Turbine Engine Research in the United States Air Force

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Abstract - Propulsion technology has always been a key to the successful development of aeronautics and has enabled new air vehicles throughout the aerospace industry. Yet advancements in propulsion have been dependent upon advancements in aerodynamics, thermodynamics and especially materials technologies. These advancements have required careful guidance in their application to propulsion through detailed technology development, a transition path and linkage to future systems. Since the late Thirties, the gas turbine engine has provided an enormous step forward in operational capability but with it has come an equal step in cost. The Air Force Research Laboratory (AFRL) Propulsion Directorate (PR) has the mission to create and transition advanced air breathing, rocket propulsion and power technologies for military dominance of air and space. Its vision is to continue to be the world leader in military propulsion and power technology. This vision has been realized through coordinated research programs like the Integrated High Performance Turbine Engine Technology (IHPTET) and should be secured for the future with the follow-on Versatile Affordable Advanced Turbine Engines, VAATE.

VAATE encompasses 3 research focus areas: Intelligent Engines, Versatile Core and Durability. Intelligent Engines will be high performance and be extremely damage tolerant. They will feature adaptive component performance, integrated propulsion and power generation, real time life tracking and proactive health management; these last 2 features are instrumental in reducing the cost of ownership. Why? Because 70% of affordability improvement is attributable to reduced cost of ownership. Engine Health Management (EHM) will enable the transition to on-condition based maintenance to provide the right support at the right time for the right reasons.

This paper covers the Propulsion Directorate’s mission and vision, IHPTET, advanced turbine engines, VAATE, and Intelligent Engines. It provides the definition about the intelligence being sought for the Joint Strike Fighter (JSF), the concept and the vision for the maturing of comprehensive EHM systems being developed by AFRL, and underpins that what we develop today must be affordable.

Common Abbreviations used in this Paper

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ac</td>
<td>Aircraft</td>
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<tr>
<td>AFRL</td>
<td>Air Force Research Laboratory</td>
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<td>AI</td>
<td>Artificial Intelligence</td>
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<tr>
<td>ASTOVL</td>
<td>Advanced Short Take Off and Vertical Landing</td>
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<tr>
<td>CEMS</td>
<td>Comprehensive Engine Maintenance System</td>
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<td>CETADS</td>
<td>Comprehensive Engine Trending and Diagnostic System</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
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<td>DoD</td>
<td>Department of Defense</td>
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<td>EHM</td>
<td>Engine Health Monitoring and Management</td>
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<td>EPA</td>
<td>Environmental Protection Agency</td>
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<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
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<tr>
<td>GOTChA</td>
<td>Goals, Objectives, Technical Challenges, Approaches</td>
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<tr>
<td>HCF</td>
<td>High Cycle Fatigue</td>
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<tr>
<td>ICBM</td>
<td>Inter Continental Ballistic Missile</td>
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<td>IGVs</td>
<td>Inlet Guide Vanes</td>
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<tr>
<td>IHPTET</td>
<td>Integrated High Performance Turbine Engine Technology</td>
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<td>JSF</td>
<td>Joint Strike Fighter</td>
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<td>LCC</td>
<td>Life Cycle Costs</td>
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<td>LCF</td>
<td>Low Cycle Fatigue</td>
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<td>LO</td>
<td>Low Observable/Observability</td>
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<tr>
<td>NASA</td>
<td>National Air and Space Administration</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>PHM</td>
<td>Prognostic Health Management</td>
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<td>PR</td>
<td>Propulsion Directorate</td>
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<td>PRDA</td>
<td>Program Research and Development Announcement</td>
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<td>PRT</td>
<td>Turbine Engine Division</td>
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<tr>
<td>P&amp;W</td>
<td>Pratt &amp; Whitney</td>
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<tr>
<td>R&amp;D</td>
<td>Research &amp; Development</td>
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<tr>
<td>RAF</td>
<td>Royal Air Force</td>
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<tr>
<td>S&amp;T</td>
<td>Science &amp; Technology</td>
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<tr>
<td>SBIR</td>
<td>Small Business Innovative Research</td>
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<tr>
<td>STOL</td>
<td>Short Take Off and Landing</td>
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<tr>
<td>T&amp;E</td>
<td>Test and Evaluation</td>
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<tr>
<td>TOGW</td>
<td>Take Off Gross Weight</td>
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<td>USAF</td>
<td>United States Air Force</td>
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<tr>
<td>UAV</td>
<td>Unmanned Air Vehicles</td>
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VAATE Versatile Affordable Advanced Turbine Engines

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1. INTRODUCTION

In early air battles fought during the First World War, in the skies over a war torn Europe, speed and height became the two most sought after requirements that provided a winning edge for aircrew. These laid the foundation to the pilot's urge for more speed and performance, and provided the key drivers that have led aircraft research and technology for decades.

Propulsion technology has been fundamental in pursuing solutions to these drivers and has enabled new ac and weapons platforms. However, whilst these remain highly sought after requirements, their priority has been tempered by cost considerations and the lean towards efficiency and affordability. The military still require the winning edge, and to maintain this by a comfortable margin, so as to carry out a wide range of duties around the World. However, maintaining this margin requires new and cutting-edge technologies that change and possibly revolutionize the way in which the military carries out its tasks. These technologies are emerging and growing at a fast rate, a growth that has been fuelled by the computer revolution and government initiatives like the Small Business Innovative Research (SBIR) program that brings ideas quickly into play to help develop new capabilities and foster new technology. However, new ideas have a cost and, as the research envelope expands, the financial pockets will continue to be stretched.

