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SENSORS TO MEASURE PARTICULATES AND DIRT IN FUEL DELIVERY SYSTEMS: OEM Survey, Practices and Requirements

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COORDINATING RESEARCH COUNCIL, INC.

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(CRC Project No. AV-04-04)

Prepared by

Vic Hughes and Melanie Thom

January 2008

CRC Aviation Fuel, Lubricant & Equipment Research Committee
of the
Coordinating Research Council, Inc.

SENSORS TO MEASURE PARTICULATES AND DIRT IN FUEL DELIVERY SYSTEMS: OEM Survey, Practices and Requirements.

(CRC Project No. AV-4-04)

Final Report:

January 2008

Prepared by

Vic Hughes and Melanie Thom

SUMMARY

The objective of this project, funded by the CRC on behalf of the Aviation Fuel, Lubricant & Equipment Research Committee, was to survey engine original equipment manufacturer (OEM) and fuel system supplier practices and requirements and thus provide data and other information to help industry reach a consensus on the most useful parameter(s) for measuring aviation fuel cleanliness (particulate contamination). It is anticipated that a further study or studies will explore available technologies that may be able to measure the parameters described in this report.

A questionnaire was widely circulated amongst the turbine engine OEMs and their component suppliers. Very few actually returned data; those that did are among the market leaders; therefore we have taken their responses as representative of the broader industry. The questionnaire addressed the impact of particulate contaminants in fuel on engine component durability, operational efficiency and operational safety.

The aerospace component manufacturers produced a wide range of responses on some specific aspects of their expectations and design philosophies. To establish functionality, engine manufacturers use traditional industry standards for durability and product testing with respect to particulate contamination while sub-tier component manufacturers test to "industry standard plus". However, specific customers sometimes require the OEM to test at elevated particulate exposure levels to accelerate wear and thus confirm safety margins.

Detailed parameters used by the engine OEMs and component suppliers to characterise particulate robustness were not obvious. The parameters are buried within the standards that apply to the engine and component approval and certification processes and are comprised of both proprietary and public domain documents. Surprisingly, most of these industry standards are no longer supported by the originating agencies but are still in use as proven processes, but revised by adopting updated materials or methods.

Component/engine robustness is affected by three particulate parameters: size, amount and composition (as one measure of hardness). Specifying a particular test

dust type and mass inevitably fixes the particulate composition, size range and numbers of such particles. Thus, OEMs use a grade of test dust for component validation (ISO 12103 A2/R2) that comprises silica (hardness 7 on Mohr Scale) and alumina dusts, with a size distribution of approximately 1-100μm. Continuous loading performance is tested at 2mg/l of the test dust or NAS1638 Class 8 (a particulate number density), but other heavier test loadings are also used for extreme testing.

Unfortunately, relating these parameters back to fuel supply industry specifications is difficult since this latter industry does not use the OEM parameters. Instead, American Petroleum Industry/Energy Institute (API/EI) filtration specifications and American Society of Testing and Materials (ASTM) / Defence Standard (Def-Stan) / Joint Inspection Group (JIG) / International Air Transportation Association (IATA) fuel specifications all use gravimetric or appearance parameters alone and for a different test dust size distribution. Despite this dichotomy, the OEM grade of test dust for component validation is an order of magnitude coarser than that used to validate the performance of ground filtration meeting API/IP standards. This actually provides the industry with a safety factor for ground filtration over that onboard the aircraft. However, this is an area that would benefit from attention by the broader industry to develop a consistent approach to defining fuel cleanliness.

In-line engine filters appear adequate to successfully protect those engine fuel system components that are considered most vulnerable to abrasive wear. The finest filtration quoted in this survey was an absolute rating of 35μm. Engine OEMs are still required to demonstrate durability under duress, to cater for the eventuality of filter by-pass under high contaminant load. Plugging of components such as filters and fuel ways has been a growing problem, with increasing incidences of impending in-flight filter by-passing. This aspect remains a cause for concern.

The impact of fuel-borne particulates was considered to be “low” on Mean Time Between Overhaul (MTBO) and service life but “high” in terms of remediation following isolated, dramatic contamination events. This, coupled with the greater concern of fuel control and other component manufacturers for internally produced fuel-borne particulates (assembly aids and debris) as opposed to externally sourced particulates, suggests that current into-plane fuel supply cleanliness levels are not an issue – although maintaining them remains a constant challenge. An airport cleanliness survey carried out in 1996 suggested that while the average level of particulate was very low at the into-plane stage, there were occasional, anomalously high levels that fuelling filters had to deal with. More recently, there have been reports of performance problems with some of the into-plane filters, and this is being addressed by the API/EI standards working group.

The OEMs appear most concerned about the isolated cases of in-flight filter plugging and subsequent remedial work. No single cause or set of causes was identified by the OEMs, and an IATA Airline-instigated study is currently addressing this issue. The OEMs indicated that they have encountered difficulties in obtaining suitable analytical data to offer solutions to the problem and this is also the Airlines' experience within their own IATA study.

It would be presumptuous for this report to include proposed limits for parameters that have not yet been agreed upon across the industry. However, the diverse range of those parameters suggests that the current overarching philosophy of building in redundancy needs to be maintained. A significant safety margin upstream of each critical operation or component should be maintained. For example, using the above quoted finest engine fuel filter rating of 35µm absolute, fuel delivered to an aircraft could safely be filtered via a system that ensures a rating of ~3µm absolute. Such absolute values can only be determined following industry consensus addressing such aspects as:

Are the parameters measurable?
Can the limits be technically justified?
Is the process commercially achievable?

Furthermore, there are reports of engine filters on smaller aircraft, including helicopters, that may be as fine as 10µm absolute, and the needs of engines such as these may be the final arbiter – unless the industry decides to deal with them as separate specialist equipment.

This report has identified some of the particulate challenges that are considered by OEMs in the design and operation of aviation turbine engines. The data were not as extensive as some in the broader aviation industry expected but did highlight some reassuring features. In particular, there is a significant safety margin between fuel supplier cleanliness control filters and engine component protection filters. However, this would seem to be fortuitous, and one recommendation of this report is that the broader industry engages in a more systematic approach to the definition of fuel cleanliness, as is the case in many other condition-monitoring industries.

Any monitoring or measuring instrumentation that may be required in the future will depend on an industry consensus on the cleanliness parameters to be adopted. The fuel supply industry has been very slow to adopt new technology, partly because of its justifiably conservative nature. However, engine technologies have advanced tremendously over the decades and it may be time for the industry to evaluate new measurement techniques. Management of Change philosophies are well documented and should be deployed to facilitate the profound mindset and cultural changes that will undoubtedly surface as measurands change.

LIST OF APPENDICES:

1.0 INTRODUCTION

The main objectives of this CRC-funded project are to:

- Survey opinions of engine original equipment manufacturers (OEMs) and their fuel system suppliers (primarily pumps, fuel nozzles and injectors and control valve systems) to determine what would be the most useful parameters to measure the (particulate) contamination impacting on aircraft fleet mean time between overhaul (MTBO).

- Establish the technical case for proposing limits for each of the parameters.

- Indicate design and development requirements for instrumentation to measure the key contaminant(s).

- The data and information thus produced should then help industry to reach a consensus on the most useful parameter(s) for measuring aviation fuel quality (particulate contamination).

2.0 BACKGROUND

Throughout the worldwide fuel distribution supply chains, aviation jet fuel is assessed for a number of key properties to ensure it is delivered to airports and airfields fit for purpose and without deterioration or contamination. One of the longest standing tests addresses the cleanliness of the fuel in terms of the levels of dispersed contaminants such as free water and/or particulates. This is usually checked by a visual assessment of the fuel (Clear & Bright) but may also be checked more quantitatively by gravimetric (for particulates) and/or colorimetric methods (for particulates and for free-water). In the distribution chain, the fuel may or may not be filtered; but, once the fuel reaches an airport or airfield, operational specifications require filtration to be used. Great efforts are made to ensure that the fuel is free from dispersed water and particulates. The filtration and separation devices used are the subject of industry specifications controlled jointly by the American Petroleum Institute (API) and the Energy Institute (EI). These devices determine the level of cleanliness of fuels delivered to the end-user. Separate military requirements may also be relevant at some airfields.

The technologies currently used in “cleaning-up” fuel delivered at high flow rates and in large volumes have finite technical and commercial limits. The technical limits have been set by the industry via API/EI standards. However, there have been recent incidents suggesting the technical capabilities of the filtration/separation devices may be at their operational (commercial) limits; consequently, other new methods of fuel quality assurance are being considered.

Particle detection technologies are available and can continuously monitor fuel cleanliness in real time for particles down to a few microns (μm, 10^{-6}m). They were abandoned by the aviation fuel industry over 30 years ago in favour of gravimetric techniques but have been used extensively in other fluid handling industries as condition monitors (including aerospace applications), where the operational life of components depends on controlling the level of particulates. In both the hydraulic and commercial diesel industries, particle-counting data are used to help in the design and specification of critical components. By measuring the wear characteristics produced by given numbers of particles at given sizes, it has been possible to specify metallurgy and other design criteria for components, and contaminant limits for fluids used by those components, and thus optimise the whole process (G. Bessee of SwRI presented "Wear Index and Particle Counting" at the 2004 CRC Aviation Fuel meetings.)

