

Small Turbine Engine Evolution

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INTRODUCTION

I would like to thank the SAE for the opportunity to present my perspective on a segment of the gas turbine engine business. An overall view of the gas turbine engine marketplace shows a very wide range of engine sizes and types. There are thrust engines and shaft output engines whose output can be in various configurations as well as a wide range of sizes. This historical perspective will be limited to aircraft propulsion of the jet variety to make comparisons manageable within the scope of this presentation.

Even with the narrowed limits of “aircraft” propulsion of the “jet” variety there are large variations in the sizes that can range from less than one-pound (4 N) to thrust levels exceeding 100,000 pounds (445,000 N) with both military and commercial applications for the subject engines as shown in Figure 1.

With a historical 50-year window of view, it will be necessary to further narrow the scope of this assignment in thrust range to trace the technology evolution within this period. The range for discussion herein is 1,000-lb_f (4,400 N) thrust all the way down to the one-pound (4 N) level and possibly below.

In addition to the traditional U.S. turbine engine manufacturers there are now many acquisitions, consortiums, joint ventures, and partnerships worldwide with engine technologies spread to many countries throughout the world. During the time period of this examination turbine engine technologies were practiced mainly in Europe, U.K., and the U.S. It is interesting to observe that the engine manufacturers in the “small engine size” used for this study were not the traditional manufacturers of the large turbine engines. Russian turbine engine developments were difficult to trace during this period.