In the aftermath of the Cold War era, western governments are being focussed by many pressing internal concerns and as the Warsaw Pact threat reduces it is not surprising that defense has taken a lower priority. The military challenge now is to get more for the same or the same for less and still maintain the deciding, battle-winning advantage. Indeed, as the military fulfill more peacekeeping and policing roles, it is essential that they remain well equipped, mobile, and swift to respond; capabilities that challenge the defense budget and focus research fields to demand the best return on investment. Therefore, it is perhaps not surprising that affordability has become the bedrock for future research efforts like Versatile Affordable Advanced Turbine Engines (VAATE) and new airborne weapon systems like the JSF.

Many aspects of defense are wide ranging and cover most industries that, in turn, affect a large product base and workforce. Support to the military is considerable and can account for over 10% of country's Gross National Domestic Product. Consequently, it is easy to see that decisions that shape the military have a direct impact on industry and the economy. Engine manufacturing has a strong economic foothold in the US and contributes toward a huge aerospace industry. This industry spans almost one and half million jobs and supports a payroll of almost $54 billion [1] as follows:

<table>
<thead>
<tr>
<th>US Jobs</th>
<th>Payroll</th>
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<tr>
<td>858,000 Aerospace Industry</td>
<td>$31.5 Billion</td>
</tr>
<tr>
<td>300,000 Aircraft Related</td>
<td>$18.3 Billion</td>
</tr>
<tr>
<td>99,800 Turbine Engine Sector</td>
<td>$ 3.7 Billion</td>
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Therefore, future large research initiatives like VAATE have a large personnel-base to satisfy. VAATE is poised to follow from the successful Integrated High Performance Turbine Engine Technology (IHTET) program and revolutionize gas turbine development and life-cycle support. It hopes to fulfill its promise to provide the best technology for the military whilst maintaining the delicate affordability balance between cost and capability, industry and government. VAATE is the research path for turbine engines for the future and future generations of scientists, engineers and operators both in and connected to the military.

Scope

The purpose of this paper is to:
1. Outline the Air Force Research Laboratory (AFRL) Propulsion Organization and set the stage for the modern coordinated research efforts being undertaken by the AFRL.

2. Discuss the evolution of gas turbine engines through the IHPTET program, from purely a performance bias to include cost and affordability, and highlight some of the individual programs like the National High Cycle Fatigue (HCF) Science and Technology (S&T) initiative.

3. Detail the work to prepare for VAATE and explore the research focus areas for developing affordable technology, highlighting the potential paths to transition the technology.

4. Highlight the significance of the Intelligent Engines program as one of these research focus areas for the success of VAATE and explain the options that could be included in the VAATE areas of research. It will deal with the fundamentals of engine and machine intelligence, look at the JSF, and the need for reducing false alarms, and identify the vehicles in a Notional Air Force for the future.

5. Discuss what Engine Health Monitoring and Management (EHM) technologies are being pursued for the JSF and how these technologies will provide the foundations for the VAATE Intelligent Engines. It suggests that proactive fleet management must be the road for the future.

This paper provides an overview USAF turbine engine research but will focus on the development of gas turbine engine technology, with the main discussion on VAATE, Intelligent Engines and EHM.

**Background – AFRL Propulsion Organization**

When the military develops aircraft (ac), systems and components, it is in complete control of the development because it sets the requirements and uses the components and devices it transitions. In contrast, NASA provides research and technology in the hope that manufacturers will incorporate its developments. Likewise other arms of the government, the Environmental Protection Agency and the Federal Aviation Administration (FAA), set standards that they expect commercial manufacturers to attain. One of NASA’s roles is to help develop technology so manufacturers can meet the standards that these other branches of government establish [2]. Each of the Services has its own research laboratories to focus on the areas that are key to their needs. Each provides solutions to current problems, develops new technology for tomorrow’s needs, and enables the vision for future forces. Research is a team effort that demands investment, visibility and a coordinated response.

The United States AFRL features ten directorates and the Propulsion Directorate (PR) is one of the larger. PR is divided into 4 divisions; turbine engines (PRT) and rockets (PRR) are the largest, Power (PRF) is the smaller and the fourth is an operation’s division (PRO). The PR Directorate has the mission to create and transition air breathing, rocket propulsion, and power technologies for military dominance of air and space. Its vision is to continue to be the World leaders in military propulsion and power technology. There are three integrating technology thrusts in propulsion and power:

1. **Air** comprises turbine engines; fuels, lubrication and combustion research; ac power; and Unmanned Air Vehicle (UAV) unique propulsion.

2. **Space** includes high performance boost; high-energy upper stages; highly maneuverable spacecraft; space power; and combined cycles.

3. **Weapons** includes hypersonic missiles; directed energy power; ICBMs; and tactical.

![Three Integrating Technology Thrusts in Propulsion and Power](image)

**Figure 2 Technology Thrusts in Propulsion & Power**

PR is the one-stop shop for all the USAF propulsion needs. Having recently subsumed the fuels, lubrication and combustion research branches, PRT is now responsible for most of the work in air.

The USAF owns about 25,000 engines and, including spares and consumables, these account for about $32 billion of assets. With the recent commitment to acquire the F-22 RAPTOR ac, this massive engine inventory is set to double in cost and could exceed $70 billion by 2015. In 2005 a year that will see the completion of the IHPTET program, the transition to VAATE will occur. VAATE will begin a new series of research thrusts for PR and continue the coordinated research theme with industry. This is an important strategy that dovetails industries research efforts to meet military objectives and enables the technologies to be transitioned into a growing civil market; a market that is
demanding leaner, cleaner and quieter engines. The achievements of the IHPTET program, a 2X increase in thrust to weight based on the YF119 engine, will be pushed again to realize a 2.5X increase in thrust to weight. However, the VAATE main focus will change from performance to affordability [1].

