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Analysis of oil for wear debris by rotrode atomic emission spectrometry (RAES) has been part of the component health monitoring used by the military services for two decades. However, the last 5–10 years have seen a number of changes, including attrition from the program, more serious budgetary constraints, improvements in the design and manufacturing of engines and other components, and changes in oil filtration. Although the need for diagnostic and prognostic information has never been stronger, RAES faces challenges from other techniques. Compounding this problem is an aging infrastructure and aging equipment. Taken together, these factors paint a less than rosy picture of sustainability. In this white paper, various sustainability issues are considered as well as possible options for addressing them.

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JOAP-TSC-TR-06-06

SUSTAINABILITY OF ROTRODE ATOMIC EMISSION SPECTROMETRY FOR WEAR DEBRIS

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October 4, 2006

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Director's statement

The Joint Oil Analysis Program is a tri-service activity that standardizes and coordinates the oil analysis programs of the Army, Navy, and Air Force. The JOAP Technical Support Center provides the scientific and engineering data and expertise necessary for the JOAP to carry out its mission. The JOAP TSC performs instrument testing and evaluation, statistical analysis, applied research, market research, and laboratory analyses for mishap investigations within the scope of its mission at the request of Defense Department components. In addition, the JOAP TSC manufactures standards, carries out certification programs for JOAP-approved laboratory instruments, runs a laboratory for analyzing oil and wear debris, and produces the JOAP manual as its major ongoing business.

In addition to the three major services, the JOAP TSC supports the Marine Corps, the Coast Guard, the National Aeronautics and Space Administration, and other allied forces. JOAP TSC services are available to any Defense Department component activity as part of our core mission. They are available to other federal government agencies through assistance agreements. The JOAP TSC addresses issues regarding lubricants, coolants, transmission fluids, and hydraulic fluids in any military system—not just vehicles and weapons systems. The JOAP TSC works with industrial partners and the Pentagon on a variety of projects to support condition-based maintenance and mechanical component (engine, gearboxes, etc.) health monitoring.

This report was reviewed and approved for publication in accordance with the Joint Instruction designated as Air Force Instruction 21-131(I), Army Regulation 700-132, and OPNAVINST 4731.1B.

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Executive summary

Analysis of oil for wear debris by rotrode atomic emission spectrometry (RAES) has been part of the component health monitoring used by the military services for two decades. However, the last 5–10 years have seen a number of changes, including attrition from the program, more serious budgetary constraints, improvements in the design and manufacturing of engines and other components, and changes in oil filtration. Although the need for diagnostic and prognostic information has never been stronger, RAES faces challenges from other techniques. Compounding this problem is an aging infrastructure and aging equipment. Taken together, these factors paint a less than rosy picture of sustainability. In this white paper, various sustainability issues are considered as well as possible options for addressing them. Although this report does not offer any recommendation, it does imply that a rapid and significant injection of funding is both appropriate and necessary to sustain this program and reverse its declining trend. Moreover, it emphasizes the need for a strategic plan that incorporates a clear vision for the utility and applicability of RAES and also ensures that suitable measures are taken to maximize its effectiveness and ensure its perceived value throughout its anticipated lifetime, which is taken to be approximately 25 more years. With corrective measures for renewal, replacement, and repair, RAES has potential to enable condition-based maintenance and provide net value to all its customers. Nevertheless, this role will only come to fruition if there is a strongly executed plan to collect, centralize, mine, and analyze all of the data; to refine and revise triggers and limits; to make the data and the analyses accessible and comprehensible; to apply what is learned broadly and thoroughly; and to obtain commitment for the use of that information from platform managers, engineers, and maintenance crews alike.

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1. Introduction

1.1. Sustainability

For any program to be sustainable, the rate of improvement must exceed or equal the rate of degradation. Improvement occurs through replacement, renewal, and repair. Degradation occurs mainly through depreciation and decapitalization. A program where the improvement and degradation rates are equal will be minimally sustainable and minimally functional. That is, it will just survive and just meet needs or objectives; it will not thrive. Programs that are minimally sustainable and minimally functional are continually at risk because they often fail to meet growing customer expectations. Most customers will have increasing expectations as a result of normal consumerism and readily apparent technological progress.

1.2. Rotrode atomic emission spectrometry

Rotrode atomic emission spectrometry (AES) has been used to detect and quantitate both wear debris and contamination for more than 20 years. The rotrode AE spectrometer is the one truly joint instrument in that every military oil analysis laboratory has one. This technique consumes a significant portion of the oil analysis budget, but even moreso for the Air Force and Navy, because it is so heavily used for aircraft oil analysis.

For the purposes of this report, the JOAP spectrometers will be referred to as a fleet of spectrometers. The fleet includes all of the spectrometers under the control of any of the service oil analysis program offices (Air Force, Army, or Navy) as well as the Air National Guard and Marine Corps.

Substantial infrastructure within the JOAP and DoD as a whole maintenance paradigm has been constructed around rotrode atomic emission spectrometry. Overall, rotrode AE spectrometry represents a major investment in assets as well as continuing costs for training, operation, upkeep, labor (collecting, shipping, and testing samples), information technology (database support)

❶ The Navy has continuously employed (or reserved billets for) two technicians whose primary role is the repair of rotrode AE spectrometers.

❷ The Air Force manages a major maintenance contract, which is also used by the Army.

❸ Much of the JOAP Manual is dedicated to the use of the spectrometer or focused on reacting to RAES data.

❹ The Navy and Air Force conduct extensive training programs. The Navy sends all its operators through a JOAP school, while the Air Force integrates rotrode AES into its nondestructive inspection (NDI) training. Most of the JOAP school focuses on rotrode AES, although there are small components on viscometry and other techniques.

❺ Most aircraft can be grounded based on rotrode AES testing results, and most aircraft are on the program. Engines may be sent for overhaul based on the same results.

❻ For many aircraft, rotrode AES is the major or only external engine health monitor for condition-based maintenance. Other measures are internal to the aircraft (e.g., chip detectors, vibration and temperature sensors). The other external techniques are filter debris analysis by energy-dispersive x-ray fluorescence (EDXRF) analysis (e.g., FilterCHECK™) or magnetic chip detectors (more accurately chip collectors) whose contents may be subjected to scanning electron microscopy-energy dispersive x-ray (SEM-EDX) analysis (e.g., JetSCAN®).

❼ A reimbursible program established through the Defense Logistics Agency enables the JOAP TSC to manufacture standards for use in the field.

❽ The JOAP TSC conducts a correlation/certification program as a measure of performance uniformity among the instruments in the fleet (pursuant to the JOAP joint instruction).

❾ Lastly, the spectrometers themselves represent a major capital investment, despite depreciation.

1.3. Specific sustainability issues

In this report, sustainability is addressed in three broad areas:

1. Depreciation and decapitalization
2. Obsolescence
3. Value, applicability, and utility

Depreciation and decapitalization refer to the effects of aging and the value of the equipment. Obsolescence refers to the aging of the technology and thus has an impact on value either by requiring replacement or renewal to meet requirements or by reducing applicability or utility. The more general issue of value will determine what resources are dedicated to addressing depreciation, decapitalization, obsolescence, applicability, and utility.

2. Depreciation and decapitalization

2.1. Definitions

Depreciation is the continuous degradation of aging equipment. Assets are lost through depreciation even when they are completely functional and they are repaired and maintained properly. In this program, the principal means by which *decapitalization* occurs is complete depreciation (zero dollar value) as a result of age. However, decapitalization also includes other total losses of capital equipment such as destruction or transfer to another property accountability area. Transferred equipment has not been treated as decapitalized here because any transferred equipment has immediately been put into service rather than treated as government surplus. As a rule, this program has no excess equipment, and spectrometers are not disposed of through DRMO.