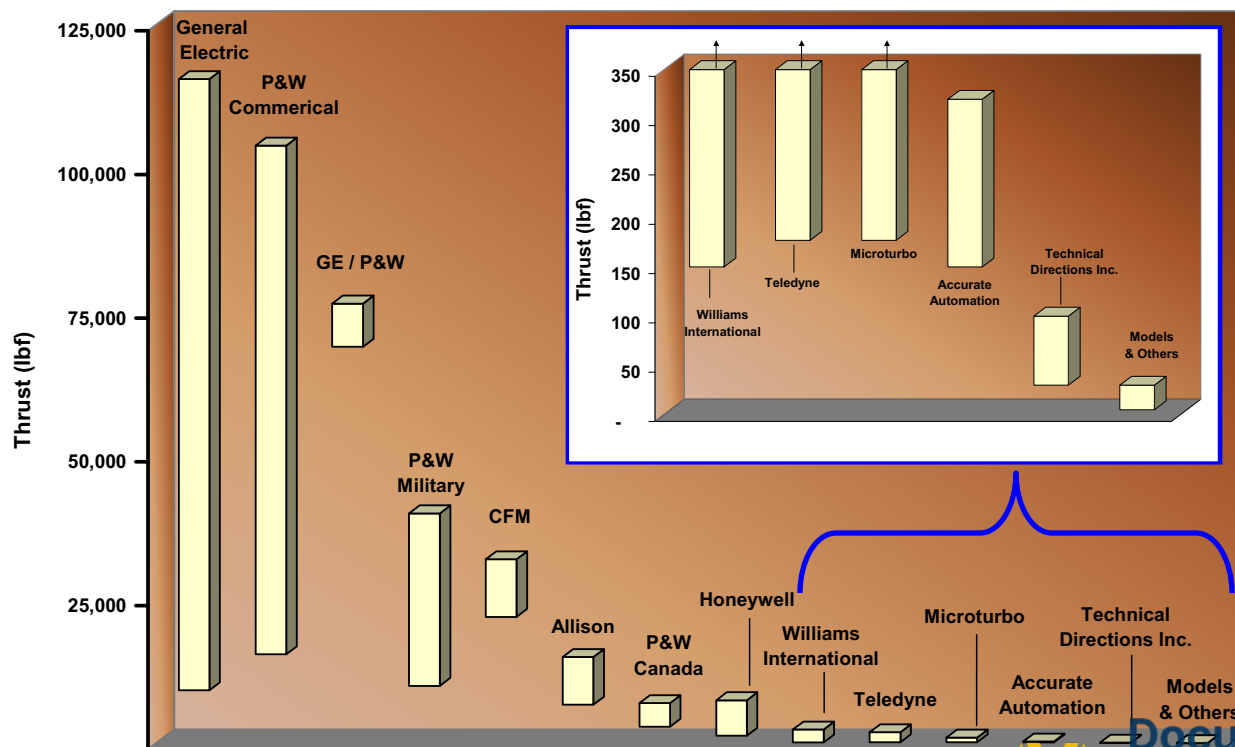


Figure 1. Turbine Engine Thrust Capacities

The selected smaller engines appear do not appear to have evolved from the technologies in place with their larger brothers. Military applications appear to have paced the technology for the small engines much in the same manner as the larger engines. The small engine could take advantage of the materials developed for the larger engines but there were other design challenges for the small engine designer to grapple with such as:

- Manufacturing limitations
- Aerodynamic effects
- Cost/budget limits
- Availability of accessories

The performance of gas turbine engines are very sensitive to the relative operating clearance of the rotating components, and manufacturing limitations created higher relative clearances for the small turbine engines with the associated performance penalties. In addition, the available processes for creating the aerodynamic surfaces could not conform to the ideal flow path as well as the larger engines with the smaller engine suffering in performance on a comparison basis. As engine designs proceeded into the smaller range of this study period these performance issues become a more important task to deal with.

As with most programs the development of the small engine had cost and budget boundaries that presented new challenges where the established technologies were not adequate. These small engines also needed a full line of accessory systems including starting, ignition, fuel, and engine control functions to be considered for aircraft applications. All new accessory systems were required that were smaller and lower in cost than the products available. Since the newly required functions were similar to those required of the larger engines, a cost reduction struggle was traditional with new

systems and suppliers being sought to satisfy these requirements. Accessory and vehicle installation systems remain as important as engine developments in the overall success of an engine application.

Engine integration into the vehicle also presents significant challenges. Adapting the engine system, and the necessary interconnections, into the available space is a struggle while maintaining propulsion performance. In cases where the engine system is required to provide the electrical power for the aircraft there are another series of requirements superimposed on the base propulsion system considerations. The following requirements are a sample of the conditions that require attention in an engine vehicle application:

- Mounting brackets
- Intake & Discharge Ducts
- Thrust/Weight Ratio
- Fuel supply
- Ignition
- Aircraft weight balance
- Engine bay operating temperature
- Electrical (if required)
 - Power requirement at flight conditions
 - Minimum/maximum voltage
 - Transient load handling
 - Electrical noise generation

In the middle of the twentieth century engine system development generally preceded the vehicle development, and engine system development was separate from the vehicle program. In this product development sequence the airframe designer had to work with the established engine configuration. In more recent vehicle design experiences each vehicle system must provide a “space claim” and be prepared to negotiate for space with the other system components. In many of these situations there would be volume and weight

limitations that must be addressed. Often the fuel storage would be the last to be addressed where it was necessary to store sufficient fuel to complete the assigned mission. The engine computer simulation for flight conditions is important in making the fuel-mission fuel consumption estimates as a fuel storage capacity guide.

Within the 1,000-lb_f (4,400 N) thrust limitation selected for this lecture there have been a series of aircraft applications considered for the small turbine-based engine such as:

- Targets
- Decoys
- Surveillance
- Weapons delivery
- Small manned aircraft

The majority of these applications are unmanned vehicles where the aircraft is small enough for an engine of the thrust capacity being reviewed in this lecture. Some of these aircraft have been in production for many years and one notable example is the cruise missile which appeared in the 1970's capable of being air or ship launched. This is the classic example where manufacturers of the large turbine engines had selected not to participate in the 1000-lb_f (4,400 N) and smaller thrust engines. Therefore new engine suppliers emerged as manufacturers of these smaller engines such as Teledyne Turbine Engines, Williams International, Turbomeca (French), Microturbo (French) and some others. These non-traditional turbine engine suppliers adapted new engine designs for the small engines and new technologies were employed that facilitated the downsizing of the engine frame and made some significant departures from the established turbine engine design configurations.

