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Feature analysis on US military aircraft engine advanced technology programs

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Abstract: US military aircraft engine advanced technology programs were overviewed and analyzed from light weight gas generator (LWGG) program initiated in 1960s through integrated high performance turbine engine technology (IHPTET) program started in 1980s, then to versatile affordable advanced turbine engine (VAATE) program. Some features and trends were summarized and concluded by literature statistics method, such as teams based on closely corporation among government, industries and academics, goals oriented with national defence strategies and weapon system development requirements, engineering manufacture and development including all relative disciplines and areas, verification measured by technology readiness level, the application extending to military aircraft engine, civilian engine, gas turbine and space vehicle, etc. The experience and lessons obtained can provide reference and guide for technology research and engineering manufacture and development of military aircraft engines in the world.

Key words: aircraft engine; military aircraft engine; advanced technology program; technology corporation; multi-discipline development; technology verification

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After changing the strategic thinking that missiles were more importance than the aircraft and the argument that turbine engines were a mature technology and nothing more needs to be done. In early 1960s, US government initiated and implemented a series of advanced military aircraft engine technology programs, developed and demonstrated the advanced core engine technologies, in order to throw off falling behind the Russia for technology level and development speed of aircraft engine.

In early 1960s, Air Force Aero Propulsion Laboratory at Wright-Patterson Air Force Base (AFB), incorporation with General Electric (GE) and Pratt & Whitney (P&W), initiated and implemented advanced core engine demonstrator program—LWGG program with zero fund, in order to develop and demonstrate future fighter engine technologies. Since then, US government combining industries and academics, initiated and implemented systematic advanced technology programs to develop and demonstrate the advanced engine and component technologies and concepts for varies generation military aircraft engine, and achieved obvious advancement in military aircraft engine technologies and products. During the programs, a large amount of experiences and lessons on technology research were demonstrated and obtained. Therefore, the features and trend on US military aircraft engine advanced technology programs summarized and concluded can provide important references for the research and development of military aircraft engines in the world. These programs include advanced turbine engine gas generator (ATEGG) program, aircraft propulsion subsystems integration (APSI) program, component improvement program (CIP), engine model derivative program (EMDP), engine structure integrated program (ENSIP), engine durability and damage

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tolerance assessment(DADTA) program, turbine engine hot section technology(HOST) program, low cycle fatigue(LCF) program, joint technology demonstrator engine (JTDE) program, integrated high performance turbine engine technology (IHPTET) program, national high cycle fatigue (HCF) program, versatile affordable advanced turbine engine (VAATE) program, high temperature engine materials program (HITEMP), titanium matrix composite turbine engine composite consortium (TMCTECC) program, affordable polymer composite(APC) program, department of defence(DoD) manufacture technology(DoD MANTECH) program[1-3].

1 Team based on government, industries and academics

Corporation and communication among government research laboratories, industries and universities were excited in US science and technology research from national to defence, then to aircraft engine industry. Since 1980s, US government successively issued a large amount of rules, laws and regulations to encourage the corporation and communication, such as *the Stevenson-Wydler technology innovation act* (1980), *national cooperation research law* (1984), *and federal technology transfer act* (1986). They facilitated the cooperation of a lot of partners on aircraft engines.

The government, industries and academics brought advantages and contributions into the corporation. The government agencies, including DoD, National Aeronautics and Space Administration (NASA), Department of Energy (DoE) and Department of Commercial (DoC), were in charge of defense application development, feasibility study of new technologies for weapon systems, the test and evaluation of the armament, a small amount of basic research and providing technology support for government agencies in making and organizing defense development program. Industry research entities were in charge of preliminary development of weapon system, and invested independent development program based on industry requirements except to the development contract charged. US government gave a large amount of economic compensation (DoD act 3204.1) to the above entities in order to accelerate defense science and technology research and weapon system development. Academic agencies were in charge of basic research (taking up 50% of defense basic research).

Advanced technologyprograms on military aircraft engine were organized by Air Force Aero Propulsion Laboratory that included basic research, exploration development and advanced development. The majority of basic research were implemented by academies, governments and industry entities and a small portion of them were implemented by Air Force Aero Propulsion Laboratory, and the exploration development and advanced development were mainly achieved by industry entities. The technology developed and demonstrated in IHPTET and VAATE programs included in exploration development and advance development. The civil aircraft engine programs were organized by NASA Glenn Research Center. The basic research, exploration development and applied development under Technology Readiness Levels(TRL) 4 were included in these programs to ensure propulsion system meeting with surrounding requirements, and sustain the advantages of US propulsion system, increase the safety and economic of air transport. The technologies developed and demonstrated in Ultra Efficient Engine Technology (UEET) program were achieved TRL 5-6 level, and the technologies developed in Air Propulsion and Power(APP) program were achieved TRL 1-3 level. Industries were in charge of DoD and NASA programs and engaged in varies technology activities from basic research to engineering development. University and other research agencies undertook foundation technology from government or military. IHPTET and VAATE programs were developed effectively by incorporating governments, industries and academic agencies.