In research and development many design considerations have to be taken into account, not least of which is that in ac design 40-60% of Take Off Gross Weight (TOGW) is engine and fuel. These have a major impact on ac size, weight, cost and capability. Moreover, the Department of Defense (DoD) burns 5 billion gallons of fuel per year so any improvement on fuel efficiency can produce significant savings. 

There are 25,000 DoD ac that are powered by 50,000 engines. These engines require $3.9 billion per year on engine maintenance and supporting acquisition. However, research is not limited to the military and over 80% of military turbine engine technology investments enhance US commercial engines.

Figure 3 Engine Thrust Growth

Ac systems grow with time and ac get heavier. The F-16 FALCON, which entered service in the late seventies at about 22,000 lb TOGW has grown to just short of 30,000 lb, an increase of almost 28%. Whilst this growth is relatively high in comparison with other combat ac, for the JSF the increase is being projected to be similar. Therefore, new engines at the forefront of technology now have to be capable of modification to maintain thrust growth and the military advantage. Figure 3.

2. IHPTET

The National IHPTET program was initiated in 1988 with an initial aim of doubling engine thrust; advancements resulting from the synergistic effect of combining advanced material developments, innovative structural designs and improved aerothermodynamics.

Figure 4 IHPTET Team

A combined team of government and industry leaders, see Figure 4, who provided matching funds, is coordinated by a steering committee that includes senior representatives from the Army, Navy, Air Force, DARPA and NASA. An Industry Advisory Panel (IAP) provides the advice to the Committee and includes Allison Advanced Development Company (AADC) - now Rolls Royce, Allied Signal Engines - now Honeywell, General Electric Ac Engines (GEAE), Pratt and Whitney (P&W), Teledyne Ryan Aeronautical and Williams International. Seven component technology panels work demonstrators, fans/compressors, combustors, turbines, exhaust systems, controls and mechanical systems. In addition, there are four pervasive technology panels: materials, computational fluid dynamics (CFD), structures and cost reduction. The IHPTET technology development approach has three Air Force program elements that provide a ‘building-block’ approach.

These include Applied Research on each of the technology panels; Advanced Development on engine and core demonstrators; and Technology Transition to selected ac and platforms. Whilst the Program is still heading for its goal to double performance, other objectives have evolved [3].
IHPTET now has 5 thrusts: improved fuel efficiency, reduced production and maintenance cost, maintaining the F119 life standard – engine in the F-22 RAPTOR, the National HCF S&T program, and doubling thrust to weight – its key objective.

IHPTET has been implemented through 3 phases:

1. **Phase I**, which was completed in 1991, was to increase thrust to weight by 30% and reduce fuel consumption by 20%; an improvement that could save $1 billion in fuel costs alone. For ease of focus, an identified start point was to extend the life of the engine hot-end components - a limiting factor on many gas turbine engines today is the life of the high-pressure turbine rotor. The transition path was for the F-22 RAPTOR ac development, and upgrades to the F-15 EAGLE, F-16 FALCON, F-18 HORNET, B-1 LANCER, C-17 GLOBEMASTER, F-117 STEALTH FIGHTER, B-777 and MD-12 CITATION ac. This varied set of platforms covers many of the major fleets in the USAF and Navy inventories.

2. **Phase II**, which was completed in 1997, was to increase thrust to weight by 60% from the baseline, reduce fuel consumption by 30% and reduce costs by 20%. The transition path has been the JSF, ASTOVL, and upgrades to the F-22 RAPTOR and B-2 SPIRIT ac. Importantly, innovative structure has been employed to reduce weight and ease maintenance. This is not a new approach, Martin Baker developed a fighter at the close of WW II, the MB-5, that was designed with maintenance in mind to simplify and speed maintenance procedures and help generate the ac quicker for flight [4]. Although the MB-5 never saw production, other manufacturers copied many of its maintenance initiatives and this paved the way for the jet age. IHPTET embraced this ideal and is working affordability through revolutionary new engine capability. Furthermore, recent operational engine maintenance problems and cost issues have increased the IHPTET affordability focus.

3. **Phase III**, which is due for completion in 2005, is to double thrust to weight, reduce fuel consumption by 40% and reduce costs by 35%. One way fuel efficiency will be achieved by the use of variable cycle engines. The transition path will be for JSF upgrades, V/STOL and perhaps an F-22 RAPTOR derivative, see Figure 5.

Achieving success for technology insertion, within stringent budget constraints, remains a high priority for the many managers and researchers involved in the IHPTET program. In PRT the research rules have been clearly identified and are easy to follow. They are 4 questions:

1. **What Are You Trying to do?** This should be identified through a number of goals which, in turn, need to be challenging, achievable, and measurable.

2. **By When?** A pace needs to be determined by the users, industry, and other advocates.

3. **What Difference Will it Make?** As the research efforts are jointly funded; the payoffs should apply equally for the military and commercial capability.

4. **What Makes You Think You Can do it?** This needs to be technically illustrated through the Goals, Objectives, Technical Challenges and Approaches (GOTChA) process and be financially assured with expenditure Roadmaps vs. budgets.

