on emergency shutdown due to perceived engine fires. During contingency discussions while enroute, the crew grouped and dealt with engines #1 and #2 separately from #3 and #4, due to availability of fire extinguishing system for #1 and #2 and lack thereof for #3 and #4.

The aircrew calculated the landing ground roll distance and planned to land using little or no reverse thrust to prevent the likelihood of engine loss upon reversal. At about 55 DME from St. John's, Gander cleared NOAA42 for descent at pilot's discretion. Desiring as stabilized an approach as absolutely possible, the crew began a descent from 14,000 feet at 43 DME from St. John's using guidance from the navigator's extended ILS glideslope through the GPS. Of note, the landing lights created a glare in the salt encrusted windshield and were turned off at the direction of the AC. The AC stayed on instruments on the ILS until approximately 500 feet above ground level and asked the CP to call airspeeds for him as he slowed. The aircraft touched down at 121 knots approximately 1200 feet from the approach end of the 8500' runway, and, using minimal reverse and brakes, stopped without difficulty with roughly 4000 feet remaining.

The aircraft landed at 0043Z (2113 local time). The 0100Z (2130 local time) airport observation was 15 statute miles visibility; few clouds at 2400 feet; wind direction was 230 at 8 knots and altimeter was 29.46.

The AC carefully taxied the aircraft back to parking using extreme caution and all observers available due to the very limited visibility through the windshield. The AC did use reverse thrust to back the aircraft into the parking spot. All engines ran smoothly during use of reverse thrust and did not show any signs of impending failure during backing operations. The crew secured the engines normally and exited the aircraft.

Postflight inspection of engines revealed significant white build up on intakes, first stage compressors, and CIP probes of all four engines. Subjectively, the #2 engine appeared to be the worst coated of all engines. Aircraft fuselage and windows were also heavily coated. Engine covers were installed and engines left as found.

View of #2 engine intake from 10 February, 2007. Note white buildup not only on walls of intake, but also on 1st stage compressor stator and rotor blades.

11. ANALYSIS

Beyond a brief initial visual inspection of the engine intakes and fuselage, no attempt was made to troubleshoot or correct for the engine failures after landing on the night of the 9th. The following morning, engine efficiency runs were conducted on all four engines and the results were as follows:

#1 Engine = 87.0%
#2 Engine = 88.9%
#3 Engine = 90.3%
#4 Engine = 91.3%

This represents a significant drop in efficiencies from the norm for these engines and would produce power well below abort criteria for any takeoff attempt. The engines were not washed initially as the investigation team wanted the technical representatives from Rolls-Royce to have an opportunity to see them as they were. Unfortunately, tech reps would not arrive until Thursday morning February 15th and the decision was made, with the approval of the tech reps over the phone, to rinse the engines on Wednesday to prevent permanent corrosion damage. Engines were rinsed according to Rolls-Royce instructions on Wednesday and efficiency runs were conducted again. The results of the post rinse efficiency runs follow:

#1 Engine = 102.1%
#2 Engine = 104.9%
#3 Engine = 101.7%
#4 Engine = 103.1%

This information will be referred to below in the discussion of those factors which are or are not considered causal in this incident.

Fuel samples were drawn from the fuel strainers and tanks of all four engines as well as from the fuel supply truck and source in St. John’s. The samples showed no water content from any source and only very minor particulate from the fuel strainers. Subsequent disassembly of the fuel strainers after return to MacDill AFB also revealed no abnormal contaminants in the fuel. **Fuel contamination is not considered a causal factor in this incident.**

Crew qualifications, medical certifications, and currency were all up to date for each member of the flight crew. Additionally, the AC is a very experienced instructor pilot in the P-3 aircraft. The crew was well rested from the previous flight and had adequate opportunity to eat and plan their day for the subject flight. There is no evidence to suggest that any member of the crew used the available time for other than rest, nourishment, and preparation for the flight. **Crew qualification and or fatigue are not considered causal factors in this incident.**

Once restarted, the engines all ran smoothly during the entire remainder of the incident flight, despite the crew’s valid concerns that they may not. Engine efficiencies were remarkably low during the initial ground check, but returned to normal values after only a fresh water rinse. Subsequent operation of all engines both on the ground and during the flight back to home base revealed no mechanical problems with any engine. The aircraft has flown since the incident and has completed a routine 150 hour inspection. No physical mechanical problems have been noted on any engine. **Mechanical failure of any internal engine part for one or more of the engines in question is not considered a causal factor in this incident.**