Recent use of this technology in the field of aviation fuels has produced arrays of data for particulate incidence as a function of number and size but with little against which to correlate. Gravimetric analysis does not differentiate between systems with many small particles and those with a few large ones; Clear & Bright is a subjective test dependent on the analyst's judgement (eyesight) and rarely differentiates between dispersed water and particulates. Presentations at the annual CRC Aviation Fuels meetings and other industry meetings have indicated that the introduction of particle counting as an "active" in-line, real-time field contaminant assay method could provide the industry with a further level of security over the more passive filtration and separation devices. Their combined use would provide the highest technical assurance to aircraft operators of the safety and durability of the fuel and fuel systems. This is a recommendation of a new industry document, API/IP 1550 published at the end of 2007. Knowledge of engine hardware requirements, especially their design limits, will constitute important input to the debate on particle detection strategies and limit setting; this is the main data package provided by this report.

From both first principles of design and feedback from the field, engine fuel systems' designers and hardware specifiers have encountered indicators of wear due to fuel quality. It is this information that this project has sought to elicit as input to the future task for the fuel supply industry in setting dispersed contaminant limits, including safety margins, and the methods for determining these.

3.0 THE QUESTIONNAIRE

The list of Engine OEM and fuel system component suppliers used in this study is given in Appendix A. Many addresses were obtained from company websites and were far less productive in producing information than those that were those individuals obtained from personal contacts and networks.

The questionnaire sent to the contact points is reproduced in Appendix B. It was designed to be open-ended to solicit more information from the engine and component OEMs regarding the types of fuel-borne contaminants that are particularly stressful or detrimental to engine and engine component operations. It was also intended to determine what design criteria are in current use within the industry. The respondents were cautioned not to disclose proprietary or otherwise confidential information so that the results of this work could be made known in the public domain.

Respondents participated on a voluntary basis and, as such, participation was relatively low. It was noted that there was no real return on investment to the participants and the people most likely to be willing or have the data were often the individuals in a location with the greatest demands on their time. For these and other possible commercial reasons, the response rate was low.

It is always possible that the best informant in a given organisation never received the request for data but at the end of almost 12 months, only three organisations had responded. However, because these three respondents represented the majority OEM and component supplier share of the market, the results of this study can be taken as representative. It is therefore to the individual credits of these organisations that did respond that this report has been produced. By agreement between CRC and the respondents, their identities have been kept confidential so, unfortunately, the authors cannot thank them by name in this report for their cooperation.

4.0 CONCLUSIONS FROM RESPONSES

The individual, detailed responses are given in Appendix C and these have been summarised in Appendix D. The survey was separated into four sections: "general", "operational", "component design and specification" and "miscellaneous". The following analysis reflects those themes.

4.1 Conclusions of General Section

The purpose of the general section was to obtain an understanding of the general parameters involved in the design and manufacture of the fuel handling and management systems. The respondents were questioned on the fuel properties they used during design and specification for use, general observations on service intervals, and critical components regarding sensitivity to contamination. A final open question was posed to define in an OEM's terms the concept of a fuel "contaminant".

Based on the responses, the components most sensitive to contamination involved tight tolerances and small passages. Thus anything negatively affecting the motion of a component or the flow of fuel through the component was considered a problem. It can be concluded that anything that was large enough, anything that can aggregate to be large enough, or anything which if present causes stiction or plugging is of concern.

The table below summarises the responses; see Appendix D for further information.

Fuel properties relevant to the engine fuel supply system.	Lubricity, viscosity, vapour pressure, specific gravity, cleanliness, specific heat, density, thermal conductivity, thermal stability.
Components requiring more frequent inspection	Filters, actuators, fuel controls, servo-valves, fuel pump splines (this last due to low lubricity; all items involve close tolerances or low flows).
Components considered sensitive to contaminants	Fuel screens and filters, spool valves, fuel pumps, combustor nozzles, fuel metering valves, solenoid (ball) valves, bleed orifices and restrictors, control orifices and nozzles, valve seats, fluid control devices and heat exchangers (for all of these, except the heat exchanger, close tolerances or small flows are the issues).
Fuel contaminants of interest to engine OEMS	Particulates (a broad compositional range from silica to rusts and clays), Free water (undissolved water that may contain salt and that is able to freeze and form ice crystals at altitude), and Microbiological growths. Also soluble components such as: Fuel system icing inhibitors, fuel additives[1], sulphur and copper content, dyes, leak check fluids, assembly lubricants, adhesives and sealants.

NOTE: The current issue foremost in most OEMs' minds is impending filter by-pass – something that has provoked intense activity operationally and is the subject of an IATA technical working Group comprising airline, OEM, equipment supplier and oil company representatives. Filter plugging, rather than abrasive wear of components, is the major concern.

4.2 Conclusions of Operational Section

The greatest emphasis of the survey was placed on operational considerations; how contaminants impinge on operational matters, component reliability, etc. The results

[1] Most optional aviation additives should only be present in the fuel by agreement with the supplier and the customer but there is evidence today that FSII is being added to some fuels as far upstream as point of production. In a long, fungible fuel distribution system, that additive notification can become "lost". OEMs are finding FSII unexpectedly in engine components. Other additives include approved aviation corrosion inhibitors and static dissipator but, again, under circumstances where they are unexpected. Also included would be additives from cross-contamination by, for example, diesel and gasoline fuels. Dyes could be included here as they tend to be used in non-taxed automotive fuels that could cross-contaminate jet turbine fuels in a multi-product distribution system.

One recommendation here might be to initiate another study relating to soluble jet fuel contaminants to assess the seriousness of the above observations.

of this section were very diverse and indicated a wide range of types of concerns that can be summarised as follows:

- Respondents identified a number of sources for particulate contaminants. Some contaminants were thought to have been introduced by the fuel, some within the operational environment, and some internally generated by the equipment itself.

- Most of the respondents indicated they did not experience component damage or operational problems due to particulate exposure. The main reason given for this is the practice of using filters that are rated and sized to provide absolute protection for any vulnerable component.

- With the important role played by these filters, filter plugging by fine particulate, cotton linters, etc., was clearly high on respondents' minds and this issue was mentioned frequently.

- Problems most often attributed to the presence of particulates have been cumulative and progressive rather than sudden, instantaneous events.

- Free water was described as both a short-term engine performance issue and a longer-term corrosion problem.

- In general, respondents did not think that there was a significant impact on the service life of components due to contaminants with the current levels of filter protection. The only indication of concern was a response indicating that once contamination took place it was difficult to remediate.

- It was felt that fuel as currently supplied to aircraft is sufficiently clean and/or the systems are robust enough to withstand current exposure levels.

- In the case of the fuel control manufacturer, the respondent indicated that contamination accounted for 10% of the fuel control removals. This is the component with the tightest tolerances.

- Most respondents indicated that they had difficulty identifying the particulate contaminants and therefore identifying their source[2].

4.3 Conclusions of Component Design and Specification Section

This section was designed to better understand how engine and component manufacturers deal with particulate contamination during the design process, and to

[2] There is a clear need for an industry approach to developing an analytical protocol for dealing with such incidents.

attempt to capture what cleanliness specifications are in use. A summary of responses is given as follows:

Specifications for components

Respondents indicated the use of a number of design specifications: industry specifications, specifications generated in-house and customer provided specifications. One respondent indicated the industry specification was a base level that was then made more stringent to provide greater margins of safety.

How much and what type of particles?

While one of the major engine manufacturers used NAS 1638, class 8, others quoted MIL-E-5007. Both are actually defunct standards but continue in use for reasons not considered here. The main point is that they provide traceable answers to the questions of how much and what size of particles. The standards quoted used various test dusts, none of which is still available. One, a silica test dust known as ACFTD – AC Fine Test Dust – was supplied as sieved material originating from the Arizona desert. "The industry" developed a number of better-defined test dusts with the publication of ISO 12103. NAS 1638 users generally migrated to ISO4406:1999 but another standard is now available as a more direct replacement (SAE AS4059). OEMs have maintained their procedures under the older nomenclature but have modified them to accommodate the new replacement materials and methods.

Despite this industry change, we have been able to define both particle counts and dust mass used by OEMs and component suppliers in component testing. Appendix G shows the particle size distribution for the ISO 12103, A2 test dust now in use. (Part 2 of this standard also refers to alumina test dusts that are also used by OEMs).

A test dust gravimetric level of 2mg/l is used as a continuous challenge for engine components (or NAS Class 8); in contrast there is an API/IP ground filtration performance requirement of 0.15mg/l maximum transmission using the finer test dust, ISO 12103, A1. There is therefore a very comfortable margin between OEM particulate test requirements and those used by the fuel supply industry, both in terms of particle size and quantities.

What size of particles?

As indicated earlier, fuel control components appear to be the most sensitive to the presence of particulate contamination and are therefore protected by filters with an absolute rating of about 35 microns. Subsequent to obtaining feedback to the questionnaire, the authors were made aware of some small aircraft applications that may use even finer filtration (10 microns absolute). API/IP ground filters are currently tested using a protocol that does not establish an absolute rating. Using a fine test dust and monitoring the filter transmission levels by using a 0.8 micron membrane, they could be described as having a nominal rating of 0.8 micron, but there will be a small level of uncertainty here in terms of the actual level of contingency provided.

What about water?

The OEM appeared to be more concerned with material consequences than with performance issues. In this respect 0.01%volume, or 100ppmv, of free dispersed water is the highest level that is tested. Again, as with particulate, this compares well with the API/IP ground filtration specification performance limit of 15ppmv – another good margin.