The pioneer of IHPTET program is high performance turbine engine technology (HPTET) program. The HPTET program as an advanced technology development began in 1982 and only in Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory (APL). Realizing the importance of advanced materials, Materials Laboratory (ML) joined the initiative soon as a partner in 1984 with an increased emphasis on advanced materials and structures. In 1985, in compliance with the direction of the Air Force Systems Commander to increase the gas turbine engine industry involvement in the HPTET, the program reviews were held with the following seven aircraft engine companies: Allison Gas Turbine Division, Garrett Turbine Engine Company, GE, Lycoming, P&W, Teledyne CAE, and Williams International. At the urging of the deputy under Secretary of Defense for research and advanced technology, the Army, Navy, Defense Advanced Research Project Agency (DARPA) and NASA were also joined the program. The resulting technology development and demonstration program represented a fully integrated government/industry/academician activity, thus the HPTET program had been consciously applied to integrated high payoff rocket propulsion technology (IHPRPT) program.

VAATE program took experience of incorporation of governments, industries and academic agencies after IHPTET program successfully. In addition to five departments such as Department of Army, Department of Air Force, Department of Navy, DoD and NASA and six companies such as GE, Honeywell, P&W, Allison Advanced Development Company(AADC), Williams International and Teledyne Continental, two government departments such as Office of the Secretary of Defense (OSD) and DoE and three aircraft companies such as Boeing, Lockheed Martin and Northrop Grumman also jointed the VAATE program.

VAATE program not only included the government military departments and aircraft engine companies, but also included the government civil departments and aircraft companies, thus integrated team was established to formulate aircraft engine development strategy and financed the research agencies jointed to provide support for development and demonstration of propulsion system and marine gas turbine technologies[4-6].

2 Long term target oriented with national defense strategies, latest target drew with product requirements

According to actual and future requirements, US government, Air Force and Navy formulated integral and prospect program to develop and demonstrate a mount of new technology, material and processing for achieving defense strategy. At the same time, they implemented the CIP to provide technology support for solving some problems and failures exposed in the in-service and developed engines. The technologies developed and demonstrated in a series and systematical programs could meet the development and upgraded requirements of the future and existing military aircraft engine to make military aircraft engine on the way that a generation engine is in service, a generation engine is improved, a generation engine is developed, and a generation engine is explored.

The long term target of US military aircraft engine program was determined by National Science and Technology Strategy, Defense Science and Technology Strategy, Army/Navy/Air Force technology strategy and the target of aero fields stage by stage, and were forecasting and challenging. STF200, ATEGG1, ATEGG2 core demonstrators and JTF22, GE1, GE9 engine demonstrators demonstrated in ATEGG program provided foundation for the third generation fighter engines such as F100, F110 and F404 in 1960s. In mid-1970s, ATEGG685, XTC65, ATEGG3, ATEGG4 and XTC45 core demonstrators demonstrated in ATEGG and JTDE690, XTE65, GE23, GE29 and GE33 engine demonstrators demonstrated in JTDE ensured the fourth generation fighter engines such as F119, YF120 to develop and certificate successfully and occupy the first place in the world. Since 1988, XTC67, XTC76, XTC77 core demonstrator and XTE66, XTE67, XTE76 and XTE77 engine demonstrators demonstrated in IHPTET program and provided technology support for F135, F136 and future generation fighter engine. Especially in 1999 to 2005 the DoD investment for new turbine engine research was reduced, AIAA Air Breathing Propulsion Technical Committee showed clearly that funding reductions of turbine engine research and development would be dramatically reduced the speed of the turbine engine research and development. The pain may not be felt immediately, but the pain will be extreme in the next decade, which may result in the loss of US turbine engine leadership, less share of the engine market, and risking job loss and critical skill erosion in 100 000 strong US turbine engine workforces. This situation could be reversed only by improved turbine engine research and development funding, thus the commission recommended that federal government initiated advanced turbine engine technology program—VAATE to maintain national defense readiness and to keep the US technological lead in gas turbine propulsion[7].

