



AEROSPACE INFORMATION REPORT

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Use of Health Monitoring Systems to Detect Aircraft Exposure to Volcanic Events

RATIONALE

The constituents, concentration, and size of volcanic ash particles are highly variable. Volcanic ash can also damage or degrade aircraft sub-systems. In the past 30 years, more than 90 jet-powered commercial airplanes have encountered clouds of volcanic ash and suffered damage as a result. The increased availability of satellites and the technology to transform satellite data into useful information for operators have reduced the number of volcanic ash encounters, but the damage that these encounters can inflict on aircraft sub-systems is also highly variable and has the potential to be catastrophic. Understanding how sensors on an airborne platform could help determine that an aircraft is in a volcanic ash environment or has recently flown through volcanic ash is thus of considerable value.

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1. SCOPE

This document collates the ways and means that existing sensors can identify the platform's exposure to volcanic ash. The capabilities include real-time detection and estimation, and post flight determinations of exposure and intensity. The document includes results of initiatives with the Federal Aviation Administration (FAA), the European Aviation Safety Agency (EASA), the International Civil Aviation Organization (ICAO), Transport Canada, various research organizations, Industry and other subject matter experts. The document illustrates the ways that an aircraft can use existing sensors to act as health monitoring tools so as to assess the operational and maintenance effects related to volcanic ash incidents and possibly help determine what remedial action to take after encountering a volcanic ash (VA) event. Finally, the document provides insight into emerging technologies and capabilities that have been specifically pursued to detect volcanic ash encounters but are not yet a part of an airplane's standard fit.

1.1 Purpose

The purpose of this document is to help the civil and military aviation community understand how the existing capabilities on an airplane could be used to help mitigate the adverse effects of volcanic ash on an individual air vehicle and possibly fleets of air vehicles.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR4175A A Guide to the Development of a Ground Station for Engine Condition Monitoring

2.1.2 Other Documents

- Reference 1 IVATF Final report: Available at
<http://www.icao.int/safety/meteorology/ivatf/Documents/IVATF.Summary.of.Accomplishments.pdf>
- Reference 2 ICAO report, April 12, *Flight Safety and Volcanic Ash* (DOC 9974), available at
http://www.icao.int/safety/Documents/ICAO_2013-Safety-Report_FINAL.pdf
- Reference 3 Guffanti, Marianne, Casadevall, T.J., and Budding, Karin, 2010, Encounters of aircraft with volcanic ash clouds; A compilation of known incidents, 1953–2009: U.S. Geological Survey Data Series 545, ver. 1.0, 12 p., plus 4 appendixes including the compilation database, available only at <http://pubs.usgs.gov/ds/545>
- Reference 4 Schumann, U., Weinzierl, B., Reitebuch, O., Schlager, H., Minikin, A., Forster, C., Baumann, R., Sailer, T., Graf, K., Mannstein, H., Voigt, C., Rahm, S., Simmet, R., Scheibe, M., Lichtenstern, M., Stock, P., Rüba, H., Schäuble, D., Tafferner, A., Rautenhaus, M., Gerz, T., Ziereis, H., Krautstrunk, M., Mallaun, C., Gayet, J.-F., Lieke, K., Kandler, K., Ebert, M., Weinbruch, S., Stohl, A., Gasteiger, J., Groß, S., Freudenthaler, V., Wiegner, M., Ansmann, A., Tesche, M., Olafsson, H., and Sturm, K.: Airborne observations of the Eyjafjallajökull volcano ash cloud over Europe during air space closure in April and May 2010, *Atmos. Chem. Phys.*, 11, 2245-2279, doi:10.5194/acp-11-2245-2011, 2011
- Reference 5 Operation of Gas Turbine Engines in an Environment Contaminated with Volcanic Ash; Journal of Turbomachinery September 2012, published by the American Society of Mechanical Engineers (ASME)