In initial conversations with the Rolls-Royce technical representatives they expressed significant surprise and even disbelief that salt alone, even in quantity, would be likely to cause a compressor stall or surge resulting in complete engine failure. They noted that they had never seen salt accretion cause an engine failure before, but that there was a body of evidence of materials like volcanic ash choking engines. Samples of the white substance removed from the intake of the number 3 engine were submitted to the Rolls-Royce chemical laboratory for analysis. X-ray energy dispersive analysis indicated the white substance was salt (NaCl) with no other material in any appreciable quantity. NOAA’s Volcanic Ash Advisory Center listed no VAAs for the Montreal sector over the preceding month. **Volcanic ash is not considered a causal factor in this incident.**

Engine anti-ice was turned on about 40 minutes into the flight and remained on until well after all engines were restarted and the crew was transiting back to St. John's. All evidence indicates that there was no malfunction with the engine anti-ice system and that the system was operating properly. **Icing is not considered a causal factor in this incident.**

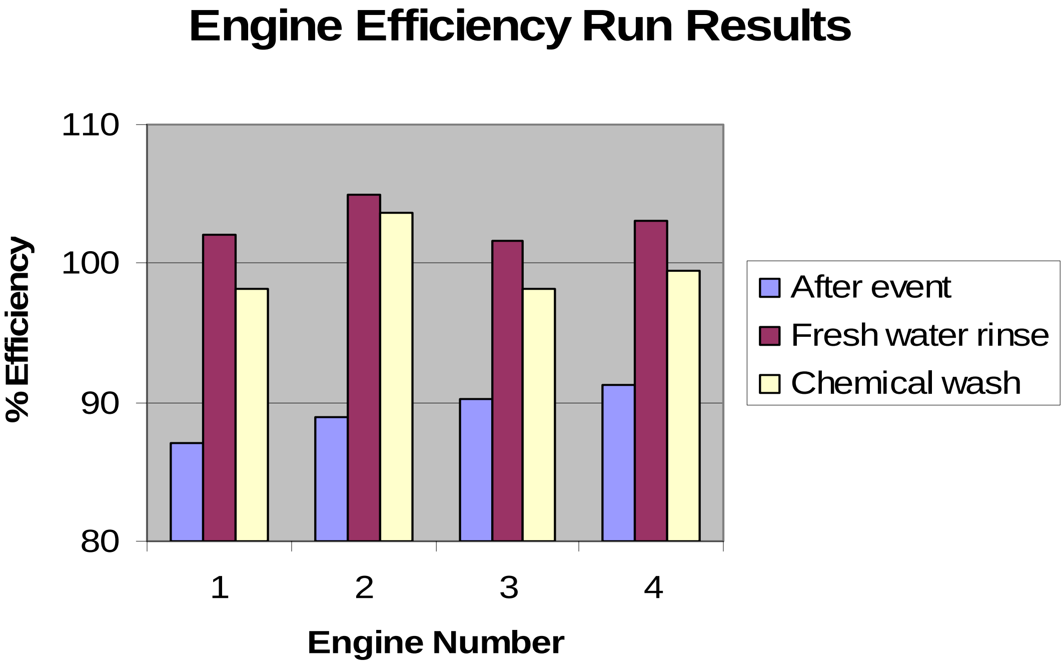
The final report from Rolls-Royce offers, as a summary, the following points:

- The degradation of the number 1, 3, and 4 engine compressor efficiencies and subsequent unscheduled engine rundowns were caused by the accretion of sea air salt on the compressor stator and rotor blades. The accretion caused deformation of the compressor airflow resulting in compressor efficiency degradation until an unscheduled engine rundown event occurred.
- No other aircraft or engine mechanical findings were found which may have contributed to the in-flight unscheduled engine rundowns.
- It is not known at what percent of degraded compressor efficiency the unscheduled rundowns finally occurred.
- It is also not known how much efficiency was recovered from the in-flight water ingestion which allowed the engines to restart in-flight and operate within apparent normal parameters.
- The number 2 engine prior performance runs indicate that the engine to be at 103.5% efficiency. As this engine was the strongest performing engine of the four, it is highly probable that this is the reason the number 2 engine did not progress to an unscheduled run down condition during flight.
- The moderate to severe accretion of sea air salt on the compressor stator and rotor blades without the presence of liquid precipitation (rain) in hurricane force winds can occur at flight levels above 1200 feet. Careful consideration and mission planning should address the salt ingestion phenomena.