The latest aim of US military aircraft engine program is determined based on the problems exposed during aircraft engine development and operation. In 1970s, special programs such as CIP and EMDP were conducted by Air Force, Navy, P&W and GE for improving reliability, durability and adaptability of F100-PW-100 and TF30-PW-414 engine. The technologies and components developed in these programs improved the reliability, durability of F404, F414, F100 and F110 engines and made these engines move to maturity. Since 1980s, while reliability, durability demonstration were added to JTDE program, some special programs such as ENSIP, DADTA, HOST, LCF and HCF were conducted by US government and the industries to develop and demonstrate a number of technologies for improving in-serve aircraft engine structure strength.

Due to adhere the development policies combining of long term programs and short term programs, US aircraft engine technologies and products have been placed world lead after developing F119 successfully, and will keep the US technological dramatically lead in gas turbine propulsion for long time.

3 Technology development be headed up and integrated

The military aircraft engine is high technological product involved multidisciplinary and multiple components, and its engineering manufacture and development should be headed up and integrated.

3.1 Development of core engine and low pressure components in parallel

Military aircraft engine is an integrated product that imperfection design of any component may result in performance decrease, even serious failure.

In mid-1960s, US government in cooperation with P&W and GE conducted LWGG and ATEGG to develop and demonstrate core engine technologies, meanwhile initiated ASPI program to develop and demonstrate core component and technology of inlet, fan, low pressure turbine, afterburner, exhaust nozzle and control system.

Since 1970s, US Air Force/Navy conducted jointly JTDE program to develop and demonstrate overall engine technologies. The program integrated the results of ATEGG and APSI program into an engine demonstrator not only to demonstrate core component, fan, low pressure turbine, afterburner, exhaust nozzle, control system and mechanical system, but also to demonstrate aircraft engine integration technology at real environment.

Since 1980s, US government, industries and academic agencies conducted jointly IHPTET and VAATE programs. ATEGG, APSI and JTDE programs were integrated into IHPTET and VAATE programs that were doubling the US military's propulsion capability in 1988 until 2005 through revolutionary aerothermodynamics, materials, structure and control technologies that provided improved performance with light weight, simple structure for the US military's new generation and currently fielded fighter systems.

All in all, US fighter engine development had gotten on scientific and specified technology demonstration road that was from advanced component to core engine demonstrator, then to overall engine demonstrator[8-9].

3.2 Demonstration of performance with reliability, durability and maintainability concurrently

The technology research and model development of military aircraft engine were refined progressively by lessons learned from success and fails that experienced the fourth phase: (1) performance emphasized; (2) reliability, durability and maintainability improved complementarily; (3) performance, reliability, durability and maintainability improved simultaneously; (4) performance, reliability, durability and maintainability developed coordinately. IHPTET, VAATE and HCF programs were typical of them.

In 1980s to 1990s, the development emphasis of fighter engine was transformed to improving performance with sustaining long life. The aims of component and engine structural assessment research (CAESAR) program under IHPTET lied on enhancing demonstration of structure material and demonstration of engine component durability for joint strike fighters F-35 and F-22.

The aim of national turbine engine high cycle fatigue science and technology program was to resolve the high fault rate resulted from HCF and accustom the trend of vibration response improvement. Its specific work was to determine main cause of HCF aircraft turbine engine failures, explore the measures on reduction of fault and provide the technology foundation to fighter engine HCF materials damage tolerance. The aim of VAATE program was to develop, demonstrate, and transition versatile, intelligence and durability turbine engine technologies that provided 10 times improvement in affordability to a wide range of legacy and future military propulsion[10-11].

3.3 Development of design and material/process simultaneously

The material and processwere contributed to fighter engine in light weight, high temperature and strength. The research results show that the new material and structure are over 70% improvement in performance, specific fuel consumption and reliability without changing aircraft engine configuration. Thus aircraft technology advanced countries such as US, United Kingdom greatly developed and demonstrated aircraft engine technologies, and emphasized the advanced material and process simultaneously.

Since 1980s, the new material and process were developed and demonstrated under the comprehensive programs such as IHPTET, VAATE as a critical field, also under some special programs such as HITEMP, TMCTECC, DoD MANTECH, and Air Force science and technology program.

With materials and processes technology area plan for Air Force science and technology program, the high benefit material and process of latest, interim and long term weapon system were developed and demonstrated; the application development of the latest improved/upgraded/sustained systems were conducted; the material and process for improving the maintenance of current system were developed and demonstrated and could be next base engine for improving sustainment; the internal experience and system of support were provided for Air Force Product Center and Maintenance and Repair Center.