2.2. Aging assets

The age distribution of the spectrometer fleet is shown in Table 2.1. A significant fraction of the capitalized assets are aged; this is especially true for the Air Force, where the average age of a spectrometer is 8.4 years. The Army is best positioned and approximately where it ought to be for a mature program since its assets are slighly younger than the half-way point for their expected lifetime. For the program as a whole, the average spectrometer age is 7.6 years, which is suboptimal considering the typical lifetime of a piece of laboratory equipment.

Table 2.1. Age distribution of rotrode atomic emission spectrometers (number of units) in the fleet

Age range, years	Average age, years	Air Force	Army	Navy	JOAP
0.00–2.00	1.0	22	2	4	28
2.01–5.00	2.5	35	25	11	71
5.01–10.00	7.5	116	11	54	181
10.01–15.00	12.5	113	0	0	113
Average age of a unit, years		8.4	3.9	6.3	7.6

Note: Numbers of units in each age range were provided by Spectro, Inc., who manufactured and sold the units and who holds the maintenance contract for these units.

For the JOAP as a whole, most spectrometers are 5–10 years old. Figures 2.1 and 2.2 illustrate the same data as Table 2.1, with breakdowns by age then service (Figure 2.1) or service then age (Figure 2.2). The Air Force owns the most spectrometers and has the most spectrometers in each age range, which is what would be expected. Figure 2.1 shows an undesirable situation where the number of spectrometers in the first two age groups (0–2 and 2–5 years old) is less than the group of units that are 5–10 years old. This distribution typifies a program with a large initial investment and relatively low renewal as opposed to simple accretion of assets. Sustainable programs require renewal and replacement rates to equal depreciation, which would mean that the heights of the bars would be 2:3:5:5. However, a program with growth and renewal would have more new units. The fact that there are more units in the 5–10-year-old group than the 10–15-year-old group demonstrates that growth occurred for a period of about 10 years and then slowed. The relative aging becomes more apparent when the data are plotted as pie graphs as has been done in Figure 2.3. What is most outstanding about the presentation in Figure 2.3 is that more than three quarters of the Air Force assets are past half their expected lifetimes; therefore, the Air Force requires a significant capital infusion to redress this issue. The sheer size of the Air Force fleet affects the JOAP fleet despite the better position of the Army (which happens to own the smallest fleet). Approximately three quarters of the JOAP spectrometers are past half their expected lifetimes.

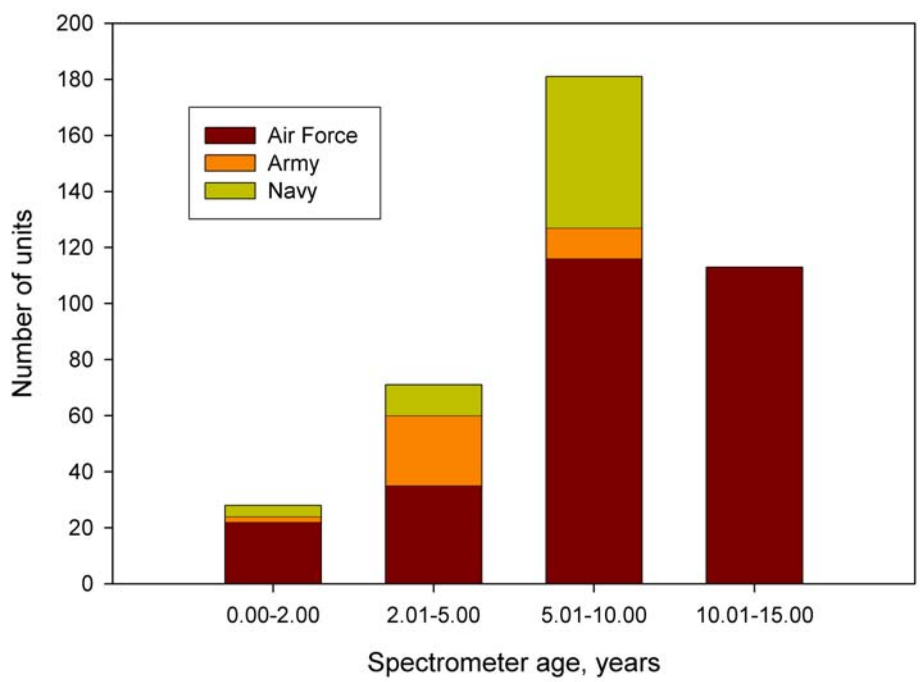

Figure 2.1. Age distribution of rotrode atomic emission spectrometers (Spectroil M or M/N) in the JOAP, further broken down by service.

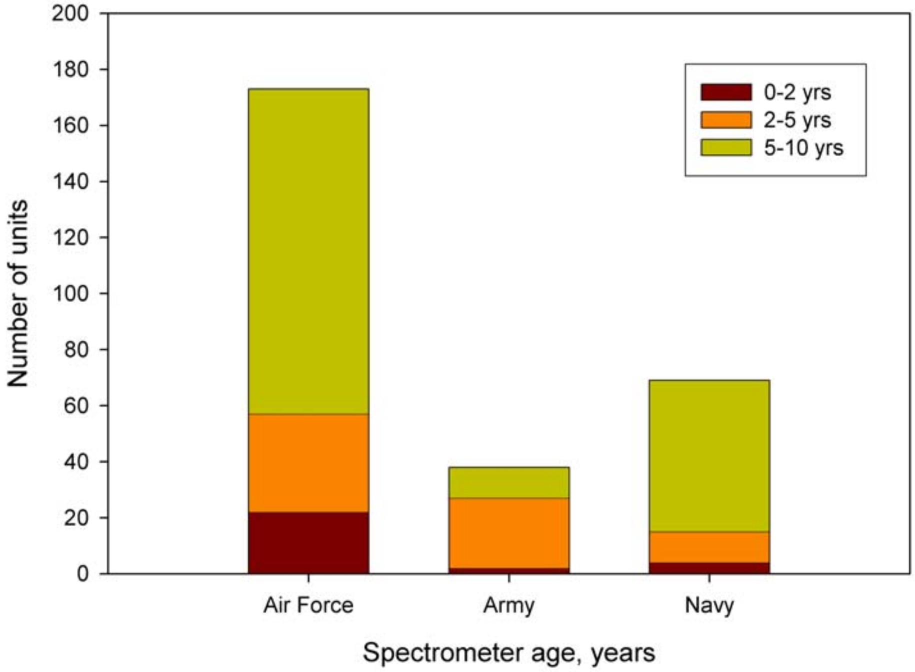

Figure 2.2. Service distribution of rotrode atomic emission spectrometers (Spectroil M or M/N) in the JOAP, further broken down by age.