These questions have steered many researchers and have remained an important foundation on which to build VAATE. For IHPTET, an extensive list of GOTChA charts exists for each of the seven technology areas. Indeed, there are separate packs of GOTChA charts for each of the 3 Phases of the Program. From these charts, comprehensive research agendas can be built and associated with complete research roadmaps. These roadmaps feature calendar-based milestones and identify the budgets that are required to achieve the necessary Technology Readiness Levels (TRLs) for technology insertion. Often the push for technology is mirrored or surpassed by industry’s pull to achieve its goals and the quickest technology transition often follows a balance in this push-and-pull situation.
HCF Initiative

Although only fleetingly mentioned, the HCF S&T program is specifically directed at supporting the MPTET program, and one of its goals: to reduce maintenance costs. The HCF program will try to achieve that goal through 8 technical action team efforts targeted at a 50% reduction in HCF-related maintenance costs. In addition, this program could contribute to a reduction in HCF-related ‘real’ development costs of over 50%. When combined with the Test & Evaluation (T&E) program and future EHM approaches, the HCF S&T should ensure the production of much more damage-tolerant high-performance engines.

The HCF S&T program is a huge cooperative effort that has required a total program investment of almost $134 million. The breakdown of the funding falls roughly a third each to MPTET and the Air Force Office of Scientific Research (AFOSR), a quarter to industry, and the remainder to others that include NASA and manufacturing technology. The HCF program has produced some significant successes that include the following 2 examples:

1. BDAMPER. The BDAMPER forced-response prediction code which, when applied to the P&W F100 engine third-stage Fan redesign, reduced the unscheduled man-hour maintenance effort from over 800,000 hours to less than 200,000, and is projected to half this to 100,000 hours by the close of calendar year 2000. See Figure 6. In addition, this remarkable achievement is mirrored by the success in materials damage tolerance through the introduction of Laser Shock-Peening (LSP).

2. LSP. There had been several fan blade failures in F101 and F110 engines that had forced a “thumb nail” inspection, capable of finding a 5 mil flaw, every 25 flight hours on the F101 and prior to the first flight of day for the F110. Worse still, 90% of failures were from cracks of less than 125 mils. LSP overcomes this problem. It uses a laser to impart a localized energy wave to propagate into the material that results in a deep compressive stress that stops both crack initiation and propagation. The process provides a compressive stress that is 4X deeper than conventional steel-ball shot Peening and replaces “thumb nail” inspections with visual inspection only. LSP is in production on the F101 engine, B-1B LANCER ac, is qualified for F110 on the F-16 FALCON ac and is under evaluation for the F414 in the F/A-18E/F SUPER HORNET ac.

Today, excellent progress in the HCF program continues. For the first time, it appears that this once arcane topic is being managed to a point where significant cost reductions are being realized, positively impacting the operations, maintenance, and readiness of USAF combat forces. However, HCF remains a very difficult technology challenge that has continued to evolve multiple technology development and transition risks. For the future, the HCF S&T program will continue as a very high priority national effort, and maybe even evolve into a collaborative effort with the UK. Meeting the total technology challenge could essentially eliminate HCF-related engine problems and greatly enhance ac readiness and availability [5].

3. Versatile Affordable Advanced Turbine Engines

Today, new technology has an established and accepted baseline so that improvements can be compared and quantified. At least since the beginning of the IHTPEET program the development of new gas turbine engines have been baselined on the latest tested and proven technology that is available in a whole engine. For VAATE, the baseline is the P&W F119 engine as fitted to the F-22 RAPTOR ac, an engine in a 35,000 lb-thrust class. Therefore, based on this already advanced engine it perhaps is no surprise that improvements in gas turbine technology have an associated large cost increase. The need now is to balance technology improvements with cost. Affordability is the number one concern of the DoD; where affordability is defined as capability over cost and is shown in Figure 7.

Affordability is not new in defense and, for the JSF, affordability was used as an ‘independent variable’ to determine how the ac was designed and how it should be manufactured, managed and maintained, to keep whole-of-life costs, Life-Cycle Costs (LCC) low. It is widely believed that an ac purchase cost provides but a small fraction of its LCC, perhaps as little as 1/3. Commonalities of the main components for the 3 JSF variants – conventional take off and landing, short take off and vertical landing and the carrier variant – is prime in keeping costs low. The emphasis may have centered on cost but, as can be seen by the affordability formula, performance and capability remain high in order of priority.

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It has been estimated that the USAF expends an average of $400/hr to operate its engines fitted in the fast jet/combat ac fleets. As new technologies are introduced to enhance performance, the military cannot afford to let this operating cost surge to higher levels. The key is to provide the same for less or more for the same. Consequently, the VAATE program will address affordability as its main goal and will drive to provide 10X affordability based on the P&W F119 engine.

In collaboration with VAATE are the Department of Energy (DoE) and NASA. VAATE includes all the DoD Government team that participates in the IHPTET program. VAATE is divided into 3 focus areas of research: Intelligent Engines, the Versatile Core, and Durability; and these will be described in more detail later. Each of these 3 areas is interwoven to achieve the key aim of a 10X improvement, an order of magnitude improvement, in affordability. In addition, the National HCF S&T program will continue and be swept up into the Durability initiative; further improvements will be sought to improve fuel efficiency; and all will continue to make inroads to reduce development, production and maintenance costs. For ac propulsion - turbine engines, fuels, lubrication and, ac power - will be worked through the 3 research initiatives and transition to fighters, bombers, transports and rotorcraft. At the same time, ac propulsion will transition to meet power and propulsion requirements for combat UAVs, ISR UAVs and missiles. The air propulsion thrust goal is to provide affordable, capable and timely propulsion technology for the war fighter’s needs.