The advanced materials such as single crystal/multiple crystal nickel-basesuperalloy, molybdenum-base and niobium-base alloy, organic matrix composite, metal matrix composite, ceramic matrix composite, carbon-carbon composite, intermetallic compounds and thermal barrier coating were developed and demonstrated greatly, and the advanced affordability process such as forging and diffusion bonding were also developed and demonstrated.

With HITEMP program started in 1988 by NASA, polymer matrix composite used on fan, casing and control system, metal matrix composite and intermetallic compounds used on compressors and turbines, ceramic matrix composite used on high pressure turbine and afterburner were developed and demonstrated.

With affordable composite of propulsion (ACP) project in affordable polymer matrix composite program started in 1993 and invested by DARPA, the team led by P&W designed and manufactured composite fan inlet casing of F119 engine successfully using resin transfer molding (RTM) process, developed and demonstrated composite fan rotor blade with 2-D fiber structure for improving F119 and F135 engines, and developed and demonstrated other composite components such as core cowl, fan inlet cowl, fan blade containment structure and fan outlet casing.

With TMCTECC started in 1994 and invested by US government, Textron Specialty Materials Company developed continuous tape making process with TMCTECC; Atlantic Research Corporation evolved into batch tape making process; GE and P&W explored the application of the titanium matrix composite component manufactured by the process in civil and military aircraft engines such as F110, F119, F135 and F136. The new, low cost, high quality and high efficiency maintenance and repair technology were developed and demonstrated with DoD MANTECH program in 1982.

4 Technology verification measured by TRL

Based on technology development law, TRL is a systematic metric/measurement approach that is applied to all stages of technologies from birth to application to some system/item. TRL supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology, and then provides a general language for scientific research personnel and technical administrator. The TRL approach was created in the early 1980s, had been firstly applied to NASA space technology planning for many years, and was incorporated in the NASA management instruction (NMI 7100) as a necessary tool for selecting projects in mid-1990s.

The DoD has adopted TRL concept similar to NASA as an important basis and references to evaluate the readiness level of key technologies and establish national defense acquisition planning. The definitions of TRL from DoD and NASA are compared in Table 1. Otherwise, NASA stipulates that technology could be applied unless it has reached TRL 6, and DoD stipulates that technology could be listed in weapon system planning unless it has reached TRL 7. The TRL approach was adopted in UEET, IHPTET and VAATE programs, and military aircraft engine development in GE, P&W and Allison to verify technologies readiness and reduce development risk.

Table 1 Comparison of TRL between DoD and NASA

TRL	DoD	NASA
TRL 1	Basic principles observed and reported	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept	Analytical and experimental critical function and/or characteristic proof of concept

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TRL	DoD	NASA
TRL 4	Component and/or breadboard validation in laboratory environment	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in an operational environment	System prototype demonstration in a space environment
TRL 8	Actual system completed and "qualified" through test and demonstration	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9	Actual system "proven" through successful mission operation	Actual system "flight proven" through successful mission operation

5 Application extending to more military and civilian sectors

US national safety science and technology strategy made by National Science and Technology Council was ordered by US president in 1995. The strategy pointed out that US implemented dual-use (commercial and military) technology strategy to gradually establish the seamless national science and technology industry foundation, and was applied to commercial and military sectors.

As an integral part of US defense science and technology advanced research, the establishment, implement and application of aircraft engine advanced technology plan and program advocated to enhance the cooperation among military aircraft engine, commercial engine, gas turbines and space engine at the height of national benefit, and largely to speed up the full and sustainable development of the national science and technology and defense weapon systems. The aircraft engine advanced technology plan and program were directed by national safety science and technology strategy, completed by engine-relative scientists and technology experts coming from military and non-military areas, complemented by preferred military and non-military research units, and shared by all related governments, industries and academics. The IHPTET and VAATE programs were the models that extended many applications through developing dual-use (commercial and military) propulsion technologies.

The technologies developed and demonstrated in IHPTET and VAATE not only would provide benefits to current traditional aviation weapon system, such as global strike fighter, advanced stealth fighter, advanced transport aircraft, vertical/short-distance take-off and landing(V/STOL) aircraft, but also provided benefits to new and revolutionary air transport and accessed to space products with long-range, low cost, high Mach number and durable, such as unmanned Combat air vehicles (UCAV), high Mach number cruise aircraft, affordable access to space. The successful demonstrations from IHPTET and VAATE programs could further develop high specific power turbine engine to meet the requirements of supersonic civil air vehicle and inter-city vertical take-off and landing (VTOL) fixed-wing aircraft. Numerous technologies proposed for IHPTET and VAATE were the essential foundation for the more advanced reusable hypersonic flight vehicle and affordable civil access to space vehicle than successful demonstrations from the NASA X-43 program.