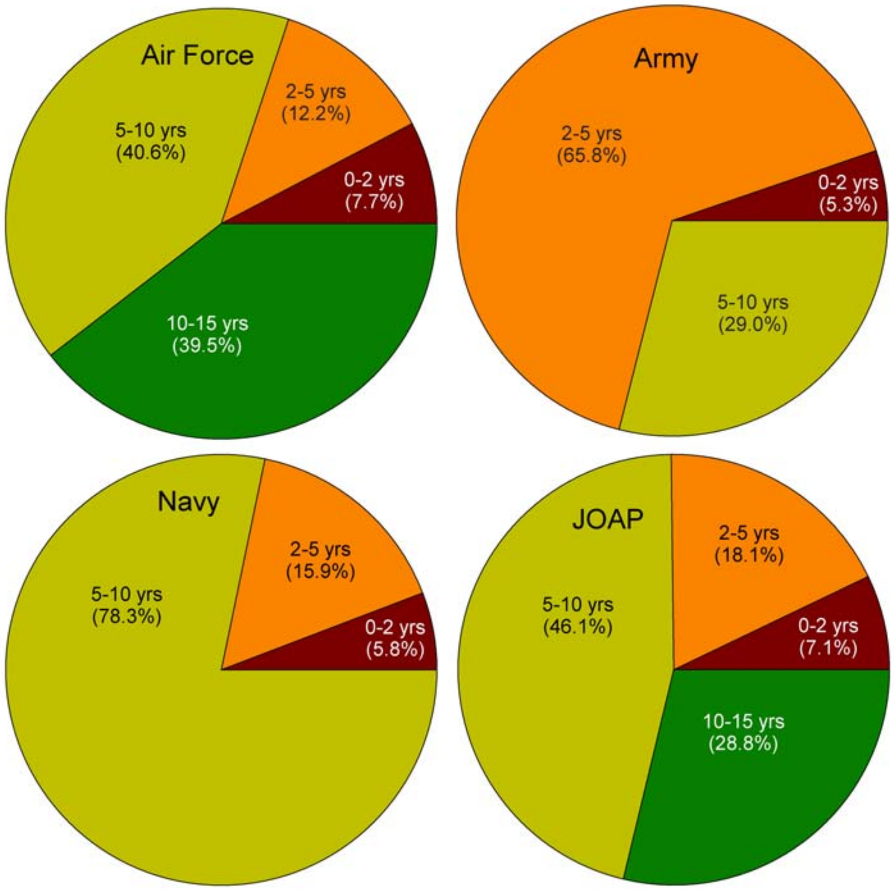

Figure 2.3. Fractional age distribution of rotrode atomic emission spectrometers within the services and within the JOAP.

2.3. Age-depreciated assets

For a laboratory instrument with a 10-year lifetime, the average rate of depreciation is 10% per annum since one year is 10% of the lifetime. For the purposes of this report, a liberal lifetime of 10 years (in accordance with the Defense Financial Management Regulations) has been used even though the more typical lifetime for laboratory technology is set to 4–8 years. The time to complete depreciation is normally 8 years, but the time until the technology is considered outdated and inadequate is normally 4 years. In some cases, the rapid advances in computing technology have driven this even lower. Because most of the control and acquisition software is tightly allied to the capabilities of the hardware, the lifetime of the computer is a controlling factor for many laboratory instruments. Based on these principles, the Air Force has a major decapitalization problem with 113 units already completely depreciated. At present, only the Air Force has units in the age range of 10–15 years. The distribution of depreciated equipment is shown in Table 2.2; all of the services have asset depreciation problems that affect sustainability based on age alone (i.e., excluding wear, damage, or technological advances). Overall, the JOAP fleet is 70% decapitalized, whereas a sustainable program needs to stay closer to 50% decapitalized or preferably even lower. This indicates a failure to reinvest profits (cost avoidances) that result from the program back into the program.

Table 2.2. Totally depreciated spectrometer assets based on average ages of extant equipment

Age, years	Depreciation rate (average), %	Air Force	Army	Navy	JOAP
0.00–2.00	10.0	2.2	0.2	0.4	2.8
2.01–5.00	35.0	12.3	8.8	3.9	24.9
5.01–10.00	75.0	87.1	8.3	40.5	135.8
10.01–15.00	1.00	113	0	0	113
Total		214.5	17.2	44.8	276.5
Fractional decapitalization		75%	45%	65%	70%

In order to not only stem this tide, but also to reverse the trend, significant resources (mostly funding, but also labor) are required and a strategic plan for renewal and replacement must be undertaken. The strategic plan should also take into account technological advances, obsolescence, and programmatic improvements to increase the value and accelerate the time to and rate of return on investment.

3. Obsolescence

3.1. Obsolescence—what it means and how to reach it

Obsolescence occurs when equipment becomes outdated relative to the state of the art or state of the science. Obsolescence becomes critical when equipment becomes unusable due to incompatibility with newer systems or general inadequacy relative to increased user expectations, standards elsewhere in the field, inability to meet expanding requirements, or inability to justify program expense based on net value. *Planned obsolescence* is an acceptable means of decapitalization; it is acceptable when either the function performed by the obsolete equipment is no longer required or new equipment will supplant the obsolete equipment.

3.1.1. Functional obsolescence

First, we must consider the case where the function itself is no longer required. Rotrode AES is essentially a support program for aircraft and, to a lesser degree, for landcraft. Therefore, as the craft that rely on rotrode AES are themselves decommissioned, it is appropriate for rotrode AES to slip away quietly. However, rotrode AES supports aircraft and landcraft that are currently in use or under procurement; a lifetime of approximately 50 years is anticipated for these systems. Consequently, the function of rotrode AES, i.e., wear debris measurement, is also expected to exist for 50 years. Accordingly, a strategic plan should extend for at least 25 years. Although the need for determining wear debris seems apt to remain important indefinitely, it is altogether possible and entirely expected that real-time, in-line, on-board sensors will one day supplant the types of off-line analysis that are performed today. Aircraft and engine manufacturers are already moving towards these technologies Moreover, they are integrating newer types of sensors as well as extant sensors (e.g., temperature, vibration) with neural nets and smart systems to perform real-time, in-line, on-board trend analysis. Certainly, this can be reassessed in another 25 years.

One of the most serious threats to the applicability of rotrode atomic emission spectrometry is fine-filtration of the lubricant. A number of platforms already use filters with 3 μm or 10 μm nominal particle size exclusion. Although 10 μm particle exclusion is not problematic for rotrode AES because the technique is sensitive to particles below that size, elimination of particles larger than 3 μm does reduce the efficacy and applicability of rotrode AES. Presently, a large number of platforms remain without fine filtration. Nevertheless, if these platforms are retrofitted with fine filtration or ultrafine filtration, the effectiveness of rotrode AES will be further reduced. In addition, existing limits and triggers would become ineffective because they were constructed during a time without the improved filtration. In some cases, the remaining particulates might be of such low concentrations as to be under the lower limit of detection. Wear particle concentrations below the detection limit would render the technique functionally obsolete unless other technological advances permit a reduction (improvement) in detection limit. In fact, development is underway of electro-chemical sensors to detect and measure trace concentrations (i.e., parts per billion) of metal ions in oil resulting from wear. This type of research and development is being pursued by the engine and aerospace manufacturers and is intended to be incorporated directly into on-board, real-time condition monitoring systems.

3.1.2. Technological obsolescence

Second, we must consider the case where the function will exist as it is today, but new instruments will replace the current instruments outright. This involves a degree of informed speculation about those instruments that are developmental and those technologies that might be adapted or expanded to replace rotrode AES. At present, most technologies reflect relatively minor changes, such as changes in detectors or excitation means. Atomic spectroscopy is a well-established, mature technique with many subtechniques. Although rotrode AES has more-or-less fallen by the wayside in mainstream analytical chemistry in favor of inductively-coupled plasma (ICP) AES, the military services have requirements of transportability/mobility, durability, celerity, usability/operability, and supportability. A rotrode spectrometer requires few consumables and no gaseous or liquid supplies. It can be shipped on a plane or truck and then ready for use within 30 minutes of arrival. It has modest requirements for user expertise and experience. It can be run on a ship or a tarmac. Although environmental conditions and operator proficiency, among other factors, can affect the quality of the data, the technique is relatively rugged when contrasted against graphite furnace atomic absorption spectrometry or ICP-AES and far easier to support in a deployed position. Consequently, rotrode AES is unlikely to be replaced by other spectrometric techniques in a military setting.