4.4 Conclusions of Miscellaneous Section

The last section was an open-ended opportunity for the participants to comment on any items felt to be important and not covered by the previous questions. These responses are provided below:

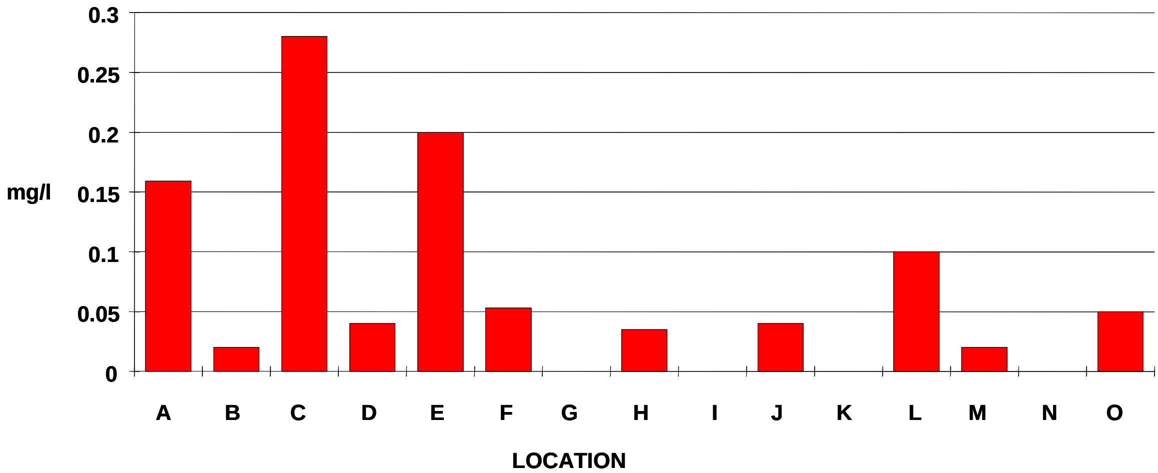
- Secondary effects from contamination, such as corrosion or varnish can be more substantial than the physical effect of the initial particle
- Concrete dust is abrasive and reduces fuel lubricity
- Green slime (microbial growth) can clog bearings and lubrication/cooling passages reducing component life
- Inlet filter plugging has been an increasing problem over the last several years – requiring reduced filter change interval for some customers
- Presence of water may affect inlet filter dirt capacity

- Sensors to measure dirt in jet fuel should measure particle loading (number of particles or mass of particles) for each particle size class up to at least 40 microns.

5.0 THE FUEL SUPPLY CONTEXT

Particle number, size and composition have all been considered by the engine OEMs and fuel system component suppliers in their respective design and testing processes. On the other side of the wing is a huge fuel supply industry that does not define fuel cleanliness in these terms. At the airport, the nature of the business does not easily permit on-line, real-time, quantitative assessments of fuel cleanliness - just simple visual checks. Instead, the industry depends heavily on the operational performance of highly specified filtration equipment (passive monitoring). Gravimetric analysis (as an indicator of the continuing positive performance of these filters) is carried out according to IATA Guidance but only at 6-month intervals. In fact, the fuel supply industry has very little collated data on fuel cleanliness at the into-plane position at airports. In 1996, API/EI sponsored a study that took a "snapshot" sample of fuel cleanliness at 20 airports[3]. The work was commissioned to establish the nature and level of the contaminant challenge at various points in an airport fuel supply system and the into-plane results are shown here for comparison with the above OEM data. The average gravimetric loading at the into-plane position was found to be 0.066mg/l. This level was determined upstream of the into-plane fuel filtration. No measurements were made on the downstream side but even at this level, the fuel is well within cleanliness limits given by IATA (0.2mg/l – notify, 1.00mg/l reject). Even the dirtiest location was only just outside the notification limit and it is fairly safe to assume that the level would reduce on the downstream side of the into-plane filters.

[3] Proceedings of the 7th International Conference on the Stability, Handling and Use of Liquid Fuels (IASH), A survey of solid contaminant types and levels found in a range of airport fuel handling systems, V.B. Hughes and P. D. Rugen.



API/IP Study 1996: Into-plane gravimetric dirt loadings per ASTM D2276
(Average loading = 0.066mg/l, Range = 0.0 - 0.28mg/l)

Unfortunately gravimetric analyses are erratic and, more importantly, there is no indication of the nature of the contaminant. Any given measured mass could comprise large numbers of small particles or small numbers of large particles or large amounts of a low-density material or small amounts of a high-density material. None of this is helpful in terms of predicting the effects of any given fuel contaminant load on airframe or engine components.

More recently, trials with particle counting equipment at airports have been reported[4]. The collated data from a large number of measurements taken downstream of the into-plane filtration equipment indicated particle counts that were far below the NAS Class 8 quoted by one of the OEM's.

After Monitor Into Plane		ISO Code - 4406 1999
	High Count	High Count Code
>4µ(c)	100	14
>6µ(c)	10	10
>14µ(c)	1	7

More of this type of data are being generated as this report comes to its conclusion and have been made available at the 10th IASH Conference (see www.iash.net). The counts are per millilitre and it is clear that negligible amounts of particulate >14µm(c)

[4] UK MoD Aviation Fuels Committee, April 2006

are being transmitted to the aircraft wing tanks. The advantages of this type of cleanliness analysis are clear in that the data are quantitative, continuous and real-time; they open up the possibility of actively monitoring fuel condition throughout the refuelling process.

The challenge for the adoption of this type of approach, however, is that there is a need to migrate from "mg/l" as a contamination concept to particle sizes and counts. That is a major cultural change for the fuel supply industry. Furthermore, limit setting requires end-user/supplier consensus and that, in turn, requires the sort of data and information that this report has sought to provide in terms of OEM requirements, together with statistically significant amounts of field generated data.

6.0 Comparison of Appearance vs. Gravimetric Tests

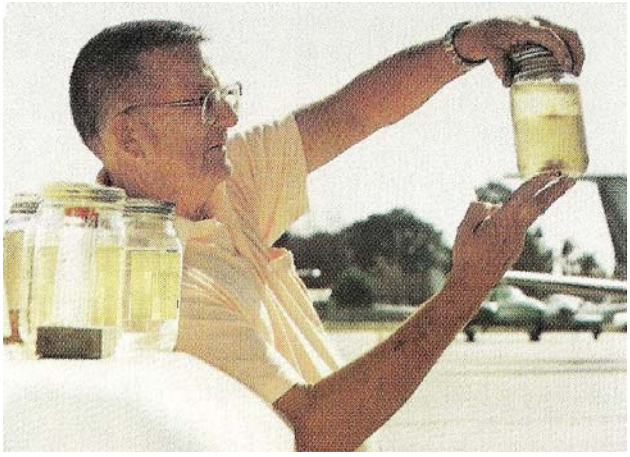
An industry-wide consensus on aviation fuel cleanliness would seem to be both technically and commercially advantageous. This report has identified the engine OEM approach to ensuring the safe operation of engines and highlighted specific components that clearly require special attention. Test dusts comprising abrasive components, at a size and concentration that will cause component failure, are used to validate the performance of protective fuel filters. Test dusts have a well-defined particle size range and composition (density) and therefore concentration can equally validly be expressed as either a gravimetric loading (mg/l) or a cleanliness code (NAS1638 Class or ISO 4406:1999) – both essentially define a number of particles. The fuel supply sector, however, has for the last 30 years defined cleanliness in terms of appearance (qualitative) and/or gravimetric loading (quantitative). This final section of this report compares and contrasts these methods.

6.1 Appearance testing:

The fuel supply sector makes use of a very simple and longstanding method of visually inspecting a sample of the jet fuel for contaminants. Known as "Clear & Bright", the method is limited by the sensitivity of the human eye – generally accepted to be capable of no better than 40μm.

The advantage of this type of analysis is its rapid applicability to any operation where a sample may be taken and viewed by an operative. Its real value is in managing gross contamination in fuel handling operations such as tank farm.

http://www.fuelsolution.com/images/innovate1.jpg



Aviation International News, 7/1/97, pg 99

The disadvantages are: that the eye cannot detect particles <40µm unless present in very large amounts (yet it is commonly accepted that these are indeed the particles that cause the most problems); the small sample volumes involved are hardly representative of the fuel loads uplifted into aircraft; and finally, the method is not continuous.

6.2 Gravimetric testing:

More quantitative, but also more cumbersome, is the use of a gravimetric method (e.g. ASTM D-2276) in which a known volume of fuel is forced through a well-defined filter membrane (rated at 0.8µm) which is weighed after drying. The result is expressed in mg/l. Under the right conditions this method can yield very accurate particulate contamination levels[5], although it still suffers from the representative sample issues raised above.