- Reference 6 Airborne Volcanic Ash, A Global Threat to Aviation, a USGS Fact Sheet available from <http://pubs.usgs.gov/fs/2010/3116/fs2010-3116.pdf>
- Reference 7 Przedpelski, Z.J., and Casadevall, T.J., 1994, Impact of volcanic ash from 15 December 1989 Redoubt Volcano eruption on GE CF6–80C2 turbofan engines, in Casadevall, T.J., ed., Volcanic ash and aviation safety; Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety held in Seattle, Washington, in July 1991: U.S. Geological Survey Bulletin 2047, p. 129–135
- Reference 8 Davison, Craig R., Rutke, Tim, “Assessment and Characterization of Volcanic Ash Threat to Gas Turbine Engine Performance,” ASME GT2013-94079, Proceedings of ASME Turbo Expo 2013, June 3-7, 2013, San Antonio, TX
- Reference 9 Sieverding, C.H. & Mathioudakis, K. (Eds.), “Gas Turbine Condition Monitoring and Fault Diagnosis,” Von Karman Institute for Fluid Dynamics, Lecture series 2003-01, January 13-17, 2003, Rhode Saint Genèse, Belgium
- Reference 10 SAE International Aerospace Information Report, “A Guide to the Development of a Ground Station for Engine Condition Monitoring,” SAE Standard AIR4175A, Reaf. Oct. 2012.
- Reference 11 The 1989-1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations. Thomas J. Casadevall, *United States Department of the Interior, Geological Survey, Box 25046, Mailstop 903, Denver Federal Center, Denver, CO 80225, USA*
- Reference 12 Grindle, T. J. and Burcham Jr., F. W., “Engine Damage to a NASA DC-8-72 Airplane from a High-altitude Encounter with a Diffuse Volcanic Ash Cloud,” NASA, NASA/TM-2003-212030, 2003
- Reference 13 Dunn, M. and Wade D, 1994, Influence of Volcanic Ash Clouds on Gas Turbine Engines: in Casadevall, T., (ed), Volcanic ash and aviation safety: Proceedings of the first international symposium on volcanic ash and aviation safety, U.S. Geological Survey Bulletin 2047, p 107-117
- Reference 14 Miller, J.L., Kitaljevich, D., “In-line Oil Debris Monitor for Aircraft Engine Condition Assessment”, Aerospace Conference Proceedings, 2000 IEEE (Volume 6), pp. 49-56, 18-25 March, 2000
- Reference 15 Gary W. Hunter, Richard W. Ross, David E. Berger, John D. Lekki, Robert W. Mah, Daniel F. Perey, Stefan R. Schuet, Donald L. Simon, and Stephen W. Smith. “A Concept of Operations for an Integrated Vehicle Health Assurance System,” NASA Technical Memorandum 2013-217825 (2013)
- Reference 16 Gary W. Hunter, John D. Lekki, Donald L. Simon. “Development and Testing of Propulsion Health Management.” Proceedings of the Workshop on Integrated Vehicle Health Management and Aviation Safety; Bangalore, India; January 2012
<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120002753.pdf>
- Reference 17 www.nicarnicaaviation.com/technology
- Reference 18 <http://www.flightglobal.com/blogs/learnmount/2014/07/volcanic-ash-longer-problem/?cmpid=NLC|FGFG|FGFIN-2014-0722-GLOB&sfid=70120000000taAh#sthash.28DiMQFh.dpuf>
- Reference 19 Rolls-Royce “The Jet Engine” 5th Edition

2.2 Terminology and Definitions

ACOC	Air-Cooled Oil Coolers
ADF	Automatic Direction Finder
AIR	Aerospace Information Report
ASME	American Society of Mechanical Engineers

AoA	Angle of Attack
APU	Auxiliary Power Unit
ATA	Airline Transport Association
ATC	Air Traffic Control
C-MAPSS	Commercial Modular Aero-Propulsion System Simulation
C-MAPSS40k	Commercial Modular Aero-Propulsion System Simulation 40k
CMAS	Calcium Magnesium Aluminum Silicate
AVOID	Airborne Volcanic Object Imaging Detector
BA	British Airways
DAASH	Dynamic Assessment of Aircraft Structural Health
DME	Distance Measuring Equipment
DEvAC	Duration of Exposure and Ash Concentration
EASA	European Aviation Safety Agency
ECS	Environmental Control System
EEC	Engine Electronic Control
EGT	Exhaust Gas Temperature
EHM	Engine Health Monitoring (or Management)
EICAS	Engine-Indication and Crew-Alerting System
EMU	Engine Management Unit
EPR	Engine Pressure Ratio
FAA	Federal Aviation Administration
FCOC	Fuel-Cooled Oil Coolers
GNC	Guidance, Navigation and Control
HF	High Frequency
HM	Health Management
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
ILS	Instrument Landing Systems
IMC	Instrument Meteorological Conditions