After its return from St. John's, N42RF was taken to Jacksonville, FL for a chemical wash of the engines. Following the wash, the efficiencies were again tested with the following results:

#1 Engine = 98.2%
#2 Engine = 103.6%
#3 Engine = 98.2%
#4 Engine = 99.4%

These are slightly lower than they were in St. John's after the fresh water rinse but the difference can be attributed to the temperature and density difference between Jacksonville and St. John's. The various engine efficiency runs are depicted graphically below.



Given the lack of other substances in the material removed from the #3 engine intake, along with the return of efficiency after washing, and the elimination of the other factors considered above, **salt accretion on the compressor stator and rotor vanes of the engines during the incident flight is considered a causal factor in this incident.**

A significant concern and question of this investigation is whether the accrual of sufficient quantities of salt to cause compressor surges and engine failures occurred solely during the subject flight, or whether a gradual buildup occurred over several flights resulting in a final failure of the engine during this flight. Engine efficiency tests are not normally conducted unless there is a reason to believe that the efficiency has been compromised. On every takeoff in this environment, the TIT required to produce 4600 SHP is predicted prior to applying power on the takeoff roll. If the predicted TIT is set and less than 4600 SHP is produced, then the efficiency of the engine is suspect. If the power is less than 95% of the predicted 4600 SHP, the takeoff is aborted and the efficiency of the engine is directly tested on the ground. On each of the flights during this project, including the incident flight, 4600 SHP was reached at a lower TIT than predicted, indicating that the engines were at a minimum of “100%” efficiency. This does not suggest that the build up of salt took place over several flights. However, previous investigations by Rolls-Royce suggest that a significant percentage (66% or more) of the surge margin is provided by the 1st through 3rd stages of the compressor. A comparatively much smaller percent is provided by the 6th through 14th stages and roughly 0% of the surge margin is provided by the 4th and 5th stages of the compressor. Surge margin is a measure of the blanket of protection between compressor stall, where flow through the compressor essentially stops momentarily, and compressor surge, where flow through the compressor actually reverses direction and air moves forward through the engine rather than aft as it should. The implication of this is that the later stages of the compressor could be fouled without a noticeable loss of performance but with a decrease in surge margin. In this case the loss of efficiency would not become noticeable until the ability of the first three stages to compress and supply air to the combustion section was compromised. At that point, when the airflow through the 1st through 3rd stages becomes unstable, the compressor sees a catastrophic decline in its ability to process air rather than a gradual decrease in efficiency. This is true in theory, but is not carefully tested or proven at this point. Over the previous several flights, it is possible that some accretion of salt was occurring but that it never reached a level sufficient to cause a problem because it was periodically rinsed by liquid precipitation. This is good for the first few stages of the compressor, but not necessarily so for the later stages. As air passes through the compressor it is heated dramatically. By the time it passes about the 6th stage, any water which may have rinsed off the initial stage rotors and stators is raised to boiling and deposits the material it brought with it on the later stages of the compressor. Visual inspections of the intakes prior to each flight indicate that there was no noticeable salt build up on the initial stage of any of the compressors, but visual inspection is not conducted on later stages of the compressors during preflight. We have no clear evidence of how much salt may have been on the later stages of the compressors, but it seems very possible that some build up was present prior to the incident flight and that this build up could have contributed to the severity of the compressor stalls/surges experienced. **Salt accretion on later stage compressor rotor and stator vanes of the engines from previous flights is considered a possible causal factor in this incident.**