Gravimetric analysis requires formal laboratory processing and is therefore not available in real-time. Consequently, it is NEVER used during into-plane refuelling,

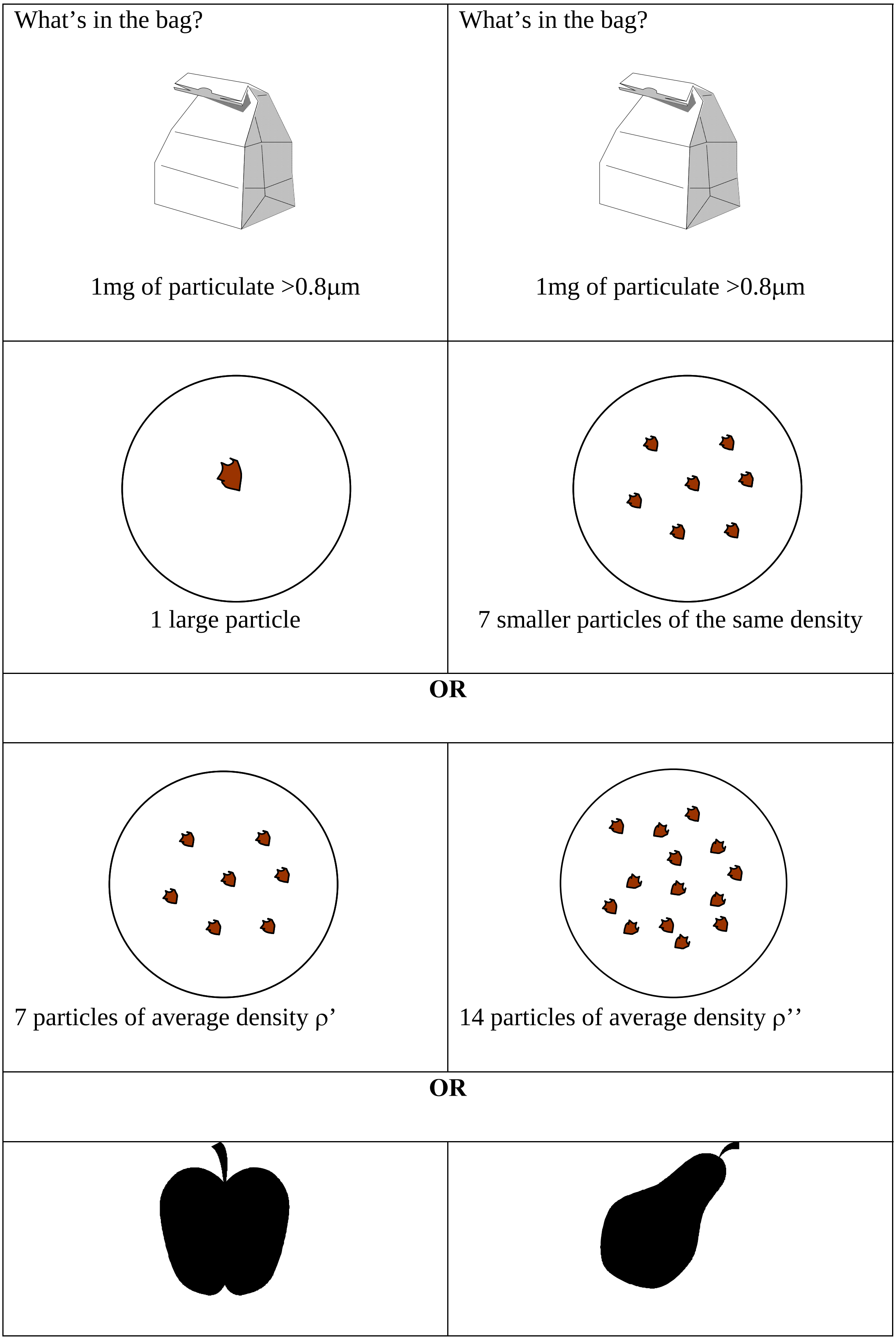
[5] This method may be found in use in many military jet fuel specifications as well as some commercial ones. It is also to be found in IATA Guidance Material

even though it is commonly quoted as a quantitative method for particulate assay. Furthermore, there are many instances of anomalous results from the gravimetric method, with the occurrence of both negative and grossly inflated results – see for example Appendix H.

Contaminants affect equipment reliability as a function of their composition, size and concentration –gravimetric assay methods do not address these parameters. A gravimetric loading of 1 mg/l does not discriminate between many small particles or a few large ones. Nor does it differentiate between small levels of a dense material or large amounts of a light material as the following cartoon in Figure 6.1 below demonstrates.

Gravimetric determinations conducted on a contaminant with an unknown composition can yield, at best, the mass of material with particle sizes greater than the defined rating of the gravimetric pad or patch. Even that can be erratic if the masses of the pads do not remain constant during the analytical process. In field testing, there is no knowledge of contaminant composition (hence density) or particle size (total volume) and therefore any given result is ambiguous in terms of these two properties. Moreover, the gravimetric limits currently quoted in a number of industry fuel specifications have no traceable origin or justification – they are merely “currently acceptable”.

Figure 6.1 Gravimetric Analysis - The Enigma Code:



Thus, there are numerous technical reasons for challenging the *status quo* and, indeed, there are future commercial and operational reasons that demand it.

7.0 Recommendations

7.1 Recommendations for a contamination level

One of the findings of this report was that there is no consensus at any level, between any manufacturers, or between parts of the industry, regarding what a contaminant is, what level of contamination is used for testing and use, or how it is measured. There is no consensus between customers regarding what level of contamination resistance is expected or what type of testing for certification is expected.

Based on the results of the survey, it appears that the current redundancies in the fuel system testing and the fuel delivery system have to date been sufficient to provide fuel of a necessary cleanliness level for operations. It is beyond the scope of the data to draw conclusions on whether it will continue to be sufficient. It is also beyond the scope of the data to determine whether future changes at any point within the system could have a negative impact on maintainability or durability of current aviation equipment.

This precludes the recommendation of even a rudimentary contamination level from the results of this program.

7.2 Recommendations for developing consensus on testing methods

The lack of consensus between the hardware designers and manufacturers, and the fuel distribution industry regarding testing method or test material is a major stumbling block to the development of a particulate contamination level. Either a consensus on method and particulate type, or a correlation between groups must be developed[6].

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[6] It should be noted that as this report is being finalised, Def Stan 91-91 is due to publish a 6th Edition in which particle counting will be a requirement at point of production. No limits have been set but all producers of jet turbine fuel using this fuel specification will be required to implement the test and

Potential options for facilitating the development of consensus include the reactivation and use of MIL-E-5007 or the creation of an equivalent civil aviation document, development of a Federal Aviation Regulation (FAR) document containing contamination and testing requirements by system or application, or incorporating the requirements into airworthiness certification.

All of these options are beyond the scope of this report but the authors feel strongly that they be addressed as a matter of some urgency by the relevant industry groups.

"Felix qui potuit rerum cognoscere causas (Virgil, 1st Century BC)
Happy is he who understands the causes of things"

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report results. These will generate a valuable quantitative data set for use in any future industry fuel cleanliness initiative.

APPENDIX A

Aviation Turbine Engine OEMs

Solus manufacturers:

Company	Web site	Contact details	Comments
Aviadvigatel	www.avid.ru	Gor-vi@jetmotors.perm.ru	Perm Engine Company Based in Russia
General Electric	www.geae.com	Terry.McClary@ae.ge.com Terry McClary, CFM International Inc., Product Support Engineering, One Neumann Way, M/D 423, Cincinnati, OH 45215 – Tel: 513-552-5936, Fax: 513-552-1859, Cell: 513-708-5142	Commercial, Corporate and Military engines
Honeywell	www.honeywellaerospace.com/prod_byfamily_propulsion_overview	602-365-3099 randy.williams.phx@honeywell.com	(Allied Signal is now Honeywell), Propulsion Systems enterprise (PSE)
MTU Aero Engines GmbH	www.mtu.de/en/index	Dr. Robert Leipold robert.leipold@muc.mtu.de Tel +49 (0)89 14 89-4512 Fax +49 (0)89 14 89-97655 Dr. Hohmann: Stefan.Hohmann@muc.mtu.de Dr. Gläser: Bernhard.Glaeser@muc.mtu.de	Based in Germany. MTU Aero Engines GmbH Wärmetechnik und Verbrennung TESW Dachauer Str. 665 80995 München Germany
Pratt & Whitney	www.pw.utc.com	Dr. Ken Baker -(815) 394-4942, ken.baker@hs.utc.com	Hamilton Sundstrand (a sister company to P&W and part of UTC) owns the fuel systems. Also include Tedd Biddle in any communications
Rolls Royce	www.rolls-royce.com	chris.lewis@rolls-royce.com	Also Allison Engine Company
Snecma	www.snecma.com	Jean Luc Leeder, Didier Detrift, Snecma Melun, Aerodrome de Villaroche – BP1936, 77019 Melun Cedex, France	Also Turbomeca, **Snecma and Sagem merge, changing name to SAFRAN**

Teledyne Technologies	www.teledyne.com	No contact found	Niche market manufacturer
Williams International	www.williams-int.com	No contact found	From 1000 to 3500 pounds thrust

Joint ventures:

Company	Web site	Contact details	Comments
Aero Engines LLC	world.honda.com/GEHondaAeroEngines	No contact found	GE/Honda – handled by GE
CFM	www.cfm56.com	No contact	GE/Snecma -
International Turbine Engine Corporation		Via Honeywell, ITEC is a company that makes the TFE1042 turbofan engine for Taiwan (part of Honeywell, based in Phoenix)	Honeywell PSE, AIDC (China) – use Honeywell as primary contact.
CFE738		Via GE and Honeywell	General Electric/Honeywell
International Aero Engines	www.i-a-e.com		P&W/RR/MTU/Japanese Aero Engine Corp.

Other control components:

Company	Web site	Contact details	Comments
MOOG	www.moog.com	none	
Sunstrand		See P&W	

Bearing Manufacturers:

Company	Web site	Contact details	Comments
F.A.G.	www.fag.com	none	Schaeffler Group
NHBB	www.nhbb.com	none	
Torrington	www.timken.com	none	

Pump Manufacturers:

Company	Web site	Contact details	Comments
Lucas (Aerospace)	?	?	
ArgoTech	www.**argo-tech**.com	Rick Henfling, 216 692 6031 and Kurt Kachler, 216 692 6121	
Imo	www.**imo**pc.com	None	
Woodward	www.**woodward**.com	None	Supply GE

APPENDIX B

Questionnaire sent to OEM contact addresses

(Direct reproduction of the questionnaire as provided to the participants)

OEM QUESTIONNAIRE

on

FUEL SYSTEM CONTAMINANTS

by

Coordinating Research Council, Inc.