INS	Inertial Navigation System
IVATF	International Volcanic Ash Task Force
IVHAS	Integrated Vehicle Health Assurance System
LORAN	Long Range Navigation
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NGV	Nozzle Guide Vane
NRC	National Research Council
OAT	Outside Air Temperature
ODM	Oil Debris Monitoring
PDP	Particle Detection Probe
PHM	Prognostics and Health Management
RF	Radio Frequency
RPM	Revolutions Per Minute (engine speed)
SATCOM	Satellite Communications
SLFCS	Survivable Low Frequency Communications System
UHF	Ultra-High Frequency
USAF	United States Air Force
USGS	United States Geological Survey
VA	Volcanic Ash
VAE	Volcanic Ash Environment
VAAC	Volcanic Ash Advisory Center
VHF	Very-High Frequency
VIPR	Vehicle Integrated Propulsion Research
VHF	Omni Directional Radio Range (VOR)

3. INTRODUCTION

3.1 Volcanoes Across the World, Monitoring of, and Effects on Aircraft

There are approximately 50 active volcanoes globally which produce eruptions. On occasion, some of the resulting ash plumes can reach jet aircraft cruising altitudes. In addition to the amount of material ejected from a volcano, the material varies in composition, intensity and particle size but is generically referred to as volcanic ash. Moreover, while the eruptions are usually in well-defined areas of the world, depicted by the red dots on Figure 1, the material is propelled thousands of feet into the air where it is subjected to the weather patterns and thus transported over vast (inter-continental) distances and altitudes.



Figure 1 - Location of active volcanoes, the source of atmospheric volcanic ash

Because of this global scenario, flying in some background level of volcanic ash occurs on a daily basis and is normally only of concern from a long-term maintenance consideration where slow degradation of an airplane's external surfaces and windows (transparencies) typically occurs. Volcanic ash can damage engines by blocking cooling holes, by eroding compressor blades and by accreting on flowpath surfaces which changes the flow areas. Other aircraft sub-systems can also be adversely affected or, at a minimum, show a change in behavior, and thus act as a sensor/detector.

When a significant volcanic eruption occurs, the aviation authorities within individual nations are likely to restrict the use of airspace to some degree (depending on the severity) in the affected zones until the risk is deemed to be insignificant. For instance, the Eyjafjallajökull eruption in Iceland in April 2010, shut down the European and transatlantic air traffic lanes for several days with resulting great disruption to almost a million travelers. The economic significance alone of this incident motivated regulatory agencies, operators and maintenance organizations across the world to investigate how the adverse impacts of volcanic ash could be safely minimized or overcome and to seek clarity on the risks posed by operating in varying ash concentrations. ICAO's international volcanic ash task force (IVATF) addressed the subject (Reference 1) and ICAO also wrote a manual (Reference 2) entitled *FLIGHT SAFETY AND VOLCANIC ASH* (doc 9974), that was published in March 2012. Air transport operators now have a scientific basis for decision-making in the event of a volcanic eruption using this ICAO manual that was endorsed by industry partners. The manual provides guidance that countries may recommend to aircraft operators when there is forecast volcanic ash contamination, placing the responsibility for such operations on the operator, under the oversight of the State regulatory authority.

A worldwide system of Volcanic Ash Advisory Centers (VAACs), as shown in Figure 2, exists for the detection of such events and they issue advisories to the concerned nations.