Literally millions of hours of flight time have been logged with jet turbine engines at relatively low altitudes over ocean environments by a myriad of operators during the last several decades. This investigation sought the aid of many outside sources in researching archives for similar incidents. Among others, the US Naval Safety Center, National Transportation Safety Board, Canadian Transport Safety, Canadian Military Directorate of Safety, US Coast Guard, US Air Force 53rd Weather Reconnaissance Squadron, National Center for Atmospheric Research, and Cougar (a helicopter outfit servicing offshore oil rigs from St. John’s) were consulted to find out if any of them had seen incidents of salt accretion fouling turbine engines of fixed wing aircraft. Not one case was provided by any of these agencies. The Navy did provide several cases of helicopters experiencing power losses and engine failures due to salt accretion. Many of the helicopter cases involved slow flight at very low altitudes over salt water. Though countless hours have been flown at low altitudes over the ocean it is unlikely that many of those hours were actually flown in the environment in which our incident flight was conducted. NOAA routinely dispatches aircraft into meteorological environments that most pilots are trained to avoid. We are in the business of exploring conditions that are outside the normal spectrum. A preliminary review of the flight-level scientific data indicates that the relative humidity on the incident flight ranged from 75% to 85%, similar to what had been observed on previous flights, but the crew all agree that there was significantly less precipitation than on previous flights. The air temperature on previous flights ranged from -10 degrees Celsius up to sometimes as much as 15 degrees C. On this flight, the temperature never climbed above about 1 degree C. Further discussion of the meteorological details will follow in a later section of this report, but suffice to say, **the meteorological environment of the incident flight is considered a causal factor in this incident.**

The incident flight and the previous flights of the ocean winds project were flown largely during hours of darkness. While the all details of the meteorological conditions which led to an environment excessively high in sea-salt aerosol are not yet understood, it is not likely that day or night played a major roll (outside of its effect on temperature). Night time operations do, however, play a significant roll in the crew's ability to identify and diagnose a salt accretion problem, especially if they do not know to be looking for one. The crew did notice a minimal build up of material on the windshield earlier in the flight, but as darkness set in and the crew's scan shifted inside the cockpit, they did not see the increase in the quantity of salt buildup until after the engine failures. By the time they were returning to St. John's the salt accretion on the windshield was severe enough that they had to turn off the landing lights because of the glare. Had this flight occurred during daylight hours, it is very possible that the crew would have observed such a salt build up and, even without previous experience of salt related engine failures, would have sought to exit the conditions in which they found themselves. While the darkness did not cause the engines to fail, maintaining a better ability to visually inspect the intakes and for that matter the windshield itself could likely have prevented the situation from becoming as severe as it did. **Darkness (flying at night) is considered a contributing factor in this incident.**

As mentioned in the previous two paragraphs, this event is representative of a very little known phenomenon. Salt related engine failures are almost unknown in the fixed wing aviation community. That said, NOAA AOC itself has seen the only other documented case of an engine failure due to sea salt aerosol accretion on the compressor vanes. The report from the Coupled Boundary Layer Air-Sea Transfer Experiment (CBLAST) engine failure in 2003 is on file, but the results do not appear to have been actively considered by the crew. While some aircrew members at AOC (primarily those who were aboard the flight in 2003) are familiar with the CBLAST incident, most others have, at best, limited knowledge of what occurred in that case. Acknowledging that the CBLAST incident occurred at a significantly lower altitude (below 1200') and in an area where there was a clearly visible boundary layer below which existed a tremendously high concentration of salt aerosols, the crew could have considered it and decided that they were in a sufficiently different environment to preclude a recurrence of that incident. Had that been the case, the result would likely have been just as it was. In truth, when the crew observed the initial white build up on the windshield there was no discussion of the CBLAST incident. Had the flight station crew received more detailed training on the results of the CBLAST investigation, they may have discussed the potential for a salt accretion hazard and may have decided to abort the mission or at least sought to rectify the problem by seeking liquid precipitation. This is seen by the investigation board as a failure on the part of AOC in two ways. The first is a dearth of corporate knowledge on the subject of high sea-salt aerosol environments and the accompanying hazards, for which no fault can be assigned and no simple resolution can be offered as the entire subject is unknown to anyone. The second is a failure to pass on the limited corporate knowledge/experience we do have on the subject. This is a training issue which can be addressed and will be discussed later in the recommendations section. Again, knowledge of the CBLAST event would not necessarily have prevented this incident, but it is possible that it could have. **A lack of corporate knowledge/experience and an organizational failure to manage information from previous incidents are considered to be contributing factors in this incident.**