An example of the engine size comparisons made in the 1970's is shown in Figure 2. This is a small Williams International turbofan engine compared to one of the large turbofan engines used for a commercial transport airplane.



Figure 2. Small Engine Meets Big Engine

TECHNOLOGY

One of the significant enabling technologies for the small aircraft evolution is the miniaturization of electronics within the study period. This new electronics capability made space within the smaller air vehicles and added functional capabilities to the vehicle system and the engine control functions. Other technology developments were also significant in solving the problems that had to be addressed in the creation of the downsized turbine engine. Some of the issues to be dealt with were:

- Combustion and fuel management
- Aerodynamic efficiency gains for smaller components
- Precision manufacturing systems

Large engines generally used an arrangement of multiple or individual combustors located around the periphery of the engine with fixed orifice fuel metering systems as shown in Figure 3. This combustion system configuration would be difficult and expensive to scale down to the subject engine size. Teledyne, Williams, and some work in the automotive industry started utilizing a centrifugal fuel atomization system that could utilize a fuel cup that could evenly dispense fuel around its central diameter that made a single combustor possible utilizing this very small device. This centrifugal fuel distribution cup is often called a “fuel slinger” and it has the secondary advantages of low fuel supply pressure requirements and the dispensing of very small fuel droplets. Lower fuel pressures reduced the cost of the small engine fuel system and the resulting small fuel droplets led to easier engine starting since the smaller fuel droplets require lower energy to ignite.



Figure 3. Multiple Combustors

The pioneer in the fuel slinger was Joseph Szydlowski who started a French company named Turbomeca. There have been as many as one hundred United States patents granted to Mr. Szydlowski for turbine engine systems and a centrifugal fuel distribution device and a sample illustration

is shown in Figure 4. The fuel slinger concept was adopted by Teledyne Turbine Technologies, Williams International, and Technical Directions Inc. Many improvements have been made to this technology by these companies since the original Turbomeca license to Teledyne Turbine Technologies in the late 1950's.

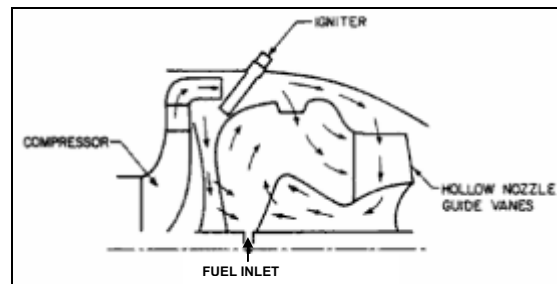


Figure 4. Centrifugal Fuel Distributor

The main shaft mounted fuel slinger maintained the engine ‘direct flow’ arrangement of airflow in the engine where there is a direct passage between the compressor discharge --- the combustor --- and the turbine stage as shown in Figure 5.

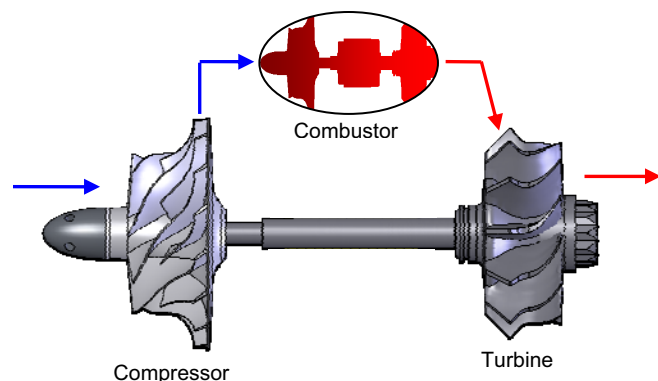


Figure 5. Direct Flow Configuration

An alternate combustor arrangement is a “reverse flow” combustor where air passes around to the rear of the engine and makes an 180° turn to exit into the turbine stage. This reverse flow combustor arrangement generally utilizes a series of high pressure atomizing nozzles in the rear of the combustor similar to the larger engine fuel

systems. With either type of combustor selected a single combustor unit can be utilized for the small turbine engine.