The greatest threat to atomic spectroscopy comes from x-ray analysis, which has become increasingly sophisticated and miniaturized for the nondestructive inspection marketplace. X-ray analysis is widely used for evaluating structural integrity, ore composition, and metallurgy. However, no manufacturer of x-ray equipment presently shows any interest in adapting it to analyze oil for wear debris, and various methodological issues preclude its immediate application. Moreover, unless costs of x-ray equipment fall dramatically, the infrastructure investment will make a changeover cost-prohibitive. Therefore, we conclude that rotrode atomic emission spectrometry could remain an appropriate technology for the identification and quantitation of wear debris for at least 10–15 years and perhaps longer. Clearly, this reflects a planned obsolescence.

In addition to x-ray techniques, laser induced breakdown spectroscopy/spectrometry (LIBS) could one day pose a challenge to rotrode atomic emission spectrometry. At present, LIBS is insufficiently mature, robust, or commercialized to have a major impact. Nevertheless, LIBS is evolving at a significant pace and may be ready to compete favorably with 8-12 years so long as it is not supplanted by another emerging technology.

Unplanned obsolescence is a symptom of poor sustainability and indicates a management failure to lay out a strategic plan for meeting known requirements. At present, unplanned obsolescence is a serious risk because individual components of the extant rotrode spectrometers will become obsolete. While this does not pose a problem for the technique as a whole, it requires appropriate planning for strategic renewal and replacement to ensure sustainability. It is primarily this type of piecemeal unplanned obsolescence that is the focus of the discussion here.

3.2. Computing software and hardware

The personal computer (PC) market really began with the Apple II in 1977 and never looked back. It was followed rapidly by the release of the Texas Instruments TI-99/4 (1979) and TI-99/4A (1981). The Commodore VIC-20, also released in 1981, became the first PC to hit one million in sales. In 1982, the release of the inexpensively priced Commodore 64 began a revolution in home and business computing (more than 10,000 software packages were written for it). Commodore, Apple, and Atari all favored Motorola central processing units (CPU). Although the Commodore 64 and other PCs reached into the business, science, and engineering arenas, another manufacturer was preparing to capture that market.

IBM had begun reaching science and engineering users with the XT in 1983 with the Intel 8088 CPU; the XT was the first widely used PC to come equipped with a hard drive. In 1984, IBM released the AT, which was built around the Intel 80286, a relative powerhouse. By the late 1980s, Apple and IBM had emerged as the industry leaders. However, clones with the Intel CPUs also became widely available. Both IBM machines and the clones (e.g., Northgate, Zeos, Epson, NEC, Zenith) had established themselves in science and engineering. The early dominance of IBM, combined with the low cost of the clones, made Intel-based processors the de facto standard in those technical disciplines, despite the expertise required for proficient use. Up through the 80386, DOS was the primary operating system for the Intel CPUs, although software applications designed to run in the Microsoft Windows environment were improving and multiplying. Early 80486 users often used a mixture of DOS and Windows software applications.

All of this ended with the Intel Pentium after which DOS applications became a thing of the past. Motorola also continued to expand its influence with CPUs modeled on the original 68000. The last of the 68k series chips were the 68060 and the 68070 (which was manufactured by Philips for a specific application). The 68060 was similar to the Pentium 5. Today, DOS applications are virtually nonexistent except for legacy systems. At present, Windows is the main standard and has expanded the role of the operating system to incorporate communication, peripheral control, security, device drivers, user interface standardization, and other features. Consequently, extant DOS-based systems are no longer capable of interfacing with current technology. Moreover, they fail to meet user expectations for graphical interfaces, protection from faults, and general friendliness in operation.

The oldest spectrometers in the fleet that are considered here are the Spectroil M and M/N type units (no Spectro Juniors), which are no more than 15 years old. By 1991, two architectures were established: the Intel x86 and the Motorola 68k series. Virtually every major software package was Microsoft DOS, so it is perfectly understandable that the government would have purchased a large number of DOS-based instruments. Although the 80386 and 80486 chips became outdated long ago, they were manufactured as replacement parts for use in embedded system. However, Intel is phasing out the 386 and 486 by September 2007. Motorola stopped producing the original 68000 in 2001.

All Spectroil M and M/N units are based on Intel x86 processors or similar architecture; both Intel and AMD 486DX2 chips were used. Prior to 2000, all units contained a single board, which Spectro assigned the part number M68800. The instrument's operation, control, and acquisition (OCA) software ran under DOS and was named OilM-DOS. The board has an 80486 central processor, parallel, serial, video, and keyboard connections; it was intended for use with DOS. It is still available, but will soon be phased out. An exact date has not been set for discontinuation by the board maker. As noted above, the 80486 chip itself is being phased out as a part of planned obsolescence by the chip manufacturers, which obviously affects the board maker. Instruments manufactured using this board and OilM-DOS require both hardware and software upgrades.

In 2000, Spectro switched to Windows. The changeover was divided into two phases. Phase one introduced the Windows strictly as a user interface. Specifically, the flat panel touch monitor with its associated processor were used to accept inputs and present all data in a Windows format. However, the internal OCA software continued to be executed on the M68800 DOS board under DOS. In addition, the hard and floppy disk drives were controlled by the M68800 board. Instruments manufactured during phase one have two computer boards, but the DOS computer runs the OCA software while the Windows computer runs the user interface. In other words, instruments made during phase one require a software upgrade, but not a hardware upgrade, because they already contain the newer board.

Phase two required changing the OilM OCA code from DOS to Windows, which was done in C++. Now rewritten for Windows, the instrument OCA software was named OilM-Windows and moved to the secondary (flat panel) board that had served only as the user interface in phase one. At the same time, control of the disk drives was shifted to the secondary computer. Once this was completed, the original computer became superfluous. In order to allow for internal consistency of part numbers, Spectro assigned the same Spectro part number to the newer boards even though the functionality and capability of the new boards were considerably greater. Phase two continues in the sense that instruments manufactured to this day have both Windows OCA software and upgraded hardware.

Table 3.1 shows the distribution of units in terms of their software and hardware. The DOS units are further divided into those built prior to phase one, which require the additional board, and those built after phase one was completed where the new board was present, but not fully utilized.

Table 3.1. Distribution of Windows-based and DOS-based rotrode AES units in the fleet

System type	Air Force	Army	Navy	JOAP
DOS (see breakdown in next two rows)	244	12	61	317
board and software (before phase 1)	*160*	*10*	*48*	*218*
software only (phase 1)	*84*	*2*	*13*	*99*
Windows (phase 2)	42	26	8	76
Total	286	38	69	393

Notes: As with Table 2.1, the data herein were provided by Spectro, Inc., the manufacturer and holder of the maintenance contract. Not all DOS units require a new board for the software upgrade.

3.3. Detectors

The photomultiplier tube was invented in 1947 and has had an illustrious history. By the 1950s, Philips (now Photonis), Radio Corporation of America (RCA) New Products Division (formerly a Navy plant run by RCA and now Burle) and Hamamatsu had become major players in PMT manufacture. Despite the fact that many laboratory instruments have moved to charge-coupled devices (CCDs), the PMT industry is still strong. PMTs and electron multiplier tubes are used extensively in medical imaging (x, β^+, and γ); this includes filmless conventional radiography, positron emission tomography (PET), and ^{99m}Tc tissue scans. PMTs remain widely used in many applications, and it seems unlikely that purchasing replacement parts will present a problem over the next 10 years, even if the prices rise somewhat as the market shrinks. However, improvements in data quality and operation that are associated with CCDs may make this a desirable option. In addition, standardization within the fleet is desirable. At present, no instruments have CCDs.