12. CONCLUSIONS

To reach the following conclusions, this board has exercised both internal investigation of the incident and consultation with outside meteorological expertise. Internal investigation has involved detailed examination of flight data from the incident flight and other flights of the same project as well as flights from projects with potentially related environmental conditions. The board has examined recorded data from the flight itself, the SFMR data from the project, satellite data, environmental data reported by ships in the area, and a variety of other sources. Numerous outside experts have been drawn upon for their insights and background knowledge and some have offered their own analysis of the situation. Dr. Ed Andreas of the Northwest Research Associates and the US Army Cold Regions Research Environmental Laboratory was helpful in the early stages of the investigation, providing both papers on the subject of sea-salt aerosol generation functions and answers to questions on extending predictions out of the normal wind speed regime and into much higher wind speeds associated with the incident flight. Ernie Lewis, of Brookhaven National Laboratory, and coauthor of the book “Sea Salt Aerosol Production: Mechanisms, Methods, Measurements, and Models – A Critical Review (Geophysical Monograph),” presented a two day seminar in Miami and answered many questions for us. Dr. Jeff Reid, of the Naval Research Laboratory, has been given the flight data from the incident flight and has been conducting a careful analysis of his own. He will be providing a report of his findings using a combination of satellite data and the U.S. Navy’s Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS®) modeling program to study the conditions of the incident flight. Paul Willis and Pete Black of the Hurricane Research Division in Miami have also provided valuable insight and suggestions.

It is clear at this point that there is insufficient information and understanding within the scientific community at large, to clearly determine and define the specific meteorological factors and their interactions which lead to a dangerous operating environment for aircraft. That said, the board has been able to identify several major contributing factors which can potentially generate a dangerous operating environment. In no particular order, these include:

-- Sea Surface Temperature; and as a subset thereof, the sea-air temperature difference, and temperature gradients within the water itself
-- Wind Speed; particularly high wind speeds (above value of approximately 30 m/s) and as a subset thereof, extended duration and fetch
-- Lack of Precipitation, particularly in ambient air temperatures near zero (0) degrees Celsius (C)
-- Relative Humidity, at or above 80%

In terms of defining the environment, it will also be important to determine the altitude of the mixing layer, which is a complex function influenced by shear turbulence, stability, convection related to air/sea temperature differences and a variety of other variables. If several of the aforementioned conditions prevail in a given environment, an increased likelihood of high salt aerosol concentration exists. Taken individually or even perhaps a couple at a time, these factors do not appear to create a significant hazard. However, the combination of several of these parameters can create a synergy allowing the production of excessive salt aerosols at the surface and their subsequent transport to altitudes which would not normally be reached at a dangerous or even discernable level. A further discussion of each of these factors and the board's development of this list follows.

A general discussion of the generation mechanisms for marine sea salt aerosol is appropriate at this time. This is a very simplified primer on the subject and should be supplemented with outside reading for anyone desiring a more complete understanding of the phenomenon. Salt aerosol particles are created in three primary processes. Film drops are created when bubbles of salt water burst, ejecting the smallest particles from the thin skin of the bubble. Jet drops result from the same bubbles collapsing and sending up a jet of water from the bottom of the bubble. Spume drops are created when high winds literally tear the tops from wave crests. The particles created by these three processes vary in size over many orders of magnitude. In general, these particles are grouped into three size categories: fine, coarse, and giant. Fine particles are typically less than 2.5 μm in diameter. Coarse particles are considered to be in the range of $2.5<Dp<15$ μm. Giant particles can exist up to sizes in excess of 200 μm in diameter. Relatively low settling velocities allow fine and coarse particles to remain airborne for periods of hours to weeks under normal conditions. The large size and higher settling velocities of giant sized particles mean that, under normal circumstances, they last only on the order of seconds to minutes in the atmosphere before falling back to the surface. At low wind speeds and stable atmospheric conditions, giant sized particles, generated primarily as spume drops, make up only a very tiny percentage of the sea salt aerosol content. At higher wind speeds, spume drop generation increases, geometrically, and the average size of airborne salt particles increases by orders of magnitude. Salt aerosol generation functions are believed to scale roughly with the 10 meter wind speed raised to the 3.4 power. That means that when the wind speed is doubled, the amount of salt aerosol generated is increased by more than a factor of 10. The large settling velocities of giant sized particles suggest that in order for a dangerous condition to exist, there will also need to be significant mixing of the atmosphere. Otherwise the large salt particles would return to the surface after a very short duration and would not pose any threat to aircraft. Under fairly "normal" conditions mid boundary layer vertical wind velocities are on the order of 0.5 to 1 m/sec which can sustain aloft particles up to around 18 μm. On the incident flight vertical velocities are believed to have been closer to 5 m/sec, allowing indefinitely sustained times aloft for particles up to 40 μm. It is important to note also, that the preceding discussion applies to dry generation and transport. Precipitation will very effectively remove these particles from the atmosphere, even in the presence of large vertical mixing velocities.