3650 Mansell Road, Suite 140, Alpharetta, Georgia 30022, USA.

Project No.	AV-4-04
Title:	Sensors to Measure Particulates and Dirt in Fuel Delivery Systems
Objectives:	To provide data and information that will help industry reach consensus on the most useful parameter(s) for measuring fuel quality (particulate contamination) by surveying engine OEM and fuel system supplier practice and requirements.
Agency:	Vic Hughes Associates Limited, Cae Einion, Corwen, LL21 9BY, Wales, UK.
Date:	August 2005

QUESTIONNAIRE:

General:

G1	What fluid properties are considered in the overall design specification for the fuel handling and delivery system on your turbine engines/fuel-wetted components?	
G2	In terms of recommended servicing intervals, which components require the most frequent attention/checking? Note: These may not be related to operational aspects or safety of flight concerns but may also include warranty claim issues or customer satisfaction.	
G3	In terms of sensitivity to fluid contaminants, we have identified the following components as possible candidates for further discussion: 1. fuel screens/filters 2. spool valves 3. fuel pumps 4. combustor nozzles. Do you know of any other specific components that might be affected by the abrasion/wear associated with contacting fluid contaminants?	
G4	Fluid contaminants are usually classified as: 1. Particulate – with a broad composition ranging from silica to rusts and clays, 2. Free water – undissolved water that may contain salts but which will freeze at altitude forming ice crystals, 3. Microbiological growths – bacterial/fungal/moulds. Are there any other types of fluid contaminant that you feel might usefully be included in this survey?	
G5	Do you have control over the design and operational specifications for components identified in G3? If not, who does? (please supply reference point(s) for any contracted-out activities here as we will wish to follow up – alternatively, if you could obtain this information for us that would be most appreciated)	

Operational:

O1	Is component damage by particulate or other fluid contamination a problem for your products? Examples of problems could include premature wear, warranty claims, general product performance concerns, customer satisfaction issues, or delays in fielding components.	
O2	What types of contamination cause the greatest problems? Examples might be "small quantities of small particles that are hard and abrasive", "large, easily friable contamination that plugs passages", metal wear debris,	

	polymer wear debris, "dirt", water.	
O3	Are the problems that have been encountered due more to cumulative wear/plugging or catastrophic contamination?	
O4	Which is more of an issue, filter and passage plugging or abrasive wear?	
O5	Can you quantify the impact of fluid contaminants on the reduction in expected service life of components?	
O6	If you could control fluid contaminant levels, how do you think that would impact on fleet mean time between overhauls for your customers?	
O7	Has your organization had difficulty in identifying the type or source of a particulate contamination?	
O8	Are particulates most frequently attributed to generation within the engine system or introduced from external sources?	

Component Design & Specification:

C1	For any of the components identified in G3, are there industry or in-house test methods to assess robustness to contaminants? (e.g. hardness, abrasive wear, full engine response to contaminant packages, dirt durability tests)	
C2	Do you have a particulate test requirement? What is measured and what are the value limits?	
C3	Do you have a free water test requirement? What is measured and what are the value limits?	
C4	Do you have a maximum particle size exposure limit? What is measured and what are the value limits?	
C5	Do you have a maximum particle size durability requirement? What is measured and what are the value limits?	
C6	How do you prevent the entrance of particulates to your system? i.e. fibre filters, screens, cyclonic separators	
C7	Is this measured/specified nominally or absolute?	
C8	SAE ARP 1827 is a recommended practice for “Measuring aircraft gas turbine engine fine fuel filter element performance”. Do you make use of this document or anything similar? If so what is the document?	

Miscellaneous:

M1	Do you have any other comments on the impact of fluid contaminants that will contribute to this study?	

Contacts:

For further information or discussion one of the contacts listed below may contact you to arrange a short interview. If you require any information on this study please contact one of the contacts below.

United Kingdom	United States
Vic Hughes	Melanie Thom
Vic Hughes Associates Limited	Baere Aerospace Consulting, Inc.
Thebusker@msn.com	melanieathom@compuserve.com
Tel/Fax: +44 1490 413529	Tel/Fax: 1-765-743-9812
Cell: +44 790 999 6003	Cell: 1-765-409-3542

We would appreciate your supplying a contact telephone number for the above supplementary discussion activities.

Contact Name, time zone and telephone number	

APPENDIX C

Responses to Questionnaire

General Section:

What fluid properties are considered in the overall design specification for the fuel handling and delivery system on your turbine engines/fuel-wetted components?	Lubricity, viscosity, and vapour pressure	Specific gravity, viscosity, vapour pressure, lubricity, cleanliness (particulates)	Specific heat, lubricity, density, thermal conductivity, stability (coking temperatures), vapour pressures, contaminants – go read the fuel spec.
In terms of recommended servicing intervals, which components require the most frequent attention/checking? Note: These may not be related to operational aspects or safety of flight concerns but may also include warranty claim issues or customer satisfa	None more than others	1, Filters, actuators, fuel controls, servo valves 2, Fuel pump splines (wear due to lower lubricity fuel)	Engines are currently designed/operated with an on-condition maintenance philosophy. It gets pulled off wing for overhaul when it runs out of thrust margin, unless some symptom triggers earlier action. More directly to your point, the main issue we see
In terms of sensitivity to fluid contaminants, we have identified the following components as possible candidates for further discussion:1. fuel screens/filters 2. spool valves 3. fuel pumps 4. combustor nozzles.Do you know of any other specific component	No	Fuel metering valves, solenoid valves (ball valves), servo valves, bleed orifices/ restrictors, control orifices/ nozzles, valve seats, fluid control devices, heat exchangers	We filter the fuel near the fuel inlet, so most components don't see any contamination except by the finest of particles. The big stuff ends up in the filters. Our experience is that fuel pumps (centrifugal and gear-types) are robust to the level of cont
Fluid contaminants are usually classified as:1. Particulate – with a broad composition ranging from silica to rusts and clays,2. Free water – undissolved water that may contain salts but which will freeze at altitude forming ice crystals,3. Microbiologica	No	Fuel system icing inhibitors, other fuel additives, sulphur and copper in fuel, dyes, leak check fluids, assembly lubricants, adhesives/sealants	Hydraulic fluids due to heat exchanger leaks. We have had much concern expressed by regulatory authorities over debris left in airplane tanks, but this would be outside scope for you, I think.

Operational Section:

Is component damage by particulate or other fluid contamination a problem for your products? Examples of problems could include premature wear, warranty claims, general product performance concerns, customer satisfaction issues, or delays in fielding components.	No	1) Yes, listed examples cover most concerns		2) Not significantly		Not damage, no. Filter clogging is more of an issue.
What types of contamination cause the greatest problems? Examples might be "small quantities of small particles that are hard and abrasive", "large, easily friable contamination that plugs passages", metal wear debris, polymer wear debris, "dirt", water.	metal wear debris and water	1) Large quantity of dirt/debris of all sizes plugs inlet filter	2) Cotton linters clog filters	3) Water, crushed quartz, and dirt corrode and wear out components	4) Very small particles can coalesce into larger particles downstream of filters plugging passages	Water causes the worst operational issues since it can actually cause an engine to roll back from the desired power setting. We have seen occasional very severe particulate contamination (out of Lagos Nigeria, for instance).
Are the problems that have been encountered due more to cumulative wear/plugging or catastrophic contamination?	cumulative wear/plugging	Cumulative wear and plugging				The second. I would not use the word catastrophic because that has a very specific meaning in aviation safety (multiple fatalities…). Very small hard particulates (< 10 to 15 mm) can "build up" silt in spool valve clearances creating functional performance issues. This seems to be more of a testing issue than actual field experience.
Which is more of an issue, filter and passage plugging or abrasive wear?	abrasive wear	1) Filter/passage plugging,		2) Abrasive wear		Filter plugging. Accumulated plugging. But the very abnormal contamination, which result in operational events are the major concern.

Can you quantify the impact of fluid contaminants on the reduction in expected service life of components?	Small	1) Cannot quantify,		2) Once contaminated, difficult to effect a complete cleanout		The worst contamination we have seen reduced filter service life from thousands of hours to a single flight. This was an extreme case. A factor of 2 or 10 on filter life would be more typical.
If you could control fluid contaminant levels, how do you think that would impact on fleet mean time between overhauls for your customers?	Small	1) Unknown	2) Less downtime and less infant mortality	3) Very little	4) Contamination accounts for ~10% of fuel control removals	No impact
Has your organization had difficulty in identifying the type or source of a particulate contamination?	No	1) Yes, very much so, ,	2) Yes, due to transportation system mixing fuel from various sources	3) Yes, hardest to identify was concrete dust – big problem with airports under construction		Yes, reporting on particulate type is the exception rather than the rule. Perhaps 1 in 10 reports lets us know anything about contaminant type.
Are particulates most frequently attributed to generation within the engine system or introduced from external sources?	Within	1) External sources – FBOs and AC fuel tanks,		2) Both – external contamination is either particulates or in solution (precipitates out), self generated usually solid and metallic		External

Component design and specification Section:

For any of the components identified in G3, are there industry or in-house test methods to assess robustness to contaminants? (e.g. hardness, abrasive wear, full engine response to contaminant packages, dirt durability tests)	industrial	1) In-house guidelines	2) Dirt durability tests, contaminated fuel tests (component and engine)	3) Customers usually specify contamination limits higher than industry standards to provide margin – some have their own test requirements from lessons learned		Yes. FAR33.67 requires we test the fuel system with the contamination expected to occur.
Do you have a particulate test requirement? What is measured and what are the value limits?	Yes, NAS 1638, class 8 Micron…….# 5-15……64,000, 15-25….11,400, 25-50……2,025, 50-100…....360, >100…………64	1) Usually per MIL-E-5007. Some customers require limited operation (4 hours up to a mission cycle) with inlet filter in full bypass.	2) Varies with customer, some have light dirt (8 gm/1000 gal) continuous, and heavy dirt (40 gm/1000 gal) extreme	3) Higher contamination limits usually required by military	4) Usually measure dirt type and particle size, dirt loading, and subsequent filter DP vs. time at rated flow, or may just verify proper component or engine operation for specified time	Yes, based upon legacy experience. 300 hours at @ 8.0 grams / 1000 gallon fine Arizona road dust.
Do you have a free water test requirement? What is measured and what are the value limits?	No, dissolved water only	1) Usually per MIL-E-5007. Some commercial applications require demonstration of proper engine operation after cold soak with water in fuel – must show proper operation (no stuck components due to ice), no corrosion	2) No	3) Yes, measured on standard test fuel (LWC) – for component certification tests use salt water (4 parts salt to 9 parts water @ 0.01% by volume) – must show proper operation and no corrosion	4) Military applications require shutdowns with salt water in fuel (up to 20 hours) – must show proper operation and no corrosion	We test system susceptibility to icing at 0.75 cc / gallon free water.