One of the real strengths of the CCD is its ability to be wherever the light is. In other words, the alignment issues characteristic of PMTs no longer exist. It is precisely this benefit that makes the CCD so attractive to spectrometer manufacturers who deal with ultraviolet or visible light. Unfortunately for the PMT, none of its strengths shine in rotrode AES. PMTs are well-known for their very low noise and high sensitivity, but the main source of noise in a rotrode spectrometer is the electric arc. In fact, the CCD is actually preferable due to the nature of the optics in the rotrode spectrometer. The CCD makes it much easier to address thermal expansion/contraction issues because regions of the CCD may be selected and deselected electronically whereas the PMT is fixed in location. Accordingly, any strategic plan for instrument renewal should incorporate detector upgrades.

3.4. Excitation source and sample introduction

In general, analytical chemistry as a field has abandoned arc spectrometry in favor of flame and plasma spectrometry. Arc spectrometry has remained primarily in those few applications where convenience and/or safety preclude the use of compressed gases. The capability of functioning without compressed gases has continued to preserve arc spectrometry in military applications. The instability and inhomogeneity of the arc in time and space, coupled with the variation in sampling by the rotating disk, are undesirable qualities that have severely reduced the use of arc spectrometry. The rotating disk electrode (rotrode) and the rod electrode cannot be reused and cannot be made sufficiently homogeneous as to eliminate all discrepancy between measurements. Moreover, as consumable items, the rods and disks contribute substantially to cost. Lastly, both rods and disks are amenable to contamination since they must be handled by the user.

Over the past five years, there have been continued advances in laser induced breakdown spectroscopy (LIBS). In this technique, the laser is tightly focused, and a small portion of the sample is irradiated. The irradiated portion is ablated. The energy from the laser pulse is sufficient to both atomize the compounds and promote electrons. Sometimes multiple pulses are used so that the ablated material is then struck again by a second pulse, which increases the populations of atoms and ions in excited states. Thereafter, the technique is analogous to other types of emission spectrometry. LIBS is already under investigation at the Army Research Laboratory. The real advantage to LIBS is the elimination of the arc and the disposable electrodes. Although no LIBS system has yet to be tested on oil, LIBS is gaining headway in environmental, structural, pathological, and pharmaceutical testing. Lasers will continue to get smaller, cheaper, more rugged, and more reliable. It is to be anticipated that LIBS or an alternative means could realistically displace the electric arc for the determination of wear debris.

4. Upgrade options

4.1. Background

Some of the DOS-based spectrometers have newer motherboards. Those manufactured in or after 2000 have a board that permits the Windows-based SpectrOilM software to be installed without a simultaneous hardware upgrade. Those spectrometers built before 2000 have an older configuration that will not support the Windows-based software and must first have the new board installed.

Table 4.1. Costs associated with individual rotrode atomic emission spectrometer upgrades (in dollars)

Improvement	Parts	Labor	Site visit
Windows upgrade	$5,500	$1,128	$4,500*
M68800 board	$1,446	none additional	none additional

Notes: *Site visit cost includes travel time, transportation, meals, and incidental expenses. Continental domestic site visit costs range from $1,239 to $4,514; Hawaii and Alaska have costs of $8,513. Foreign site visits costs can be substantially higher; however, Spectro states that it costs about $1000 to ship an instrument one way. Therefore, a reasonable option is to use a cost of $2,000 per instrument and ship the instruments rather than a $4,500 site visit cost. If one extra instrument were purchased, it would be sent out and each field instrument would be sent back, upgraded, and redeployed to a new location.

4.2. Replacing all at once

The first option is to replace outdated boards and software all at once. This would reflect a relatively major renewal effort, but it would be manageable. Nonetheless, past experience shows that such significant capital investment is uncommon. The Navy program office reports that it is attempting to obtain funds because the rotrode spectrometers are classified as common support equipment, i.e., they support many different platforms. The Air Force program office reports that it is seeking money for a mass renewal. The Army program office reports that it has already obtained the money needed and begun the procurement process to upgrade all units en masse. Given that the overall cost is approximately $3.5 million, this is an achievable goal. In addition, there are volume discounts to be realized. It seems likely that a more favorable price could be negotiated on labor and parts if the fleet is upgraded in one fell swoop. Estimated costs are given in Table 4.2.

Table 4.2. Estimated one time procurement costs for upgrading instruments (2006 prices)

Expense type	Air Force $K	Army $K	Navy $K	JOAP $K
Parts	1,573	81	405	2,059
Labor	275	14	69	358
Site visits	488	24	122	634
Grand	2,336	119	596	3,051

Notes: The figure of $2,000 was used as the average cost for a site visit based on the number of units in the continental U.S., the presumed ability to negotiate more favorable terms based on volume, the savings realized from consolidated travel to proximally located instruments and bases, and the ability to ship instruments rather than conducting site visits. See also notes for Table 4.1.

4.3. Replacing on a schedule

The second option is to replace on a schedule, for example, 10% annually, amortizing cost over 10 years. Spreading the upgrades over a period of time results in amortizing costs so that relatively smaller amounts of money from each year's budget are required when contrasted with an en masse procurement. The disadvantages of this approach are as follows: unrealized connectivity and operability benefits until all units are upgraded, inflationary increases, competition with other programs, risk of higher maintenance costs on non-upgraded units, inability to take full advantage of volume discounts or proximal (efficient) travel. Although 10 years has been used here, amortization can be over any time period. Any period longer than 10 years is unreasonable because of the planned obsolescence of rotrode atomic emission spectrometry in 20–25 years. In other words, the benefits of the upgrades would simply not be in effect long enough to merit the upgrades. Instead, early phase out would be used. Table 4.3 shows the schedule for a 10-year plan.

Table 4.3. Number of rotrode atomic emission spectrometers still needing Windows upgrades at the end of each year in the 10-year replacement plan

Year	Air Force	Army	Navy	Total
2007	219.6	10.8	54.9	285.3
2008	195.2	9.6	48.8	253.6
2009	170.8	8.4	42.7	221.9
2010	146.4	7.2	36.6	190.2
2011	122.0	6.0	30.5	158.5
2012	97.6	4.8	24.4	126.8
2013	73.2	3.6	18.3	95.1
2014	48.8	2.4	12.2	63.4
2015	24.4*	1.2*	6.1*	31.7*
2016	0	0	0	0

Notes: *The red data represent the yearly average for the number of upgrades for a 10-year plan. The years are valid only if the upgrade initiative is started in 2007.

The current retail inflation rate is predicted to remain near 2.2% until around 2010, when it is expected to jump to 3.0%. Since laboratory technology usually escalates somewhat faster, an extra 1.0% has been added to the predicted retail inflation rate. A reasonable rate of replacement is 10% per year so that complete replacement of the obsolete technology occurs within 10 years. Such a schedule allows for two important factors: First, it is likely that additional technological improvements will make the new technology obsolete by the end of the replacement cycle. That will allow the cycle to begin again (or even for the abandonment of the technology). Second, it will allow for all communications, security, and related issues to be brought up to a uniform standard under Windows. Any time period longer than 10 years is unlikely to be able to maintain uniformity because of compatibility issues. As Windows evolves or is perhaps supplanted by an alternative system, the best that can be hoped for is a 10-year window of compatibility or at least interoperability.

Currently, we are replacing DOS boards at a rate below 5 per year fleetwide. Although this rate will creep upwards as the technology ages, it is unlikely that failures will occur at a rate sufficient to permit complete replacement over 10 years during regular service calls. We will assume that the rate of replacement that can occur without accruing additional site visit costs is 5 annually over the 10-year replacement period for the purposes of cost estimation. Although amortizing the replacements over 10 years increases expenses due to inflationary changes, it also reduces expenses resulting from the site visits since the technician has already arrived at the site for another reason. A comparison of the cost breakdowns (incorporating simple, linear inflationary effects) and cost avoidance from en masse renewal is provided in Table 4.4.