In the case of the incident flight, powerful and sometimes hurricane force winds existed over a duration of days and had a fetch of nearly 500 miles (albeit not hurricane force over the entire period or fetch). These sustained winds, along with high sea states generated giant spume particles at a remarkable rate. Due to relatively high sea surface temperatures, high horizontal water temperature gradients, low air temperatures, and atmospheric instability, there was exceptional mixing of the lower atmosphere resulting in high vertical velocity components and allowing transport of huge quantities of salt aerosol particles to altitudes far above what would normally be observed. These conditions also allowed salt aerosol particles to remain aloft much longer than would normally be the case and to continue to build in the atmosphere over the multiple day storm.

13. RECOMMENDATIONS

Due to the nature of this incident and the lack of a clear understanding of the phenomena involved the board recommends a two pronged approach to preventing a recurrence in the future. These recommendations will include short term solutions, which may be more restrictive than necessary once a larger knowledge base is developed, and longer term solutions which will help to develop that knowledge base and allow us to later expand our operating envelope as we gain a more precise understanding of the environment. These recommendations are intended to be a living document. As understanding improves, it is our intent that these be revisited and revised periodically to reflect that growing comprehension of the hazard. We do not intend that the recommendations of this board be set in stone and remain unchanged in the face of a greater database of experience.

Recommendations will be given to address each of the factors which were determined to be causal or contributing in the Analysis section of this report. Some other issues have been identified which were neither “causal” nor “contributing” to the occurrence of this incident, but which nonetheless bear closer review. Recommendations will be offered as well to address these issues.

As listed in the Conclusions section, the following factors are considered either causal or contributing

Salt accretion on the compressor stator and rotor vanes of the engines during the incident flight is considered a causal factor in this incident.- *If accretion of salt is observed, exit the high salt aerosol environment and abort the mission.* Flying through precipitation can remove some accreted salt and potentially restore some engine efficiency. However, maneuvers requiring large power setting changes should be avoided. Rapid power changes in salt contaminated engines may cause compressor stalls.

The meteorological environment of the incident flight is considered a causal factor in this incident. –*Avoid conducting operations in high concentration sea-salt aerosol environments by observing the following guidance.* As discussed in the Conclusions section of this report, the board has determined that the following factors contribute to a high concentration sea-salt aerosol environment:

1. A large difference between the sea surface temperature and the air temperature, particularly with warm water and cold air. Along with this, large horizontal temperature gradients within the ocean appear to contribute significantly.
2. High surface wind speeds. We are currently defining this to mean in excess of approximately 30 m/s, a value which would certainly be subject to refinement. Included along with wind speed are large distance of fetch and long duration of continued high wind speeds. No specific values are offered at this time to define large fetch or long duration, but based on this incident, 500 nm and 48 hours would seem to qualify.
3. Lack of precipitation, particularly in ambient air temperatures near zero (0) degrees Celsius.
4. Relative humidity at or above 80%.
5. Height of the Marine boundary layer. The high salt environment will not extend above a well defined boundary layer.

Expected meteorological conditions will be given a careful review by the Flight Director to assess the factors listed above. If several of these conditions prevail in the flight environment, a heightened likelihood of dangerous salt aerosol concentration exists and crews should take extra caution in their planning. In this case the crew will comply with the following 4 directives:

1. The Flight Director will review the expected conditions in the area of operations and present the results in the preflight weather brief. At this time the flight director may recommend the addition of a dropsonde or other changes in the flight profile to help determine the flight environment in the operations area.

2. Flight at night or in hours of darkness will be given careful consideration. Flying during the day does allow for better situational awareness of whether there is an excessive presence of salt in the air. Visual cues and observation of the aircraft surfaces are facilitated by daylight, thus there is a better chance that an accumulation will be noticed sooner in daylight conditions. If flying at night the crew will use a flashlight to frequently check for accretion of salt on the windscreen and airframe.

3. Transit to the operations area at a higher altitude, well above the mixing layer. Once over the operations area, determine the height of the mixing layer visually or using a dropsonde or aircraft sounding. Conduct operations at or above 1000 ft above the identified level of the mixing layer or above 5000 ft. If the mixing layer can not be identified, aircraft will remain at or above 5000 ft unless or until a mixing layer can be defined. Dropping below the level of the mixing layer would be acceptable for sounding profiles with a climb out of the layer immediately following. Mixing layer heights are subject to change over time and across air mass boundaries. Therefore the mixing layer height should be reassessed periodically. Based on current research, dangerous concentrations of salt aerosol particles will not exist above the top of the mixing layer. Due to dilution and settling, dangerous concentrations are not anticipated above 5000 ft regardless of the height of the mixing layer.