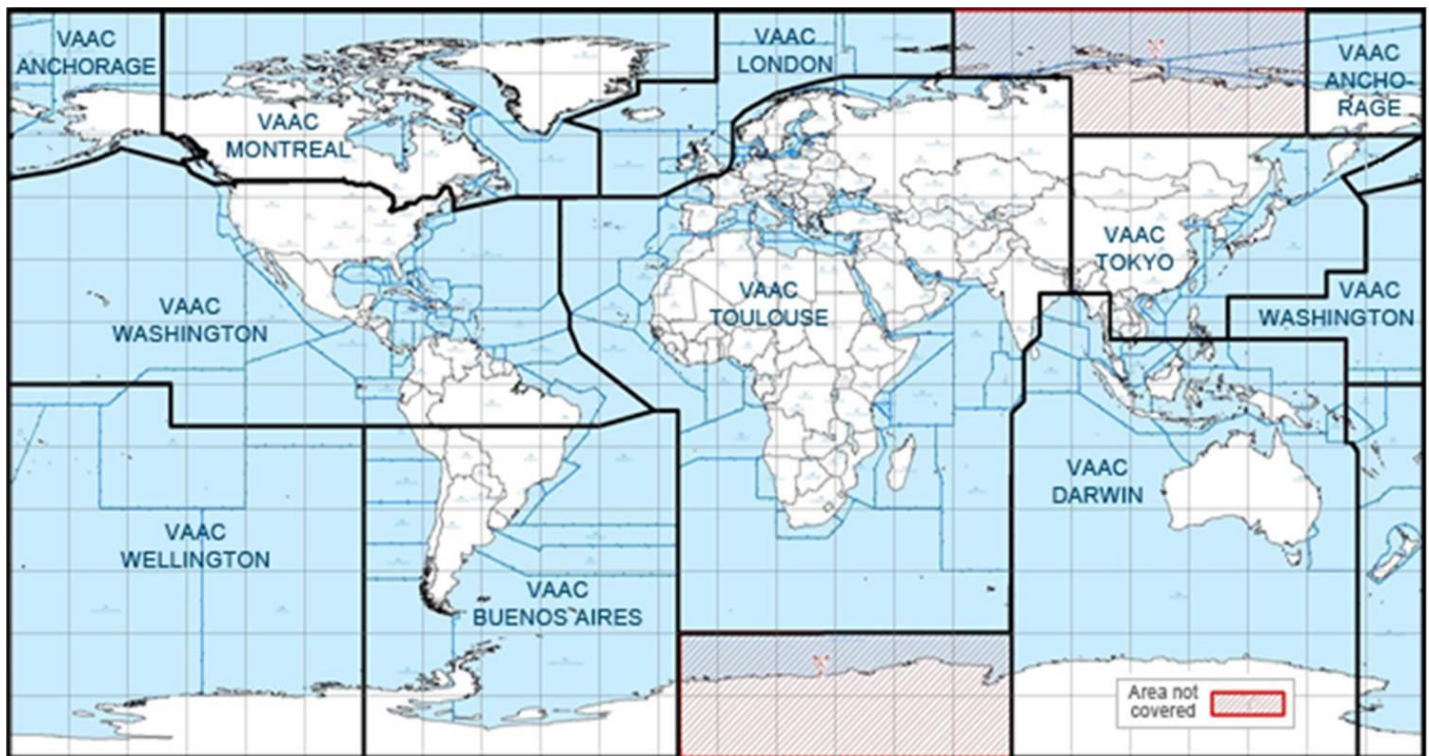


Figure 2 - Volcanic ash advisory centers (VAACS)

The VAACs receive input data from a number of sources (including transiting aircraft, surface observations, webcams, etc.) but data from meteorological satellite sensors are the principal detection and tracking tools for airborne volcanic ash plumes. VAACs leverage global numerical weather prediction models (winds, moisture, temperature, etc.) and employ dispersion models to forecast ash plume location/height with respect to air traffic lanes and aircraft flight paths. Based on the information gathered, nations determine where and when civil flight operations are permitted with safety of flight being the prime concern.

While volcanic eruptions have, so far, not caused the direct loss of an aircraft, there have been eruptions that have resulted in significant economic impact and/or significant damage to aircraft. To avoid recurrence of damage from some prior close encounters, (e.g., cockpit windows almost opaque, engines shut down), operators tend to cease flight operations in areas of concentrated volcanic ash. As can be seen in Figure 3, the normally busy air traffic lanes over Europe were empty in the days after the Eyjafjallajökull eruption.