Table 4.4. Comparison of estimated costs for amortization versus en masse replacement

Expense type	Cost computation	Air Force $K	Army $K	Navy $K	JOAP $K
Parts	Total amortized inflated	1,864	95	480	2,439
	One time	1,573	80	405	2,059
	Cost avoidance	290	15	75	380
Labor	Total amortized inflated	326	16	82	424
	One time	275	14	69	358
	Cost avoidance	51	2.5	13	66
Parts and labor	Total amortized inflated	2,190	111	561	2,862
	One time	1,848	94	474	2,416
	Cost avoidance	341	17	87	446
Site visit costs	Total amortized inflated	1,095	54	274	1,423
	One time	1,081	53	270	1,404
	Cost avoidance*	14	1	4	19
Grand	Total amortized inflated	3,285	165	835	4,285
	One time	2,929	147	744	3,820
	Cost avoidance	356	18	91	465

Notes: Total amortized inflated cost (TAIC) is amortized over 10 years with inflation rates of 3.02% for 2007–2010 and 4.00% thereafter. One time cost (OTC) is valid if all items are purchased immediately at current contract or market rates. Cost avoidance from immediate purchase is the difference between the one time cost and total amortized inflated cost: CA = TAIC – OTC. Site visit costs include transportation, travel time, lodging, meals, and incidental expenses. A constant site visit cost of $4,500 was used although this does vary geographically. *The cost avoidance is small; because this approach does not take into account the 5 replacements per year, 45 additional site visits are required to complete the renewal in one fell swoop (there are still 5 replacements covered during the first year).

Given the disadvantages associated with a phased upgrade approach as well as the increased cost, amortization over a 10-year period is not recommended. Although 12% may not sound high, it corresponds to nearly $0.5 million, which is enough to purchase about 10 new spectrometers. A three-year plan would preferable. This would require about $1 million for the Air Force, $50,000 for the Army, and $250,000 for the Navy for each of three years. These sums of money should be manageable, especially given the size of the maintenance contract already.

4.4. Creating a parts stockpile

This is not an upgrade at all, but it is a possibility. Under this option, the government would pre-purchase a supply of the outdated boards. In order to estimate the cost of this approach, some assumptions must be made. We will assume a failure rate of five DOS boards per year, a program lifetime of 25 years, and a 10% failure rate of boards over the 25 year program lifetime. After rounding, the government will need to buy 139 boards if the assumptions are correct. This will require an initial outlay of about $201,000 for the boards. This option does not buffer the government from costs associated with the labor, site visits, or inflationary effects. Someone will have to install the boards and ensure they function correctly, but this would be covered under a maintenance contract.

As a result of the purchase of irreplaceable parts, the government will assume certain risks. First, there may unidentified failures in the purchased parts, but it will be impractical to test all of them. Second, even boards that function perfectly at purchase may malfunction by the time they are needed as a result of normal aging. Third, there will be a risk of loss from unexpected events (e.g., hurricanes, floods, accidental destruction). One way to minimize this is to house boards at several locations, but that creates a new risk associated with inventory tracking; it will be harder to ensure their security, integrity, and availability if they are scattered. Realistically, even with a supply of boards intended to last 5 or 10 years, this is a poor option because it consumes resources without resolving the obsolescence problem. It is essentially squandering the money because even the new boards may begin to fail, and there will have been no renewal or improved functionality.

4.5. Contracting for board production

It is possible to contract for the production of the outdated boards, but this seems unlikely to be feasible economically. If the current manufacturer has already decided to stop production, it seems that the cost of paying the same or another contractor to gear up to make the same part would be prohibitively high. Furthermore, the cost and delay associated with testing would also appear to make this option unsatisfactory. Finally, it may be that there is sufficient proprietary or patented technology that it would not be legally possible for any contractor, save the original manufacturer, to reproduce the board. Given the issues with CPU obsolescence, it is anticipated to be cost-prohibitive to continue to manufacture the outdated boards.

4.6. Recompeting the maintenance contract

Currently, the maintenance contract is the major means used to sustain this program. It is the most successful effort as well. In general, downtime has been minimized because of the priority treatment the government receives under the service agreement. Given the past performance of the contractor (who is also the manufacturer), it would be hard to argue against renewing the service contract or writing a new service contract. Nevertheless, there is no requirement that the maintenance be carried out by the manufacturer, and the government has a long history of hiring large aerospace or engineering firms as prime contractors to take care of various types of equipment. It seems unlikely that any other company would be able to resolve this issue without buying replacement parts. Given the magnitude of the infrastructure and the global reach of the program, it would be prudent to evaluate all options for practicability and economy.

4.7. Recompeting the instrument contract

Although it may mean a transition to another type of measurement, one option is to reconsider the role of the Spectroil M and M/N as the principal types of instrumentation. Although there is a large investment and infrastructure to support the Spectro platform, there has been so much depreciation and so much decapitalization that the present may be a good time to start phasing out these units. With the program on the edge of sustainability, this option has to be seriously evaluated. Even with the depreciated loss, there is sufficient functional equipment to allow for a smooth transition to an alternative technology. It is not clear what would be phased in or if any technique (instrument) external to the aircraft and/or landcraft would be phased in; however, there is at least one viable option: filter debris analysis. In addition, extant systems based on SEM-EDX or EDXRF can be modified to work with particulates in oil rather than larger debris found in filters or on magnetic chip collectors (detectors).

Phasing out rotrode atomic emission spectrometry would be a major paradigm change despite the fact that the technique and the data are under appreciated. Despite all the weaknesses in the program, it seems unlikely that the engineering authorities and platform managers will be willing to give up this measure of component health in the near future. That notwithstanding, it may be possible to find other condition-based maintenance enablers that provide prognostic and diagnostic information that meets or exceeds the value associated with rotrode atomic emission spectrometry. To that end, a careful reassessment of programmatic value is warranted.

It would be possible for the existing JOAP rotrode AES program to continue for another 10 years with minor renewal and replacement. Although maintenance costs will increase, these may be offset both by redistributing functional spectrometers to areas of greatest need and by removing platforms from the program in order of increasing value (i.e., start by removing the programs receiving the lowest benefits). If a tiered approach is used, series of components or platforms could be switched over from one CBM-enabling testing technology to another. Those with the lowest RAES benefits as well as those with the highest benefits from the new technology would be part of the first tier. Alternatively, the tiered approach could be spiraled so that there is essentially a continuum of platforms switching from one technology to another. The Army would appear to be the best candidate for starting such a transition either way since it has the smallest number of instruments and the most landcraft. In that way, the Army instruments could be redistributed to the sister services. Given the small number of Army laboratories, less capitalized equipment would be required for initial implementation.

With the current trend towards unsustainability, the perceptions of value of the RAES data, attrition of platforms from the program, the costs of renewal, replacement, and repair, and the overall lifetime relative to planned obsolescence, the technology is at a critical point where a decision must be made to either reverse the trend and upgrade the technology or hasten its demise and plan for the transition to a superior technology. If no such technology exists, then it must be created. Otherwise, the value will decline until the program is eliminated outright—with or without a replacement. Certainly, a 10-year strategic plan for the cessation of RAES and the institution of an alternative external testing technology is feasible, but such an effort must begin now. An assessment of alternative technologies must be conducted soon so that resources can be apportioned appropriately between the diminishing RAES program and its growing, developing replacement. Moreover, customer buy-in must be achieved. Lastly, a plan for the transition and construction or conversion of infrastructure is required.