4. Conduct engine efficiency checks before and after each flight and hourly in flight. If an engine efficiency check was performed after the last flight, a before flight check is not required. Onset of engine failure may not provide signs which are easily noticeable from normal operating procedures, but closer attention to engine performance during flights in potentially higher concentration salt environments may facilitate earlier crew identification of salt accretion, and will also aid in the long term goal of identifying when salt buildup is likely to occur. Efficiency checks should be recorded and compared to determine if any flights do indicate a gradual loss of performance. If so, the flight data from those flights should be studied to improve our meteorological knowledge base. It should be noted that salt accretion which effects engine performance could also effect temperature indications and may, therefore, provide readings of performance which are not correct. If any significant degradation is noted an engine wash will be done.

Salt accretion on later stage compressor rotor and stator vanes of the engines from previous flights is considered a possible causal factor in this incident. - *Fresh water engine washes should be conducted after every flight where salt accretion or engine degradation is suspected.* At minimum, engine washes will be conducted in accordance with the Maintenance Operating Instructions. Engines should be motored over, not running, when washes are conducted. The intent of the wash is to rinse clear any accumulated salt on later stage rotors and stators which may not be observable from outside the engine. If the engine is running, temperatures at later stages of the compressor are sufficient to boil the water and reduce the effectiveness of the rinse. This runs the risk of resulting in the deposit of salt and other contaminants from the early stages onto the later stages potentially leaving the crew with the false impression that they had cleaned the engine when, in fact, they had exacerbated the situation by priming the engine for a catastrophic failure later. As long as the engines are not running, fresh water rinses should aid in preventing later stage buildups of salt from decreasing the engine’s surge margin and contributing to catastrophic failures without warning.

Darkness (flying at night) is considered a contributing factor in this incident. – *Avoid flying at night in suspected high concentration sea-salt aerosol environments.* This is addressed above with the recommendations regarding the environment.

A lack of corporate knowledge/experience and an organizational failure to manage information from previous incidents are considered to be contributing factors in this incident. *–Conduct CRM training for all crew members flying regularly aboard AOC aircraft, and continue to encourage full communication between all stations. Conduct periodic training on previous incidents to ensure culture wide understanding of lessons learned.* This is a difficult issue to address directly. The problem is one of "unknowns" which affect our ability to conduct our mission. Had the flight station crew discussed the white material build up they observed on the windshield earlier in the flight with the crew in the back of the plane, someone may have mentioned the CBLAST event and sparked a conversation which could have prevented this incident. The flight station crew's omission was not a conscious decision to avoid communication with the aft crew; they simply did not identify the phenomenon as something which would later become significant. It is much easier in hindsight to identify important events and pick out what should have been communicated. There is no fault to be placed on any member of the crew in this regard, but there may be some things we can improve on as a group. We currently conduct Crew Resource Management (CRM) training regularly for flight crew, but there is no program in place for mission crew. The board recommends the installation of CRM training for anyone who flies regularly on AOC aircraft. There is no reason to believe that the critical piece of information will come initially to a flight crew member when a situation arises. It is every bit as likely that another member of the crew will have valuable information to offer and the communication is more likely to flow smoothly if everyone has received the same training. To address the issue of carrying on knowledge from previous incidents is equally difficult. The knowledge gained from the CBLAST incident was not lost in this case. It was simply not identified as significant and was not accessed. Nevertheless, an improved system for passing on such knowledge and ensuring that it is understood by all would be a valuable tool in preventing future recurrences of any particular hazard. Periodic training sessions to include review of hazard reports for all aircrew would be of benefit to the organization.