Do you have a maximum particle size exposure limit? What is measured and what are the value limits?	Yes, see C2 above	1) Yes – inlet filters are typically 25 to 40 microns absolute – filter manufacturer measures max particle size through filter.	2) Yes – typically per MIL-E-5007	3) Typical max particles are 300 micron crushed quartz	We filter to 35 micron absolute based upon legacy experience.
Do you have a maximum particle size durability requirement? What is measured and what are the value limits?	No	1) Yes – inlet filters are typically 25 to 40 microns absolute	2) Yes – typically per MIL-E-5007	3) Some customers require FOD test (Al chips, lockwire, fibres, tank sealant, rivet heads) – must pass through boost pump with no degradation	No
How do you prevent the entrance of particulates to your system? i.e. fibre filters, screens, cyclonic separators	Fibre filters	1) Fibre filters	2) Yes – all those mentioned	3) Yes – fibre inlet filters, wash and "last chance" screens – single engine military augment above with cyclonic separators	Filters, screens, wash flow screens, cyclones.
Is this measured/specified nominally or absolute?	Absolute	1) nominal plus absolute – for both specifications and test			Absolute
SAE ARP 1827 is a recommended practice for "Measuring aircraft gas turbine engine fine fuel filter element performance". Do you make use of this document or anything similar? If so what is the document?	no	1) Yes, also MIL-E-5007 and customer specifications			Filter elements performance is tested by sub-tier supplier IAW 1827.

Miscellaneous Section:

Do you have any other comments on the impact of fluid contaminants that will contribute to this study?	No	1) Secondary effects from contamination, such as corrosion or varnish can be more substantial than the physical effect of the initial particle.	2) Concrete dust is abrasive and reduces fuel lubricity	3) Green slime (microbial growth) can clog bearings and lubrication/cooling passages reducing component life	4) Inlet filter plugging has been increasing problem over last several years – requiring reduced filter change interval for some customers	5) Presence of water may affect inlet filter dirt capacity	6) Sensors to measure dirt in jet fuel should measure particle loading (number of particles or mass of particles) for each particle size class up to at least 40 microns.	Understanding the normal and worst case extreme contamination threat is our biggest problem. We are not the user, and have difficulty gathering actual use data.

APPENDIX D

Summarised Responses

Detailed analysis of questionnaire responses:

General:

Qu.G1. What fluid properties are considered in the overall design specification for the fuel handling and delivery system on your turbine engines/fuel-wetted components?

Whilst all of the fuel properties covered in the various fuel specifications were considered relevant to this question, one or more of the respondents highlighted the following:

a. lubricity
b. viscosity
c. vapour pressure
d. specific gravity
e. cleanliness (particulates)
f. specific heat
g. density
h. thermal conductivity
i. thermal stability

Qu.G2. In terms of recommended servicing intervals, which components require the most frequent attention/checking? Note: These may not be related to operational aspects or safety of flight concerns but may also include warranty claim issues or customer satisfaction.

- There were widely diverging views on this aspect. In general, no one particular component emerged as needing more frequent attention than any other. One respondent explained that engines in service are monitored and removed for service when they fall outside some given thrust margin. The exception to this would be when some specific symptom required earlier attention.
- **Fuel pumps** were specifically mentioned as having a known wear mode with one respondent pointing to **lower lubricity fuels** as the cause.
- Fuel leakage due to **seal failure** was identified by another respondent as a leading cause for component removal.
- **Actuators, fuel controls and servo valves** were all listed as components needing attention.
- Currently, the issue foremost in some OEM's minds, is impending **filter bypass**.

Qu.G3. In terms of sensitivity to fluid contaminants, we have identified the following components as possible candidates for further discussion: 1. Fuel screens/filters, 2. Spool valves, 3. Fuel pumps, 4. Combustor nozzles. Do you know of any other specific components that might be affected by the abrasion/wear associated with contacting fluid contaminants?

A more comprehensive list of systems and components that are sensitive to the presence of fuel contaminants is now presented as follows:

1. **Fuel screens/filters**
2. Spool valves
3. Fuel pumps
4. Combustor nozzles
5. Fuel metering valves
6. Solenoid valves (ball valves)
7. Servo valves
8. Bleed orifices/ restrictors
9. Control orifices/ nozzles
10. Valve seats
11. Fluid control devices
12. Heat exchangers
13. Dynamic seals in actuators

However, the "sensitivity" may not be just abrasive wear. **Plugging** has also been identified as a significant problem. Note that for most if not all of the above components the OEMs include protection in the form of filtration.

Qu.G4. Fluid contaminants are usually classified as: 1. Particulate – with a broad composition ranging from silica to rusts and clays, 2. Free water – undissolved water that may contain salts but which will freeze at altitude forming ice crystals, 3. Microbiological growths – bacterial/fungal/moulds. Are there any other types of fluid contaminant that you feel might usefully be included in this survey?

Although outside the scope of this study, on-aircraft fluid contaminants such as leaked hydraulic fluids, lubricants, adhesives and sealants were identified as problems as were instances of additives and trace components in fuels delivered to the aircraft, e.g.

- Fuel system icing inhibitor (FSII),
- Other fuel additives,
- Sulphur
- Copper,
- Dyes,
- Leak check fluids.

Additives should only be present in the fuel by agreement with the supplier and the customer but there is evidence today that FSII is being added to some fuels as far upstream as point of production. In a long fungible distribution system, that additive notification can become "lost". OEMs are finding FSII unexpectedly in engine components. Other additives include regular aviation corrosion inhibitors and static dissipater but again under circumstances where they are unexpected. Also included would be additives from cross-contamination by diesel and gasoline fuels for example. Dyes could be included here as they tend to be used in non-taxed automotive fuels that could cross-contaminate jet turbine fuels in a multi-product distribution system.

One recommendation here might be to initiate a CRC study relating to soluble jet fuel contaminants to assess the seriousness of the above observations.

Qu.G5. Do you have control over the design and operational specifications for components identified in G3? If not, who does? (Please supply reference point(s) for any contracted-out activities here as we will wish to follow up – alternatively, if you could obtain this information for us that would be most appreciated.)

This question was designed to catch any relevant contracted out activities. One OEM pointed out that they had control over the performance specification of components used in the engine. Since this would be the most informative area for the purposes of this study, it was thought unnecessary to drill down too deeply to the vendor level.

Operational:

Qu.O1. Is component damage by particulate or other fluid contamination a problem for your products? Examples of problems could include premature wear, warranty claims, general product performance concerns, customer satisfaction issues, or delays in fielding components.

Responses to this question were quite varied. For the most part component damage does not seem to be an issue with maybe one exception but **filter-clogging** was clearly identified as an issue.

Qu.O2. What types of contamination cause the greatest problems? Examples might be "small quantities of small particles that are hard and abrasive", "large, easily friable contamination that plugs passages", metal wear debris, polymer wear debris, "dirt", water.

- "Yes" would be the correct answer summarising the respondents' views! Each had a view that included at least one of the given examples.
- **Water** was identified as having both long- and short-term effects. In the latter case, water can immediately affect engine operation in terms of power output or even flameout in extremis. In the former case, corrosion was seen as the main effect (probably associated with microbiological activity).

- The main effect of **particulate** contamination no matter what type was claimed to be **filter plugging**. Specifically mentioned particulates included metal swarf (wear debris) and cotton linters that together with other finer particulates cause filter plugging. Silica quartz, with a Mohr's hardness of 7 will cause abrasive wear.

Qu.O3. Are the problems that have been encountered due more to cumulative wear/plugging or catastrophic contamination?

Generally the feeling was that contaminant impact was a gradual process and in view of other later responses regarding the filtration regimes used, **plugging** would seem to be the most important problem.

Qu.O4 Which is more of an issue, filter and passage plugging or abrasive wear?

Both **abrasive wear and plugging** appear to be equally rated as issues.

Qu.O5 Can you quantify the impact of fluid contaminants on the reduction in expected service life of components?

"Little or none" were the main replies suggesting that this was not a relevant question to the engine OEMs. In a worst case example, filters were plugged in the course of a single flight but more typically plugging might reduce filter service life by a factor of two. There did not appear to be an impact on other components.

Qu.O6. If you could control fluid contaminant levels, how do you think that would impact on fleet mean time between overhauls for your customers?

Following on from the previous answer, it is clear that fuel contamination does not impinge greatly on the long-term performance of engines.