The research objectives for the Versatile Core are to provide the necessary versatility through High Excess Horsepower, Superior Fuel Efficiency, Durable/Robust Design, and Efficient, Wide Flow Range.
Durability

The interaction between durability and readiness is significant. USAF and US Navy experiences are similar in creating the unavailability 'death spiral' induced by insufficient maintenance and hardware replacement in the name of economy. Engine durability is a pressing concern and is being addressed currently under the auspices of the HCF S&T program. However, due to its association with life, safety and cost, and its importance in VAATE, a durability initiative was launched by a Workshop in April 2000. Durability is now being managed as a separate program that will feed into the IHPTET transition paths and be well underway for the commencement of VAATE [6].

There are many aspects being covered under Durability. The definition and research areas are in their infancy and work is on going. Collaborative research teams are focused on several areas that include Life prediction methods, Hot Section Aerothermal, Structural Analysis, Instrumentation, Inspection, Manufacturing and Repair, Materials and Coatings, and T&E. Gotcha maps are being produced and research agendas formulated. Even at this early stage, the value of government and industry cooperation is being demonstrated in the scope and depth of these maps. Moreover, integrated product development efforts are critical to effectively balancing all of the factors involved with the design of new engines or in increasing life in legacy and current engines, particularly in light of the budgets available to the Services and engine OEMs.

For legacy/current engines, repairing parts or retrofitting new parts is attaining durability. Repair processes for single-crystal turbine blades need further development; additional work is needed in surface treatments; and life-prediction methods for repaired components are essential. For retrofit, lowering the cost of current materials and processes is critical to preventing prohibitively high acquisition costs for new parts.

4. INTELLIGENT ENGINES

Intelligence is the interpreting, setting or modifying objectives, and taking action to accomplish those objectives. This requires extensive knowledge of the environment and engine health based on sensor data, engine and expert models, and the fusion of these to provide the best information. It requires active self-management of performance and health, and the balancing of mission requirements against environmental factors. The payoffs are significant improvements in performance with lower cost of ownership, enhanced safety, and improved availability; these payoffs are at the very heart of the VAATE program.

Current USAF aero-engines spread across many ac and human generations. Perhaps the oldest is the TF33 fitted to the B-52 STRATOFORTRESS, which was developed in 1948 at WPAFB and the most recent, the F119 engine in the F-22 RAPTOR ac. Thus the spread of technology, reliability and LCC are massive. However, newer does not always mean better. Moreover, it is where these engines are fitted and how they are operated that become dominant in the complex algorithms that determines their reliability and availability.

Reliability is key to ac availability and operational readiness; a field commander has to rely on his ac to provide the punch to attack, the defense to protect and the cover to re-supply and rescue. Ac today are increasingly being used as a first-use/first-strike force to gain air superiority, and later air supremacy, to safeguard the movement and prepare for the attack of his ground forces. The drive for the increased use of air power is the ability to soften the defenses of a target or reduce the punch of an attack, whilst reducing the risk to ground forces and the loss of life. This last factor, loss of life, has become an increasingly important priority since cameras and the press became prominent on the battlefield. In World War (WW) II, and many of the large conflicts since, achieving the aim - to take control of a hill or area - was the priority, sometimes regardless of the cost in human life, but the success was often gauged by the number lost in achieving this aim. Today the press, visibility of the conflict to the public, and their combined pressure on governments mean that the loss of even one life can influence commanders to change tactics and the order of battle. So reliability is extremely important to a commander.

The statistics that show reliability of engines makes interesting reading [1]. In 1997 44% of USAF aero-engines were changed due to faults or time-related inspections and replacements; time-related inspections and replacements accounted for more than 20% of all removals. Each engine fleet is managed separately by several teams that include the major command, Air Force Material Command, the
equipment System Program Office, and industry. Indeed, for the larger fleets like the P&W F100 and GEAE F110 engines, fitted in the F-16 FALCON and F-15 EAGLE ac respectively, these are subdivided by marks and thrust class and managed the same. The management teams provide a high level of experience and expertise to support the bases where the engines are maintained and operated.

**Intelligent Machines**

It is expected that engines will evolve and develop into intelligent machines. Intelligent machines are capable of adapting their goal-oriented behavior by sensing and interpreting their environment, making decisions and plans, and then carrying out those plans using physical actions [7]. However, current engines are fixed, inflexible, and do not respond to changing environmental conditions. They are not designed for worst-case deterioration and operating conditions, which leads to large safety margins in design, operation, and maintenance concept. Consequently, performance is compromised and support cost is increased. In the future, ultra-intelligent engines will be flexible, be able to adapt - either actively or passively - to changing environmental factors and be influenced by the following:

1. The factors can be internal - engine health - or external - new/changed missions.
2. Engines must still meet performance requirements at component end-of-life condition.
3. Life can be extended via adaptive control of the engine and individual components.
4. Engines require thorough knowledge of the flowpath and mechanical condition.
5. Auto-optimization based on EHM that will incorporate self-diagnosis, self-prognosis. This is covered later in EHM.

**Joint Strike Fighter**

The JSF will be an Intelligent Air Vehicle with an enabled autonomic logistics system, which will provide unprecedented affordability, reliability, maintainability, and supportability while meeting sortie generation rates, mission reliability, and logistics footprint requirements. This later requirement is exceptionally important, numerous generals have cited it. In conflicts like the Gulf war, and beyond, the front line has demanded the mobilization of reserve forces to generate a huge support tail. The quest for the future is to balance the front line, the ‘teeth’, against the support structure, the ‘tail’. Intelligent vehicles promise to enable this by providing unprecedented visibility of vehicle health and accurate forecasting of spares requirement to meet precise needs. EHM researchers are poised to meet the true ‘on condition’ maintenance requirements.