Over the longer term, we need to develop a quantitative body of knowledge on the subject of salt aerosol if we intend to continue flying missions which are likely to encounter this environment. This report takes a step to limit the envelope in which we fly for the time being, but the restrictions advocated here will likely appear too tight once our understanding of the phenomena involved is improved. When we have a better definition of what is safe and what is not, we should seek to incrementally expand the envelope again. To do this we will need a system of determining whether the aircraft is being exposed to salt aerosol, and if so, quantifying the level of exposure. The board recommends the development of a sensor package which will be able to measure aerosol particulate matter and provide a warning to the crew if the concentration of particles exceeds a given level. One initial step toward this could be the installation of the Rosemount Icing detector which operates by reading the vibration frequency of a small metal tab extended into the slipstream of the aircraft. As material (ice normally, but anything accumulating on the probe will suffice) builds up on the probe, the frequency of its vibration changes and the sensor reads this. This device could be configured to provide an alarm when a sufficient quantity of material had adhered to the probe. Calibrating the device and determining what constitutes a "sufficient quantity" of material are beyond the capability of the board at this time and would be the subject of ongoing study. There is also a cloud physics particle sensor available which seeks to measure particulates in a more quantitative manner. This report will not specify a particular sensor which should be used or the specific parameters to be measured, but recommends that this be a subject of further study over the next several years.

The preceding paragraphs address recommendations for those factors which were considered either “causal” or “contributing” to the multiple engine failure event. In any investigation, some issues will be discovered which, though they do not bear directly on the incident involved, nonetheless warrant attention of their own. These issues will be addressed in the next few paragraphs.

Although by all accounts, the aft crew’s preparation for ditching went smoothly as a whole, several people did note difficulty getting into their anti-exposure suits and confusion over how to don the suits. Many had difficulties adjusting the length of their seatbelts and harnesses to accommodate their larger size once wearing the suits. Also, the navigator found that he was unable to discharge the duties of his position with the anti-exposure suit fully on as the “lobster hands” of his suit prevented the manipulation of radio controls. The board recommends that emergency training continue to be required prior to the start of each project, or at a minimum once per year, for all crewmembers. This training should include, at a minimum, donning and use of anti-exposure suits, emergency egress from the aircraft, use of firefighting equipment and emergency equipment aboard aircraft, and CRM communications skills, and should be conducted in a training environment which seeks to replicate the stress and conditions of an in-flight emergency. The training should be documented in training jackets for AOC employees. Documentation is encouraged, but not necessarily required for visiting scientists. Individuals on a one time flight waiver will receive a thorough preflight safety brief to include donning of an anti-exposure suit when the aircraft is so equipped. As a practical matter, use of “demo” suit(s) for training drills will preclude wear damage to operational suits. The board recommends investigating replacement of current suits with an available commercial alternative or modifications to the anti-exposure suits to allow a gloved hand to be withdrawn from the “lobster hand” of the suit for improved dexterity when needed. Currently there are a few such modified suits in the inventory, but most suits do not have this modification.

Emergency gear must always be immediately available without obstruction. It is unacceptable to allow emergency gear to be fouled with personal items or other equipment. This concept is essential and should be made inherent to our culture. Proper stowage of loose gear is paramount to survival in an emergency situation. This incident identified a potential difficulty with launching the port life raft due to its physical location relative to the emergency exit. The board recommends a deliberate evaluation of the location of life rafts relative to emergency exits for all aircraft to facilitate launch and identify possible improvements.

Although the flight station crew did an excellent job of handling this extremely rare and stressful situation, some improvement was still possible. Under considerable pressure with multiple engine failures and a hostile physical environment, the flight crew did have some breakdowns in communication which ultimately did not cost them anything in this case, but very easily could have. Again, this is not an indication that the board finds any fault with any of the actions taken by the crew, but the incident offers an opportunity to reevaluate our program and find points we could improve. We have fairly limited availability of assets for training flight crew in the actual aircraft, and simulator periods tend to focus on systems and procedure training with relatively straight forward malfunctions. In this case in the aircraft, extreme duress and an exceptionally rare scenario put to the test the crew's ability to maintain clear communications. It would be advantageous to increase the frequency of simulator training periods in general and specifically to add sessions which focus on maintaining good communications despite the creation of a high stress environment. It is easy to perform the right procedure and communicate well in a low stress environment with straight forward malfunctions. We sometimes test system knowledge by introducing more complicated scenarios, but do not often stress the communications of the crew in high anxiety, time critical situations. The addition of simulator periods for this expressed purpose would be a worthwhile part of the training regiment.

Finally, in the opinion of the board, the program planning process would be improved by including appropriate personnel earlier. The board recommends that at least 2-3 months prior to execution of a project an AOC research meteorologist be assigned to evaluate the proposed operational environment for potential hazards to include dangerous salt aerosol concentrations. Several tools for assessing salt aerosols are available in Dr Reid's report. Findings will be forwarded to the project manager for inclusion into further project planning.

End of report.