Qu.O7. Has your organization had difficulty in identifying the type or source of a particulate contamination?

- "Yes" was the majority answer. One of the most important aspects of fuel contamination investigations involves identifying the nature of the problem. Identification leads to the source and subsequent resolution of contamination problems and yet this aspect appears to be problematic.
- There is a clear need for an industry approach to developing an analytical protocol for dealing with such incidents.

Qu.O8. Are particulates most frequently attributed to generation within the engine system or introduced from external sources?

The very varied answer to this question may reflect the lack of analysis suggested by the response to Qu.O7. One respondent was adamant that the contamination was generated within the engine, another that it was generated externally whilst another said both. The aircraft wing-tank environment was also identified as a contributor to problems.

Component design and specification:

Qu.C1. For any of the components identified in G3, are there industry or in-house test methods to assess robustness to contaminants (e.g. hardness, abrasive wear, full engine response to contaminant packages, dirt durability tests)?

In short – yes there are. The methods range from formal Federal Aviation Regulations (FAR 33.67) to in-house guidelines. Testing covers particulate durability of components to complete engines. One respondent noted that customers might also occasionally add test requirements for higher contaminant loadings reflecting the need for margin in a particular application.

Qu.C2. Do you have a particulate test requirement? What is measured and what are the value limits?

Ranges of particulate challenges were given with no single real commonality. The list of responses was as follows:

1. NAS1638, Class 8 (See Appendix E):

Particle size, μm	Numbers of particles
5 - 15	64 000
15 - 25	11 400
25 - 50	2 025
50 - 100	360
>100	64

.

2. MIL-E-5007 (See Appendix F)
3. A light dirt challenge would be 8g/1000 gal continuous, and heavy dirt 40g/1000 gal. These are equivalent approximately to 2mg/l and 10mg/l respectively.
4. Higher contamination limits than above usually required by military.

5. Usually measure dirt type and particle size, dirt loading, and subsequent filter DP vs. time at rated flow, or may just verify proper component or engine operation for specified time.

6. Some customers require limited operation with inlet filter in full bypass (anything from 4 hours up to a mission cycle).

One respondent was particularly concerned about the occasional but regularly encountered abnormal levels of fuel contamination. Whilst nothing appears to be known for definite as to their epidemiology it would appear that the whole industry is implicated and the situation requires an international effort to ensure a technically robust study. Only when the issues are properly understood can there be any remedial action.

Qu.C3. Do you have a free water test requirement? What is measured and what are the value limits?

For free water testing the answers ranged from none to a variety of combinations. The emphasis here though appeared to be on the material specification for components rather than operational specification limits that could be translated into a fuel specification.

MIL-E-5007 was referred to again but this relates only to corrosion processes following exposure to saline solutions (viz. – for component certification tests use salt water (4 parts salt to 9 parts water @ 0.01% by volume) – must show proper operation and no corrosion. Military applications require shutdowns with salt water in fuel (up to 20 hours) – must show proper operation and no corrosion.)

Some commercial applications require demonstration of proper engine operation after cold soak with water in fuel (0.75cc water / USG fuel equivalent to about 200ppmv– must show proper operation (no stuck components due to ice), no corrosion.

Qu. C4 Do you have a maximum particle size exposure limit? What is measured and what are the value limits?

Without dwelling too much on definitions, two responses to this question referred to the absolute filter rating rather than a particle size per se. This measurement appeared to derive from supplier performance testing and was quoted as 25-40 microns. As an absolute rating a single figure should have been quoted and one respondent did do so at 35 microns. This is an important data point. Previous presentations at CRC aviation meetings have occasionally quoted similar values for the finest engine filter ratings although these values sometimes become confused by the inclusion of "nominal" ratings at smaller particle sizes. Nominal ratings can usually be taken as supplier aspirations or marketing information or at best "a quoted percentage removal efficiency for particles of the size rating".

A useful limit to take forward would seem to be 35±10 microns.

Qu. C5 Do you have a maximum particle size durability requirement? What is measured and what are the value limits?

Again, and related to the previous question, durability requirements relate to the fine fuel filtration at 35±10 microns. In a more extreme environment boost pumps appear to be required to operate with what can only be described as "macro-contamination" (aluminium chips, lock-wire, fibres, tank sealant, rivet heads).

Qu. C6 How do you prevent the entrance of particulates to your system? e.g. fibre filters, screens, cyclonic separators

The responses indicated that all the examples were used. Screens have an absolute rating given by the mesh dimension but fibre filters have to be tested to yield either nominal or absolute ratings. Single engine military engines were augmented with cyclonic separators.

Qu. C7 Is this measured/specified nominally or absolute?

The respondents all procured absolute rated filters.

Qu.C8 SAE ARP 1827 is a recommended practice for "Measuring aircraft gas turbine engine fine fuel filter element performance". Do you make use of this document or anything similar? If so what is the document?

Surprisingly, none of the respondents thought that their organisations made use of ARP 1827. It is still possible that the filter manufacturers do but this was not followed up. The respondents quoted operational (MIL-E-5007 and IAW 1827) and customer requirements as more relevant.

Miscellaneous:

Qu.M1 Do you have any other comments on the impact of fluid contaminants that will contribute to this study?

Some interesting further comments were captured in this section:

1) Secondary effects from contamination, such as corrosion or varnish can be more substantial than the physical effect of the initial particle.
2) Concrete dust is abrasive and reduces fuel lubricity.
3) Green slime (microbial growth) can clog bearings and lubrication/cooling passages reducing component life.
4) Presence of water may affect inlet filter dirt capacity.

5) Inlet filter plugging has been increasing problem over last several years – requiring reduced filter change interval for some customers.
6) Sensors to measure dirt in jet fuel should measure particle loading (number of particles or mass of particles) for each particle size class up to at least 40 microns.
7) Understanding the normal and worst case extreme contamination threat is our biggest problem. We are not the user, and have difficulty gathering actual use data.

The first four items add emphasis to the need to exclude specific contaminants from the fuel system of an engine. Filter plugging is more generic comment highlighting a possible fuel supply cleanliness issue that appears to be a recent phenomenon. A number of industry groups are currently investigating this. The last comment supports the reintroduction of particle detection/counting and recommends a size range up to 40 microns.

APPENDIX E

NAS 1638

NAS 1638

In this industry standard, fluid cleanliness is measured using a light obscuration particle counter. It is one technology that is currently being considered for aviation fuels and the stimulus for this report. The results are presented as differential counts of particles within a number of size ranges, e.g., 5-15 micron, 15-25 micron, etc. Numbers of particles counted can be large (tens of thousands per size range) and so the industry determined to reduce any confusion that might arise from handling such large numbers by introducing a *"Class"* system – a single digit that represents a range of counts. This also reduced count accuracy concerns – with such large numbers it is common to find fairly large number variations that are actually statistically insignificant but appear dramatic.

Since nature determines that for most particulate systems there are many more smaller particles than larger ones and that there are regular patterns of size distributions, this standard gives limits for a number of particle size ranges that can each be used individually to equate to a given Class. One respondent claimed to use this standard as a limit for particulate and quotes the following:

Particle size, µm	Numbers of particles
5 - 15	64 000
15 - 25	11 400
25 - 50	2 025
50 - 100	360
>100	64

This equates to a NAS 1638, Class 8.

IMPORTANT NOTE:

Whilst many in the industry are still using NAS Class, the standard is defunct. It is still used and quoted, mainly due to its long-term adoption by military organisations that are relatively unwilling to migrate to the new standards (logistical reasons can be persuasive). A correlation between new and old standards does exist and this allows organisations to continue to quote cleanliness in NAS Class.

The problem for NAS Class arose when the calibrating test dust ACTFD became unavailable. The industry then had to address this serious situation urgently and produced ISO 12103, a standard that defines particle distributions of a number of test dusts, e.g. for silica there are A-1, A-2, A-3, and A4. With those test dusts as calibrants and new technologies in particle sizing, NAS 1638 was replaced with SAE AS4059. A new size definition has been introduced - μm(c) – (c) means that the new calibrants have been used and that the size determination uses an "equivalent sphere" rather than "longest chord" approach[7]. This introduces a slight difference in the quoted dimension of any given particle as shown in Table E.1 reproduced below.

Optical microscopy count, ISO 4402, size in μm	>1	>5	>15	>25	>50	>100
Electron microscopy count, ISO11171, size in μm(c)	>4	>6	>14	>21	>38	>70

Table E.1 Equivalent particle sizes in new and old particle sizing standards.

Whilst NAS 1638 expressed particle number as differential counts (e.g. 5-15, 15-25, etc.), SAE AS4059 quotes sizes cumulatively (>4, >6, etc.). SAE AS4059 is currently available as Revision C, with another revision to be published.. The reason for so many revisions is the need to allow the industry to adjust progressively to the changes in calibrants and technology brought about as described earlier. There is another equivalent and less complex system available in ISO 4406 that also uses the calibration systems in ISO 11171. It would be advisable for any industry seeking to adopt particle-counting methods to use the most up-to-date and widely accepted protocols from the start; ISO 4406 and 11171 are highly recommended.

[7] See CRC 2005, Particulate Panel presentation by Gary Bessee of SwRI entitled "An explanation of μm(c)".

APPENDIX F

MIL-E-5007

MIL-E-5007 is a very comprehensive document that contains specifications on the performance and testing of jet turbine engines. It covers every conceivable aspect of testing, reporting, inspection, operation, and many other aspects of these engines. As such, it is a voluminous document within which the fuel contamination detail is deeply buried.