The JSF Prognostic Health Management (PHM) program has been hungry for new technologies to get the maximum life from new equipment and improve availability. Moreover, it will provide the commander in the field with unequalled visibility of the performance of the Ac to allow precise selection for operations and individual sorties. It seeks to provide predictive diagnostics of faults, performance and life - prognostics - and transmit this information from the Ac via a secure communications link to a ground system. This system, the Joint Distributive Information System (JDIS), will link the ac to a comprehensive maintenance network that will include equipment suppliers and the ac OEM. PHM is being applied to many systems on the JSF including the engine, auxiliary power unit, environmental control system, electric’s, and structure, areas that are known to be a source of concern or have seen a high number of faults on ac like the F-15 EAGLE or F-16 FALCON. PHM will provide almost total visibility of vehicle health and has been referred to as the Vehicle Management System.

![The Boeing JSF](image1)

The Intelligent Air Vehicle comprises: the Airframe; PHM Systems; Mission Systems; Vehicle Maintenance System; and Accurate, real-time performance and life models with specialized diagnostic sensors to enable automated troubleshooting and maintenance forecasting. Furthermore, Information fusion technologies will make every engine a web site and will provide instant awareness when problems arise, provide accurate decisions based on redundant information, and be accessible to all users. In addition, active control of compressor, combustor, clearance, and vibration will enhance performance, durability, and survivability. An example would be a smart compressor. This would feature HCF detection and suppression and would have the Inlet Guide Vanes (IGVs), blade vibrations, dynamic pressure, fuel flow and nozzle all controlled. It may offer:

- Sensing of blade tip displacement, dynamic pressures, and case vibration.
- Actuation will include conventional means to change fan or compressor operating points, direct damping or
cancellation via “smart” airfoils or micro-adaptive flow control.

- Control strategy featuring indirect, speed avoidance, and direct, active vibration control.

Reduction of False Alarms

In modern health management systems false alarms would not be tolerated, they would undermine confidence, and ultimately would lead to warnings being ignored. Moreover, in a fighter aircraft, space and weight are at a premium and equipment must win its way onto the ac by proving its operational value and cost effectiveness. Equally, whilst a sensor must be rugged and compact, it must not represent the “tip of the iceberg” and have a mass of circuity and supporting hardware.

False alarms can be kept to a minimum by incorporating improved sensors and by employing information-fusion capabilities that use multiple parameters and sensory data to provide the best information. Many of the first piezoelectric vibration sensors suffered from countless errors and gave too many false alarms. This eventually led to vibration alarms being ignored and in some case the sensors being disconnected and tied back. Future sensors must be highly reliable and provide ultimately 100% confidence in alarms and warnings to the operators and maintainers.

Advanced intelligent systems will incorporate self-learning to gain knowledge from mistakes or misdiagnosis, and gain experience from within the engine fleet or other engine ranges, and become expert at their own management, all this with minimal human input. Perhaps a better understanding of engine operations will lead to more use of virtually sensed parameters that will be combined with data from actual sensors to provide a comprehensive indication of health and life.

Engine sensors have evolved greatly since the advent of the gas turbine engine where they were predominantly used to measure speed and temperature. Many of the sensors of today have at least a dual capability and can measure, sense and monitor different engine parameters. Moreover, if these parameters were combined to provide a multi-dimensional mean-line of operation, see Figure 13, any diversion from that mean could be seen as being a fault or trended - prognostics - to provide an indication of a pending failure. Information fusion is key to this approach and is being worked through many new technologies that include neural networks, model-based approaches and data-mining rule extraction.

Data fusion is essential to future EHM to keep false alarms to a minimum and prevent the EHM system becoming a scourge to the maintainer, operator and commander. Once employed, EHM and, better still VHM, will provide unparalleled visibility of health to meet mission requirements and maintain safety.

A vision for sensors of the future is that one sensor will have the ability to read more than one parameter, perhaps even several, and be self powered by engine heat or vibration. Consequently, for a limit alarm, the sensor will turn itself on when a limit has been reached and alert the control center or pilot of an exceedance leading to a potential failure, long before that failure occurs. For VAATE applications, this could be integrated into controlling systems that will be aware of mission criteria and adapt engine operation to maintain aircraft and system availability.
Air Force of the Future

The Air Force of the future will undoubtedly include a blend of capabilities to cover many different and diverse operations. Multi-role will evolve to provide multi-variance and the growth for operations in space. The Air Force could become the Air and Space Force and may even extend to a separate Space Force, akin to when the Air Force formed from the Army in 1947.

In Figure 14 the vision for future military flying machines shows:

1. A supersonic fighter capable of vertical take off and landing. In addition, a versatile mission combat ac able to change roles in flight to suit changing threats, whilst transitioning to the target.

2. A global strike ac that can strike at any target around the World and return home without refueling.

Figure 14 Notional Air Force of the Future

3. A Transport that will offer 2 capabilities: a global transport ac with the ability to fly around the World, un-refuelled; and an ultra short take off and landing ac, perhaps capable of taking off and landing in a distance less than its own length.

4. Space vehicle access will perhaps be provided on a routine basis from any airfield without special operations or control measures.

5. The future battlefield will undoubtedly include an array of UAVs capable of covering many or all of the roles in the USAF of today. There is belief at Lockheed Martin that the JSF will be the last manned combat ac.