5. Value

5.1. Defining and classifying value

Value may be defined in many ways. In the end, value is normally calculated in real dollars in terms of cost avoidance (labor, parts, and loss of readiness), but there are pitfalls to this approach. Rotrode atomic emission spectrometry is a condition-based maintenance enabler. Through cost avoidance, the program allows opportunity costs to be turned into opportunity rewards. Economists define the *opportunity cost* as the next best thing that would be procured if the first best thing did not have to be procured. This can be illustrated with notional data. Let us begin with a $20 million fighter jet and an activity, JetOne whose missions rely upon them. Suppose that JetOne requires 16 fighter jets to achieve readiness requirements, but continually has 8 fighter jets undergoing maintenance. JetOne needs 24 jets to achieve readiness requirements. Further suppose that CBM-enabling RAES reduces the number of jets in maintenance status to 4 so that JetOne now requires only 20 jets to maintain 16 jets at readiness. The CBM-enabler has yielded a cost avoidance of 4 jets or $80 million; this is an accounting value, i.e., an accounting cost that has been avoided. If the CBM-enabler program costs 0.5 jets ($10 million) to run, the net benefit is 3.5 jets ($70 million), the net accounting value. The opportunity costs associated with the 3.5 jets can be represented in terms of tanks, trucks, other aircraft, etc. that would not have been purchased otherwise *plus all the benefits derived from them*. In this way, opportunity costs reflect much more than accounting costs and need not be monetary, as opposed to accounting costs, which are always in dollars.

In macroeconomics, opportunity costs are often illustrated in terms of the classic example of the guns-butter curve where diminishing marginal returns occur at extremes of the curve. Similar problems can occur if CBM-enablers take on a life of their own, independent of net value. For example, if spending twice as much on the CBM-enabling program ($20 million) translates to 4.2 jets of cost-avoidance, there has been no value added relative to the $10 million program. When such a phenomenon is observed, it demonstrates a need for optimization; the break-even point would have been 4.5 jets in terms of maintaining the return on investment ($1 out for each $1 in). This is well-known as the theory of diminishing marginal returns and is similar to a concept known as the theory of marginal value.

In actual practice, JetOne would probably still have 24 fighter jets, but would have an opportunity reward associated with increased readiness. Rather than operate with 16 of 24 jets (66% readiness), JetOne has used a CBM-enabler to operate with 20 of 24 jets (83% readiness). Although the CBM-enabler has a net accounting value of $70 million, it has an opportunity value that may be incalculable because it represents intangibles such as preserving lives or defending national interests. Nevertheless, it is often possible to make use of opportunity costs in representing marginal value. Value can be calculated as an accrual of opportunity rewards estimated by their respective accounting costs so that the net value can actually exceed the net accounting value of a program.

Value can always be expressed in financial or fiscal terms. What is this worth to the government as a whole? Virtually any program can be viewed in terms of input and output. The input is primarily budgetary dollars, and the output is a combination of goods and services. These goods and services must be equal to or greater than the input for a program to have value. When the output exceeds the input, the program may be referred to as value added. Value may be further broken down into three classes for the purpose of assessing sustainability: actual value, potential value, and perceived value.

Applicability and utility are tightly tied to assessments of value. Without applicability and usability, much of the potential value of a program may stay unrealized. Because potential value is often used in determinations of total value and sustainability, it is critical that potential value be exploited as much as reasonably achievable. Another way to say this is that untapped potential must be kept as low as reasonably achievable.

5.2. Actual value

5.2.1. Contributors to actual value

Actual value for rotrode AES is primarily in the form of cost avoidance, but some of it can be as direct savings. The program is normally justified in terms of the following: increased readiness, preserved lives, preserved capital, and reduced maintenance costs. These categories are not necessarily mutually exclusive, but they are useful.

Increased readiness can be converted to dollars by realizing that an organization requires less equipment to complete a mission if more of that equipment can be counted on. If a mission requires 10 planes and there are normally 2 planes undergoing repair, then it is necessary to own 12 planes. By following a condition-based maintenance program, down time is minimized and more equipment stays operational, which means less equipment overall must be devoted to any single mission. Increasing readiness requires continually reassessing limits, improving data quality, and converting analytical results into meaningful conclusions and then revisiting and revising maintenance policies. It appears that most engineering functions are not engaged in this function and that the oil analysis programs do not construct knowledge from the data in their custody. Given the maturity of the program and the age of instrumentation, further increases in readiness are unlikely to be achieved unless changes are made to how the program is administered.

Saved lives require no further justification. However, it is worth pointing out that saved lives refer not only to pilots and other on-board personnel, but to ground personnel and those who are protected by the mission. In an aerial sortie, the pilot who has to return for an engine problem may be the safest of all, but his comrades who can no longer depend on him for assistance may be the ones not to return. Of course, this goes back to the readiness issue above.

Capital (aircraft, engines, gearboxes, etc.) is preserved when problems are found before damage occurs. This effect is easily observed when contamination is observed. If water or dirt enter the lubricant stream, engine performance and health deteriorate. The earlier this is caught, the less damage is done to the component. This means fewer gearboxes must be purchased. A very liberal approach to accounting for preserved capital is to count the cost of replacement aircraft (not just the component) when a true positive occurs. A more conservative approach counts the component, which is more reasonable when dealing with multi-engine aircraft, for example.

Reduced maintenance costs (disassembly, component shipping, overhaul) may be realized when mechanical failures are caught early and secondary part failures do not occur. Maintenance costs are also reduced when all useful life is eked out of a component. This requires careful prognostics to be successful and appropriate safety factors must still be built in. Proper diagnostics can also reduce maintenance costs by pinpointing failing subcomponents to ensure that all failing subcomponents are replaced during overhaul. However, this requires a significant feedback to the depot. Lastly, the data can be analyzed to root out systemic problems that may suggest engineering improvements or operational changes that increase performance or longevity.

5.2.2. Detractors to actual value

Actual value may be lost for scientific, engineering, and technological reasons, for economic reasons, and for programmatic reasons. These categories are not mutually exclusive.

5.2.2.1. Scientific, engineering, and technological detractors

The technique is incapable of providing meaningful information that can diagnose a problem, predict the remaining useful lifetime or period before repair is required, or prevent a catastrophic disaster from occurring. This may occur due to factors outside the control of the program. In many cases, SET detractors affect the *applicability* of the technique to the platform. The technique is not applicable when some factor interferes with its ability to provide meaningful information even when done correctly. Below is a list of possible SET detractors.

❶ The analytes are absent. For example, the adoption of fine filtration by many aircraft platforms removed the analytes from the oil. It is impossible to measure the wear debris by oil analysis when all the debris is in the filter.

❷ The analytes are not unique to any particular subcomponent. Although high iron may indicate a failure somewhere, it is not especially helpful in locating the failing subcomponent as nearly all of them contain iron.

❸ Uncertainties in the data or results are too large relative to the size of a significant difference. In other words, it is impossible to distinguish between 5 ppm and 8 ppm reliably, for example. Because the actual construction of limits begins with the data, the inability to distinguish between values precludes meaningful limits that are too close together. In many cases, the JOAP Manual wear tables specify normal, marginal, and abnormal levels that would be indistinguishable based on experimental error. Limits were set because of the large number of data available for consideration, but the problem lies with the individual analysis of a sample and the decision that must be made on one or two measurements.

❹ The data are wrong. Although a number of checks are performed, it is still possible for an analytical datum to be wrong. This may occur due to a malfunction, contamination, an environmental factor, or mishandling.

❺ The limits are wrong. Because component improvement projects often eliminate mechanisms of failure, it is possible that outdated limits lead to high rates of false positives or false negatives. Both of these increase maintenance costs and decrease user confidence.