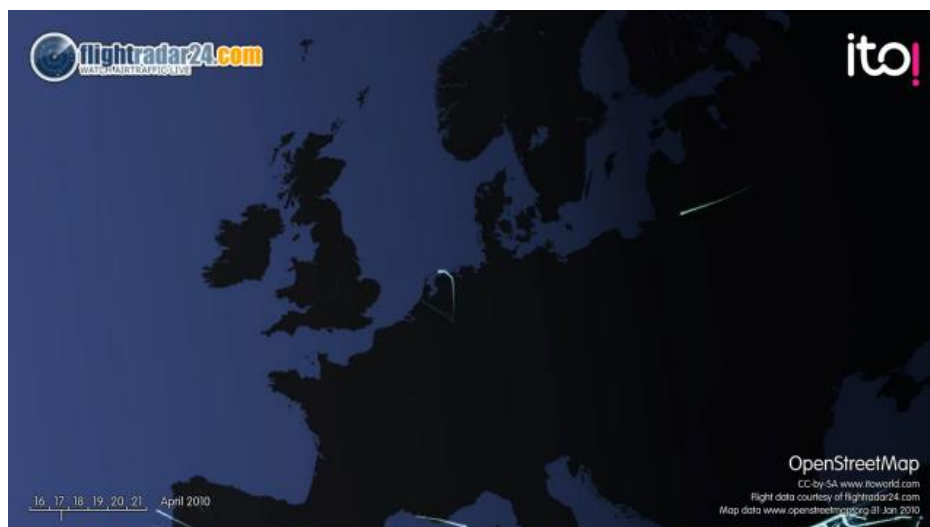


Figure 3 - European flight operations April 17, 2010



Documents

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IVATF completed its study in June 2012 (Reference 1) and the United States Geological Survey (USGS) completed a survey of all the known instances of past flight into volcanic ash conditions (Reference 3). This survey is discussed in more detail in 3.2 and although there was a significant amount of data available, it was largely anecdotal, and lacked sufficient engineering data to be of use in making accurate technical decisions for future operations.

The SAE E-32 Technical Committee, comprising an industry-wide core of specialists in aerospace propulsion systems health, and helicopter drive train monitoring, has existed since the early 1970s. Health and condition monitoring has evolved from the simple gathering of data to be studied on the ground, to systems capable of performing in-flight diagnostics and prognostics related to propulsion system health.

In addition to aircraft propulsion systems, other groups have made similar progress on health management aspects related to other aircraft sub-systems to the point where, in 2009, it was realized that the real value of such systems lay in considering the complete vehicle health. This led to the concept of Integrated Vehicle Health Management (IVHM) led by the relatively new SAE HM-1 Technical Committee.

In 2012, SAE decided that the topic of aircraft exposure to volcanic ash in flight was within the HM-1 area of expertise, i.e., detection and measurement of aircraft degradation (irrespective of cause) and could provide guidance for the monitoring and correction of such degradation in the interests of operational efficiency. A working group was established including many individuals who had participated in the IVATF.

After studying the data available to date, it was concluded that while much knowledge exists, very little can be used to make truly informed decisions regarding safety-of-flight based on measurable parameters. Some of these concerns are being addressed by new test programs (Sections 5 and 6). As data from these programs become available, they will be included in future revisions of this document. However, the airplane itself has some inherent potential to reveal when it is in a VA environment if the totality of behaviors by the various sub-systems is considered and understood. For instance, what parameters would change or be “observable” by any means during a VA encounter and what would be necessary to capture and measure those parameters to potentially use them for providing:

- Real-time data to VAACs to improve the process of detection and forecasting the location of the ash cloud.
- Aircraft operators with indications that the aircraft has experienced an inadvertent encounter so that appropriate maintenance operations can be performed.
- An engineering/scientific database on which future tests and measurement techniques may be developed.
- A fact-based background to assist future decision-making by the appropriate bodies.