VAATE has a significant area to fill and a successful program, IHPTET, as its foundation. It is poised ready to expand the performance and affordability envelopes of the latest engines of today. It will power new air vehicles, upgrade old and provide revolutionary capabilities. Its commencement will continue the growth of the gas turbine engine and this should maintain it as the power source for the next 2 generations of ac and possibly beyond.

Figure 15 VAATE Potential

5. ENGINE HEALTH MONITORING AND MANAGEMENT

The USAF commenced R&D into artificially intelligent engine condition monitoring several years ago as part of the drive towards the IHPTET program [8]. Recognizing the spiraling costs of technology and the need to provide the maximum availability of ac and equipment, specific research into EHM was borne. The key goals for EHM then were to make engines more available and more affordable, and these goals have not changed. However, within the Propulsion R&D community, and as already mentioned, there is a growing shift from performance to affordability, which increases the importance of EHM and makes it key for VAATE.

Engine health monitoring is the basic measurement and monitoring of engine control parameters. These parameters are typically independent and are manually referenced, and sometimes they are occasionally trended to determine life and health. The technician and mechanic bring the experience to the monitoring in selecting the parameters that are significant to determine health, diagnose faults and suggest the maintenance action required. The quest is to harvest all the experience, build an expert model that incorporates this rich knowledge, and provide this wisdom to all users and maintainers, irrespective of their there background or experience.

Today it is still customary to monitor mainly temperatures and pressures but there is a beginning to explore broadband and high frequency vibration, oil condition and particulate analysis, and other parameters that could be combined to give an accurate - comprehensive - indication of health.
Recent research has been to provide options for artificial intelligence on engine test facilities and incorporate them in ground-based systems like the USAF Comprehensive Engine Trending and Diagnostic System (CETADS) and the Comprehensive Engine Management System (CEMS). In the future, research initiatives may be focused to flight test AI advanced EHM systems, fit them to new ac and retrospectively fit them to older aircraft to improve their management, visibility, LCC and availability. EHM has to prove its worth and begin to realize the savings it promises. When this can be achieved it will win its way on to all new equipment.

**Proactive Fleet Management**

In the USAF several separate and often disparate management organizations currently manage and maintain engine fleets. Some operate within their own rules and agendas, and from there own budgets. Communication between these organizations is complex and can vary; many operators foresee the existence of ‘stovepipes’ where organizations work vertically through their own organizational structure. The benefit will be the integration of these ‘stovepipes’ through a lateral communication network to meet one aim or objective, to keep the engines flying at the lowest cost to the operator. Speed of communication and the transfer and processing of data are vital to this cause. Future communication networks must integrate the supporting organizations to provide the tools to enable field commanders the visibility to select the right vehicles to achieve mission success. This total support strategy is not new but can be improved to provide flexibility, improve visibility to everyone in the support loop, and reduce costs.

EHM starts at the sensor level providing measurement data of various engine parameters. Typically, these data are shown on cockpit instrumentation and are used in the control of the engine. It is envisioned that engine monitoring functions will be integrated at the sensor level and the output integrated again with component, engine and fleet maintenance histories, to provide the best information on engine health to the operator and maintainers. This data fusion process is key to proactive engine health management. However, as this will provide considerable data, and as computers are fundamental to this process, it may be several years before they are capable of processing all the data on board.

Several airlines have worked around this and supplement limited on-board capabilities with autonomous facilities, telemetry linking the data and information via RF communication links, and processing it remotely. However, there is a time delay in processing the data and providing the health information back to managers. Thus, its use is dependent on how far forward the prognostic capabilities can extend and their accuracy when extended. Nevertheless, this type of health management is being seen as providing good visibility for power-by-the-hour engine support; the regional jet manufacturer, Embraer, has embraced this technology.

By 2002 the first Rolls-Royce engine will be fitted with a high-tech Black Box that will examine its performance in minute detail. So sophisticated are the new monitoring systems – including lasers, radar, acoustic sensors and particle detectors – they will put engine health on a fully scientific basis for the first time. This system and future EHM system could offer autonomic logistics, the automatic provisioning of spares and call for certified maintenance personnel. The idea is to get the Right support or maintenance at the Right time for the Right reason. The R support methodology could include the call for tools, provision of electronic maintenance manuals/details and electronic equipment log card recording [9].

![Figure 16 Proactive Fleet management](image)

Engine component lfiting can now be calculated in real time, on wing, instead of using a worse case scenario and applying this across an engine fleet. This old, safe-life methodology maintains safety but wastes significant component life by requiring the rejection of components before their actual life limit has been met. This aspect is seen as having the potential to save many millions, perhaps even billions of dollars in the USAF alone, and may help refine designs based on new, whole-of-life measurement and recording.

6. **Summary**

Propulsion technology remains the key to enable new air vehicles. However, the cost of new technology must be focused on providing a new capability, or significant improvement, and obtain good return on investment. In these times, living through the computer revolution, seeing rapid and large changes that are providing an inspirational glimpse into the future, we need to check this advancement
against the chill of similarly massive increases in cost and ensure we get the right balance in value and effort. Defense is a major economic player and it is important that future research programs address this balance.

The AFRL PRT is responsible for the USAF research work on gas turbine engines and dovetailing future needs to meet current, real-world needs for the USAF’s 25,000 engines. It is the World leader in military propulsion and power technologies. Through the IHPTET program it is committed to double engine thrust to weight and reduce engine support and fuel costs; costs that extend to almost $10 billion per year.