The military aircraft engine, component and sub-component technology developed and demonstrated during versatile core area of the VAATE program would allow greater hardware commonality between military and commercial product, so its cost can be greatly reduced through economy of quantity sales. The concept of the prognostics and health maintenance concepts developed and demonstrated in the intelligent engine area of the VAATE program would be directly beneficial to almost all commercial products and many technologies and products developed in the durability focus area of VAATE would have direct and pervasive economical impact. For example, VAATE's investments in weight reduction, improved maintenance time, and reduced parts count for military aircraft engines would have complementary effects on cost reduction of commercial products. Likewise, advancements in engine thermal management would impact commercial engine development by enabling a more thermally optimized engine cycle, leading to reduced fuel burn characteristics and hence an overall reduction in fuel cost and pollutant emissions.

The benefits obtained from IHPTET and VAATE programs were dual-use not only in terms of military and commercial synergy, but also in terms of payoffs to rocket, marine, ground transport, and other non-aircraft applications. Compressor and turbine technologies developed and demonstrated in IHPTET and VAATE could be applied to turbomachinery-based rocket fuel pumps, and translated into traditional rocket engine and turbine based on combine cycle engine. Combustion technologies developed and demonstrated in IHPTET and VAATE programs could be applied to low emission combustors of gas turbine for marine, power generation, mechanic drive, tank, etc. The various manufacture technologies, analytical design tools, intelligence engine control system and advanced light and high-temperature durable materials developed and demonstrated in IHPTET and VAATE programs would benefit turbine engine end users regardless of application[12-15].

6 Conclusions

The conclusions were found by investigating the US military aircraft engine advanced technology programs implemented since 1960s.

1) A large amount of programs were conducted and a large amount of experiences and lessons were demonstrated and obtained.

2) The goals of the programs were pulled by current and future defence strategies and requirements.

3) The technologies demonstrated in these programs will be applied to from military aircraft engine to civilian and other military vehicle.

4) The team of the programs is the national team.

5) Technology development were achieved with mature method such as TRL and "advanced research is earlier than product development".

The above features and experiences can provide technology references for all military aircraft engine development.

References:

[1] Hong W S, Collopy P D. Technology for jet engines: a case study in science and technology development[R]. AIAA-2004-6236, 2004.

[2] LIANG Chunhua. Key features of versatile affordable advanced turbine engine program[J]. Aeroengine, 2011, 37(5): 58-62. (in Chinese)

[3] LIANG Chunhua. Technology program of European Union high bypass ratio aeroengine[J]. Aeroengine, 2007, 33(2): 57-58. (in Chinese)

[4] LIANG Chunhua. Advance of IHPTET[J]. International Aviation, 2004(2): 58-60. (in Chinese)

[5] WU Daguan. New version IHPTET program: important role of base technology and demonstrator in aircraft engine development[J]. Aeroengine, 2003, 29(2): 1-4. (in Chinese)

[6] Hill R J. The purpose and status of IHPTET[R]. Advisory Group for Aerospace Research and Development, AGARD-CP-572, 1996.

[7] Dadd G J. Multivariable control of military engines[R].

Advisory Group for Aerospace Research and Development，AGARD-CP-572，1996.

[8] Stricker J M. Advanced turbine engine concepts and their impact on the next millennium[R]. International Society for Air Breathing Engines，ISABE 97-7174，1997.

[9] Chamis C C. Technology insertion benefits assessment in engines and aircraft[R]. AIAA 97-1191，1997.

[10] Dunbar L W. Turbine configuration impact on advanced IHPTET engine system mission capabilities[R]. AIAA 90-2739，1990.

[11] AIAA Air Breathing Propulsion Technical Committee. The versatile affordable advanced turbine engines (VAATE) initiative[EB/OL]. [2014-01-01]. http://www.aiaa.org.

[12] Mehta P P. Determining the affordability of advanced propulsion systems[R]. ASME Paper 99-GT-393，1999.

[13] Huffman M F. Component and engine structural assessment research (CAESAR)[R]. AIAA 93-2609，1993.

[14] LIANG Chunhua，LIU Hongxia. Approach and goals of reducing maintenance cost for VAATE program[J]. Aeroengine，2009，35(1)：32. (in Chinese)

[15] SUN Mingxia，LIANG Chunhua. Innovative engine technology in versatile affordable advanced turbine engines program[J]. Aeronautical Science and Technolgoy，2011(5)：18-21. (in Chinese)