3.2 Efforts to Categorize Effects of Volcanic Ash

The damage to aircraft from encountering volcanic ash in the upper atmosphere varies greatly and is a strong function of particle size, as well as concentration. Moreover, there are many factors that influence the size of volcanic ash particles in the atmosphere. While the distance downwind from an erupting volcano that an aircraft encounters ash loosely correlates with concentration, there are many parameters that affect the total grain-size distribution of the eruptive plume, its altitude, areal extent, concentration, and componentry. For example:

- The properties of the magma erupted (e.g., its pre-eruptive volume, cooling history, volatile content and chemical composition);
- The eruption dynamics, magma fragmentation efficiency, eruption duration, plume height and mass eruption rate;
- The environmental conditions at the eruption site (e.g., interactions with external water, atmospheric humidity, meteorological conditions, etc.).

In general, for a given eruption, the particle sizes will reduce with distance from the volcano as the larger and denser particles fall out first: a large proportion do so within the first few hours. The size and concentration of particles at the encounter point will therefore be heavily influenced by the magnitude of the eruption, distance from the volcanic vent, time elapsed since onset of eruption, as well as meteorological conditions such as wind speed. (Larger particles for example can be transported further than might otherwise be expected if high wind speeds are present; e.g., jet streams.) As a result the size distribution of volcanic particles that an aero engine may encounter will vary greatly.

Volcanologists estimate the grain-size distribution at particular locations from an eruption by analyzing the resulting deposits on the ground. These will give an upper estimate of the size distribution of the particles that would have been present in the atmosphere above that location because the sample will be biased towards the larger particles that fall out while the finer particles can be transported further. In-situ measurements of cloud particle sizes are rare and may be limited to the smaller grain sizes due to detection limits in the sensors or collectors used. During the Eyjafjallajökull eruption of 2010 Schumann et al. (Reference 4) took a series of measurements of the days-old distal ash clouds. They found that the particles in their collectors had diameters of up to 20 microns. Some 16 years before the 2010 eruption of Eyjafjallajökull, the USGS developed an Ash Encounter Severity Index (in conjunction with engine and airframe manufactures and the Air Line Pilots Association). The index was subsequently endorsed by the ICAO. Table 1 shows the ascending order of effects on the air vehicle as a whole.

The USGS Report (Reference 3) is an extensive compilation of reported incidents of aircraft exposed to VA from 1953 through 2009 and the impact on the aircraft. Appendix 4 of the study is a tabulation which correlates these events with effects noted and assigns a degree of severity to each incident wherever possible. The improvements discussed in the document include ground-based and airborne sampling of ash clouds to provide data on how ash concentrations in the atmosphere vary in space and time, and placing sensors on board aircraft to provide a tactical means to avoid ash-contaminated airspace. It is from this latter suggestion that SAE was motivated to examine how aircraft sub-systems, in their current configurations, could provide data that would not only protect the individual aircraft in real-time, but also others which might be entering the airspace in the near future.

The majority of the recorded events show notification of either “minor” or “none” for damage to the airframe.

Table 1 - Categorization of effects based on severity of encounter

Ash Encounter Severity Matrix	
Class	Criteria
0	Acrid odor (e.g., sulfur gas) noted in cabin
	Electrostatic discharge (St. Elmo's fire) on windscreen nose and engine cowls
	No notable damage to exterior or interior
1	Light dust in cabin, no oxygen used
	Exhaust gas temperature (EGT) fluctuations with return to normal values
2	Heavy cabin dust; “dark as night” in cabin
	Contamination of air handling and air conditioning systems requiring use of oxygen
	Minor abrasion damage to exterior surfaces, engine inlet and compressor fan blades
	Deposition of ash in engine
3	Vibration of engines owing to mismatch; surging
	Frosting or breaking of windows because of impact of ash
	Minor plugging of pitot-static system; insufficient to affect instrument readings
	Plugging of pitot-static system to give erroneous instrument readings
	Contamination of engine oil and hydraulic system fluids
	Damage to electrical system
4	Engine damage
	Temporary engine failure requiring in-flight restart
5	Engine failure or other engine with significant potential of flight safety incident

Many of the noted effects were visual and, while they may be somewhat subjective in terms of degree, they are nonetheless valuable from a health monitoring perspective. Moreover, it is probably more cost-effective to gather information in this manner than by using special or additional sensor systems. This report explores how the platform can make use of its current sensors, and/or noted changes in the behavior of sub-systems and their performance to augment the historical approach of Table 1.