IHPTET was initiated in 1988 and is a National program that has been expanded to include 5 research thrusts. It has been implemented through 3 phases, in three classes, with each phase an extension of the last. It supports the F-22 ac, the JSF - or their derivates - as well as many of the current ac types. The rules for technology insertion follow 4 simple questions that lead to the development of GOTChA charts and research roadmaps. A significant part of IHPTET has been the HCF S&T initiative that was commenced in December 1994 and specifically targeted the reduction of maintenance costs. It is a huge cooperative effort that has required massive investment but has provided significant success. It has given rise to technologies that have reduced maintenance effort and the chance of component failure from foreign object damage or material flaws. The HCF S&T program has recently become collaborative with the inclusion of the United Kingdom.

VAATE is the agreed National collaborative research path for turbine engines for the future and is set to start in 2003, as a follow-on to IHPTET. It is predicted to run for 15 years, developing turbine engines to further levels of capability. The key driver is affordability with the goal to provide 10X the affordability based on the P&W F119 engine. It will have 3 research thrusts: versatile core, intelligent engines, and durability; durability will include the HCF S&T program. The versatile core or cores offer the possibility of a series of similar cores to fit many turbine engines. The Durability initiative was launched in April 2000 and will be well underway for the commencement of VAATE.

Artificial Intelligence will feature in all new engines and is at the very heart of VAATE. It will improve reliability, and offer unparalleled visibility of engine and system health to the commander in the field, maintainer and operator. As health is incorporated into control systems, engines will develop into intelligent machines and be able to adapt to situations without compromising performance or safety. The JSF will be an intelligent air vehicle that will feature PHM on many systems to target and reduce support. It will ensure the right maintenance is received at the right time for the right reason, to improve availability by improving the visibility of health. However, the need for no or very few false alarms is fundamental to the acceptance of intelligent machines and to win the confidence of the System users. Data fusion techniques can be applied to keep false alarms to an acceptable minimum and the Systems can use the false alarms as feedback to improve themselves and warn other engines of incorrect diagnostics and prognostics. New, multi-capable, perhaps even multi-parameter sensors will feature in intelligent systems to ensure the best information is always available. Intelligent machines are depicted in a notional air force of the future, which could provide the step to develop an air and space force or even a separate space force, and promises many revolutionary capabilities. These include global reach for transport and strike ac, routine access to space, and includes UAVs in many or all-future roles.

Figure 17 The Joint Strike Fighter

With spiraling engine support costs and the advent of new technology, offering more complex and expensive equipment, the USAF is seeking reductions in LCC in the form of new technologies and advanced health monitoring. Work on advanced, intelligent EHM feeds directly into the intelligent engine work in VAATE. Through advanced diagnostics and prognostics it will be possible to predict problems before failures occur and ensure preventative maintenance is scheduled at a time to suit the operator and maintainer. Therefore, a system that monitors and provides prognostics is a major advantage to any management. Health monitoring is being applied to many inherently unreliable systems in order to improve visibility, reliability and maintainability. Advanced EHM will be incorporated into ground-based systems, like CEMS and CETADS, that will allow engines to be base-lined off test, and combine this with fleet histories for performance monitoring and diagnostics. Furthermore, future communications will integrate the many suppliers and supporting organizations to provide a total support network that will allow commanders in the field to select the best aircraft to provide the highest chance of operational success. This total support strategy can provide many battle-winning features and reduce costs. Many airlines today already use similar EHM systems to reduce support costs and improve health visibility for lower
power-by-the-hour engine operating costs. Accurate component lifing alone has the potential to save billions of dollars in the USAF. Engine cost and affordability are large factors that VAATe is poised to confront and conquer.

Continued success and confidence in health management will reduce failure, and expensive and disruptive corrective maintenance, and allow the aerospace industry to move towards condition-based maintenance, based purely on equipment condition and not worse case estimated life. In the future, engine data could be further fused with aircraft data and be embedded in active control systems that will change engine operating conditions to minimize the effects of HCF, extend life and reduce LCC. Advanced EHM will realize its potential; it will help to provide more reliable engines and make engines more affordable. Affordability is key to continuing the development of gas turbine engine technology and VAATe will continue down this path for at least the next fifteen years.

REFERENCES


BIOGRAPHY

Squadron Leader Richard Friend is a Royal Air Force engineering officer serving on an exchange program in the Propulsion Directorate at the United States Air Force Research Laboratory, Wright Patterson Air Force Base, Ohio. He is the senior manager for USAF EHM applied research projects underway in industry. He is also the Secretariat for the Steering Committee for the High Cycle Fatigue Science and Technology Initiative, and is a member of the DARPA-led Integrated Project Team for the JSF PHM. An aero-mechanical engineer, he is specialized in gas turbine engines and has accrued over 23-years experience in the maintenance and management of fighter aircraft, engines and engine test facilities. Formally a senior engineering officer/chief maintenance officer on a Tornado F3 equipped squadron at Coningsby, England, he has served at the Defence Evaluation & Research Agency (DERA) at Pyestock, Farnborough, England, where he researched Foreign Object Damage, the mechanisms of object ingestion, and aero-engine operating costs. As a Flight Lieutenant he was: an engineering authority responsible for the management of installed and uninstalled engine test facilities for the UK Armed Forces; was officer in charge of a Tornado RB199 engine overhaul facility, repairing engines and provided specially modified engines for the Royal Air Force Tornado aircraft that operated in Operation DESERT STORM. As a junior engineering officer, junior maintenance officer, he served on the Phantom F4 Operation Conversion Unit that trained pilots for operational service. He served 9 years as an engine and airframe technician, saw active service in the Falklands Island conflict, and achieved the rank of sergeant. He was commissioned into the Royal Air Force Engineering Branch in 1986. He enjoys golf, albeit as a high handicap, snow skiing and fly-fishing.