Oil filtration is the first contaminant aspect to be covered, but not here. Interestingly, and somewhat bizarrely, inlet air contamination by 4-ounce and up to 4-pound weight birds is included to simulate "bird strike". Ice injection, also into the inlet air stream, is required to simulate flight through hailstorms, and finally, sand (75-1000 μm range) injection, to simulate operations in wind-blown sand-storms.

However, Section 3.7.3.3.2 is the most relevant to this study. It has a stated requirement for the engine to function satisfactorily when using fuel contaminated up to the limits specified in Table X, which is reproduced below:

TABLE X. Fuel Contaminants

REF.- 3.7.3.3.2, 3.7.3.4

CONTAMINANT	PARTICLE SIZE	QUANTITY
Ferroso-Ferric Iron Oxide (Fe_3O_4, (Black color) Magnetite)	0 - 5 microns	14.5 gm/1,000 gal.
Ferric Iron Oxide (Fe_2O_3, Hematite)	0 - 5 microns	14.5 gm/1,000 gal.
Iron Oxide	5 - 10 microns	1.5 gm/1,000 gal.
Crushed Quartz	1000 - 1500 microns	.25 gm/1,000 gal.
Crushed Quartz	420 - 1000 microns	1.75 gm/1,000 gal.
Crushed Quartz	300 - 420 microns	1.0 gm/1,000 gal.
Crushed Quartz	150 - 300 microns	1.0 gm/1,000 gal.
Prepared dirt conforming to A.C. Spark Plug Co. Part No. 1543637 (coarse Arizona road dust)	Mixture as follows: 0 - 5 microns (12 percent) 5 - 10 microns (12 percent) 10 - 20 microns (14 percent) 20 - 40 microns (23 percent) 40 - 80 microns (30 percent) 80 - 200 microns (9 percent)	8.0 gm/1,000 gal.
Cotton Linters	Below 7 staple (U.S. Department of Agriculture Grading Standards SRA- AMS 180 and 251)	0.1 gm/1,000 gal.
Crude Napthenic Acid		0.03 percent by volume
Salt water prepared by dissolving salt in distilled water of other water containing not more than 200 parts per million of total solids	4 parts by weight of NaCl 96 parts by weight of H_2O	0.01 percent by volume entrained

14.5g/1000USG is actually 3.8mg/l, whilst 8g/1000USG is 2.1mg/l. In summary, the above contaminant loadings are not particularly severe per se, but contaminant components such as coarse Arizona road dust and cotton linters would be very damaging to engine components.

A subsequent section, 3.7.3.4 describes requirements for a fuel filter that may be required to be mounted within the engine to deal with contaminants finer than 1500µm. A size rating is not given for this filter, but it is required to operate for at least 12 hours of continuous exposure to fuel contaminated as described in Table X. Both impending by-pass (filter almost blocked) and actual by-pass (filter blocked) alarms are required to warn the pilot of the fuel quality status.

Unfortunately, this specification was subject to the notice reproduced below:

MIL-E-5007D
NOTICE 1
8 January 1997
MILITARY SPECIFICATION
ENGINE, AIRCRAFT, TURBOJET AND TURBOFAN
GENERAL SPECIFICATION FOR
This notice should be filed in front of MIL-E-5007D, dated 15 October 1973, and Amendment 3,
dated 27 December 1995.
MIL-E-5007D is inactive for new design and is no longer used, except for replacement purposes.

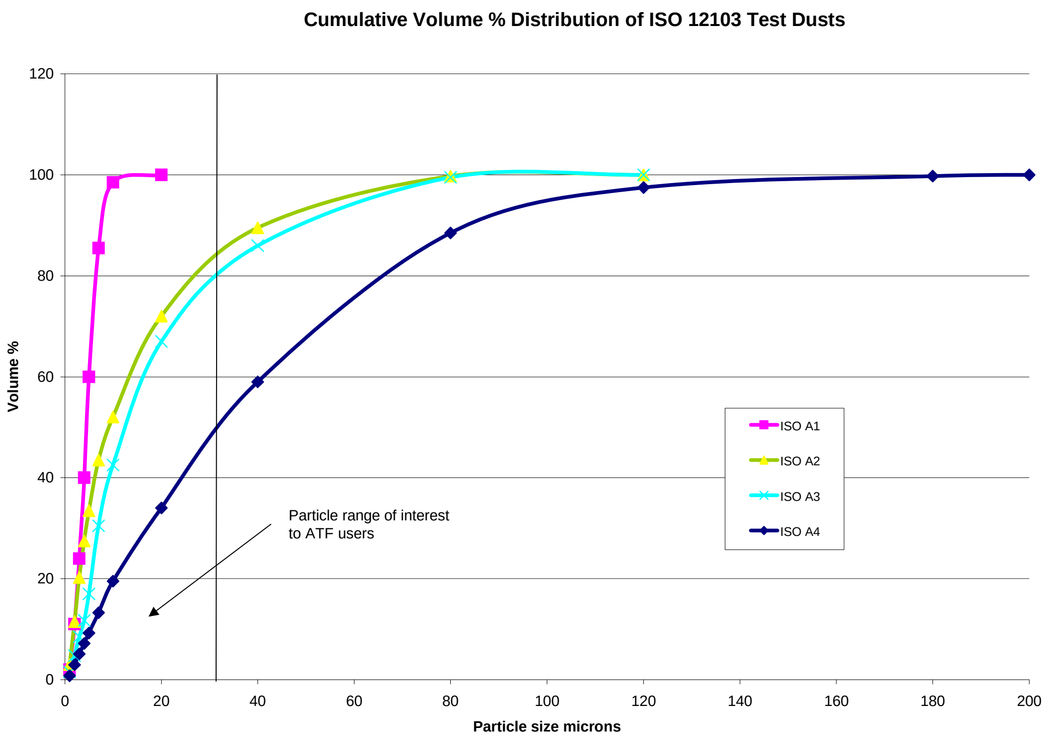
The specification only applies to legacy equipment. Just as with NAS1638, the OEMs appear to be using specifications that are no longer supported. However, subsequent queries have revealed that whilst OEMs continue to use the processes identified in MIL-E-5007, they have updated materials and test methods according to broader industry guidelines. As with NAS 1638, the changes were precipitated by the sudden withdrawal of ACFTD and other test dusts. These have been replaced within the MIL document by the ISO test dusts referenced earlier.

APPENDIX G

ISO 12103 Part 1 Test dusts

Size (µm)	A1 Ultrafine	A2 Fine	A3 Medium	A4 Coarse
1	1 to 3	2.5 to 3.5	1 to 2	0.6 to 1
2	9 to 13	10.5 to 12.5	4.0 to 5.5	2.2 to 3.7
3	21 to 27	18.5 to 22.0	7.5 to 9.5	4.2 to 6.0
4	36 to 44	25.5 to 29.5	10.5 to 13.0	6.2 to 8.2
5	56 to 64	31 to 36	15 to 19	8.0 to 10.5
7	83 to 88	41 to 46	28 to 33	12.0 to 14.5
10	97 to 100	50 to 54	40 to 45	17.0 to 22.0
20	100	70 to 74	65 to 69	32.0 to 36.0
40	--	88 to 91	84 to 88	57.0 to 61.0
80	--	99.5 to 100	99 to 100	87.5 to 89.5
120	--	100	100	97.0 to 98.0
180	--	--	--	99.5 to 100
200	--	--	--	100

ISO 12103-1 Test Dusts as Volume Fraction, %
:



APPENDIX H

Examples of anomalies using Gravimetric Analyses

Gravimetric and colorimetric results for a range of test dust loadings in filtered jet fuel and a cross-correlation with two field samples.

The data below show some recent anomalies encountered in using the gravimetric assay method. They are reproduced here out of context and with the permission of the data owners. The fuel samples comprised a number of field samples, together with filtered fuel accurately dosed with a mixture of test dusts. In this example the gravimetric method appeared to overestimate the levels of contaminant but there have been many other examples in which under-estimation has been encountered.

Sample	Expected Dirt loading/mg/l	Gravimetric Mass/ mg/l	Control Before	Test Before	Control After	Test After	Vol (ml)	Rating
1	0.0	0	81.4	68.1	81.5	68.2	1000	A1
2	0.25	0.4	81.6	68.1	81.5	68.4	1000	A2
3	0.5	1.2	82.3	68.2	81.9	69.0	1000	A3
4	0.75	1.5	81.6	67.9	80.7	68.5	1000	A3
5	1.0	2.2	81.8	67.3	80.9	68.6	1000	A3
6	1.5	1.7	81.8	68.6	81.7	70.2	1000	A4
7	2.0	2.2	81.1	68.6	81.0	70.7	1000	A4
8	0.75	0	74.9	69.1	75.3	69.5	1000	A4
9	Field Sample	1.1	75.4	70.9	75.2	71.8	1000	A1
10	Field Sample	0.2	74.2	68.2	74.0	68.2	1000	A2
13	0.75	1.2	66.3	71.5	66.1	72.5	1000	A3

Reference to the picture below shows that the colorimetric assay is aligned with the expected dirt loading, confirming this latter and challenging the veracity of the calculated gravimetric loadings. These measurements were all made under controlled laboratory conditions.

Note: The field samples #9 and #10 illustrate the real problems encountered in the field. Sample #9 yields a gravimetric result that would cause rejection of the cargo whilst colorimetrically it is lighter than sample #10. Sample #10 appears to be the same colour as sample #5, which was designed to contain an amount of contaminant that would constitute a "rejection" but gravimetrically appears to be only a level that would cause "notification". But which is correct?

Photograph of the gravimetric pads used in the above particulate assay showing the colorimetric correlation with expected loading.