❻ The detection limit is too high. When a component has especially tight tolerances or its oil is fine-filtered, the concentration of debris capable of being detected is simply too low. For example, it is not possible to distinguish between 50 and 100 ppb.

❼ There is no relationship between component failure and wear debris or contaminant levels. This may be due to the nature of the failure mode and the type of debris generated. Alternatively, it may be that metallurgically similar subcomponents produce most of the debris but do not actually fail.

5.2.2.2. Economic detractors

The size of the cost savings is directly related to the setting of limits and the minimization of false positives and false negatives (maximization of true positives and true negatives). As the rate of false positives and false negatives increases, the actual value sharply declines. False positives lead to a loss of confidence and reduce actual value because they cause the user to incur costs associated with additional testing and/or maintenance. If the sum of the cost avoidance and the savings is not greater than the overall cost of the program, then the program is not cost effective and is unsustainable.

The value of the component or equipment may not be sufficiently high to justify condition-based maintenance at this level. Presumably, the Army withdrew high mobility multipurpose wheeled vehicles (HMMWVs or Humvees) because the rate of loss attributable to engine and oil failures was low and there was little correlation between the data and Humvee engine failures. The program operated at a net cost for the Humvee because of the large number of samples and the small number of saves. Accordingly, wear debris analysis must be performed in a judicious manner so as to have a net value.

5.2.2.3. Programmatic detractors

Many programmatic detractors are *usability* problems. The data are not used by the customer or are not made usable for the customer. This category also includes problems that result from limitations on resources or systemic/organizational issues within the military materiel commands. They also arise from perceptions about platforms and doctrines about maintenance. A list of programmatic detractors is provided below.

❶ Platforms or components are viewed as expendable, and maintenance policies do not make use of the available data to identify root causes that may be eliminated. With increased modularization and a trend to line replaceable units (LRUs), a component replacement mentality has come to dominate maintenance philosophies. There are good reasons for pursuing this approach in the field in terms of efficiency and readiness, but there is little interest in knowing what went wrong even if it is a recurring or widespread problem. This is a *usability* problem; the data are not used in a way to maximize their value.

❷ Data are not used in a predictive fashion to enable condition-based maintenance. This is a systemic problem because no organizational unit is required to process the data and to update or validate the limits on a recurring basis. In addition, there is no mechanism for linking problems discovered during overhauls with spectrometric data. Engineering investigations of removed or "failed" components to verify the failure or to determine the cause are rarely done unless the situation is exceptionally bad. This is also a usability problem.

❸ Complete databases are unavailable, weakening any conclusions drawn from the data. Submission to central repositories is not complete or timely. Therefore, there are gaps in the data. The authority to compel submission rests with the individual commands, and there is no easy way to identify or penalize noncompliance.

❹ Feedback to confirm laboratory findings or to incorporate maintenance actions is too cumbersome. For example, Air Force laboratory operators must ascertain and then enter into the database what actions were taken as a consequence of the laboratory recommendation and whether any mechanical problems were found. There is no systematic follow-up to ensure a continuous feedback loop of information.

❺ Individual platforms are believed to be highly reliable or they have onboard sensors that are believed to be highly reliable. Thus, there is no perceived value in additional testing. In many cases, there are no data available to argue the case either way. In this fashion, SET detractors become commingled with programmatic detractors.

❻ Meaningful information is not fed back to cognizant engineering authorities or platform managers. There is a disjunction between the program offices and the engineering authorities. The program offices are the masters of data, but the engineers have the authority over the equipment. No tools are available to allow the engineers to access the data and carry out analyses in a convenient manner. The three services use incongruous databases that preclude the easy and rapid transfer of data among them despite more than three years working on a joint data management effort. The three services do not share or exchange data in any meaningful way. No effort is made to assemble or evaluate the data for jointly owned equipment types so that the services might learn from one another's data.

❼ Compliance with prompt submission of samples is poor. The Navy has had problems with mechanics waiting until there are boxes full of samples before taking them to the oil analysis laboratory. When multiple samples (from many sampling periods) for the same component arrive simultaneously, the data tell a story about what happened perhaps, but had no value as a CBM-enabling tool because the opportunity to take a maintenance action has already been lost.

❽ Oil analysis is viewed as a nuisance with insufficient demonstration of value to the field commander or to the troops. Lack of immediate feedback reduces the interest in the result. Slow turnaround is less common with the Navy on account of shipboard laboratories or with the Air Force because the laboratories are tightly allied to and colocated with the aircraft sites. However, with the Army's centralized laboratories, delays occur normally.

5.3. Potential value

Potential value has modest use in sustainability. Many times, potential value is incorporated into value calculations prior to the inception of a new initiative. On the other hand, a mature program will often be viewed as having reached its optimal performance. Unrealized potential that stands unrealized for too long may even be perceived as value lost. This may adversely impact sustainability if the benefits had previously been figured into a cost-benefit analysis for the program as a whole. Because of how long rotrode AES has been used by the military, the general perception is that there will be no further realization of any untapped potential.

Issues of usability or applicability often reduce value. Although unrealized potential can be converted to actual value and perceived value, this requires directed action to bring about the conversion of potential applicability or utility to real applicability and real utility. For example, the raw spectrometric data have value only if they can be converted to dollars. At present, the only real use of the spectrometric data is a measure of airworthiness.

As a general rule, the cognizant engineering authorities do not access, examine, or analyze the rotrode spectrometry data. This is an area of entirely untapped potential. The program managers defer to the engineers with responsibility over safety, but the engineers say they have inadequate resources to review the data and make meaningful conclusions and inferences. This neglect has severely affected the perceived value of the program.

Potential value is lost if maintenance policies do not make use of the data. For much of the Army's equipment, the main focus is on the oil quality and not the component health. However, rotrode AES tells relatively little about the oil quality. Recently, the Army Oil Analysis Program had planned to invest in a new data management system designed for engineering and technical data. That system would have allowed the program office to set up specific canned views of data and would have converted data into charts, tables, and graphs that conveyed meaningful information to the engineering authorities. The business case was solid because it increased the usability of the raw data to the engineering community; nevertheless, the project went unfunded because it posed an opportunity cost that was too high. In other words, financial resources were diverted to more pressing needs in the war effort.

5.4. Perceived value

Even when actual value is high, perceived value can be low. It can be low when the actual value is not effectively communicated, when the programs are not customer-oriented, or when the actual value is in fact low due to the various detractors described above.

There are three customers for oil analysis data: the major commands who own the aircraft and landcraft, the cognizant engineering authorities, and the field users (maintenance chiefs). At present,the maintenance chiefs are really the only customers who receive a product. For the major commands, oil analysis can be a nuisance that keeps them from completing missions and divert staff time. For the engineering authorities, the oil analysis data amount to millions of unmanageable and meaningless numbers with no semblance of structure and no framework for rapidly mining or visualizing what is occurring.

6. Conclusions

In general, the spectrometric analysis programs for wear debris have not been subject to strategic technology management, which has resulted in a lack of sustainability, reduced return on investment, and perceptual problems with data quality. Without quantitative programmatic objectives, the instruments and their data have been unable to demonstrate their worth. In addition, lack of continual data mining and data analysis have left the military service programs open to challenges of their utility and value. This has been further compounded by other factors: a lack of engineering or teardown investigations to support any actions on limits; an unwillingness of the services to orchestrate unified, coherent data format and exchange protocols; an inability of the services to agree on or to adopt standardized calibration, certification, or true performance evaluation procedures; and a failure to implement algorithms and processes to flag possible errors in sampling and labeling. Finally, a failure to plan for or account for technological advancements has now created a situation that will shortly result in significantly dissimilar instruments being used throughout the fleet.

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