The aerodynamic efficiency of compressor and turbine elements increases with increasing size of the rotating elements. Larger engines have an advantage over smaller engines as shown in Figure 6. Also shown in Figure 6 is the relative gain in efficiency of the smaller components in the period of review for this lecture. The sharp knee in the curve should be noted here below the mass flow of 3-lb_m/sec. This lower available efficiency with smaller components limits the efficiency of turbojet engines below 200-lb_f thrust.

Much of the basic science in the aerodynamic component efficiency characterization and development was completed by the National Advisory Committee for Aeronautics (NACA), the predecessor to NASA. The basic NACA work was completed in the 1940's and 1950's in support of larger engines and other aerodynamic systems. Further efficiency improvements were made in large components by the large engine manufacturers in the latter half of the 20th century. During this same period the smaller components received limited development improvements due to lower military and commercial interests. However the turbocharger industry was starting to gain commercial interest and some development attention was being directed toward compressor and turbine components in the size range that was considered very small from the turbine engine perspective.

As a benchmark of component efficiency, the engine developed by Frank Whittle in the 1930's used compressor and turbine stages that were in the 70% range in overall efficiency. The early Whittle engine produced 800-lb_f (3,600 N) of thrust with

16-inch (41 cm) diameter components which are relatively large by current standards for that thrust level.

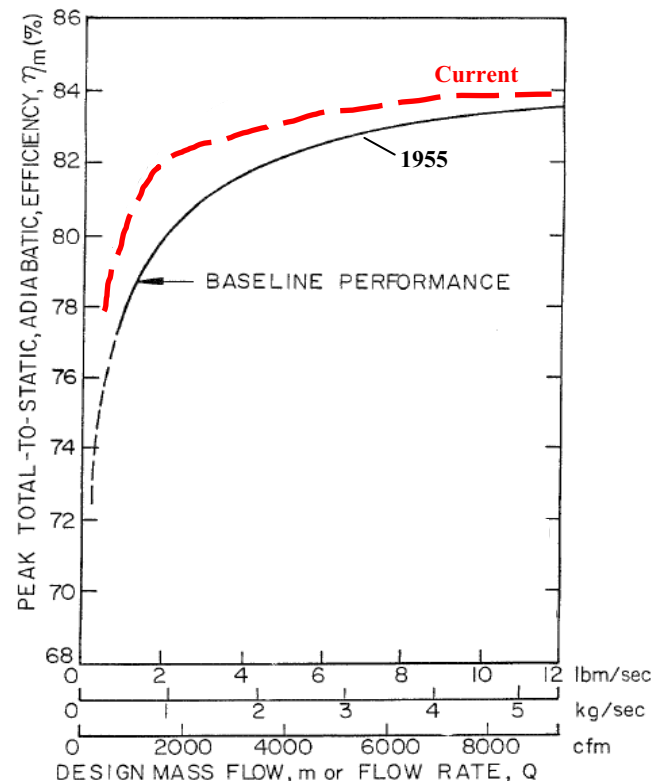


Figure 6. Efficiency vs Mass Flow

With today's technology 70% compression efficiency can be achieved by compressor components with 5% of the mass flow capacity of the Whittle engine.

It is difficult to generalize the aerodynamic components and make direct comparisons on efficiency levels and the relative change within this discussion period. There are many performance factors that must be considered in making such comparisons:

- Stage pressure ratio
- Specific speed
- Reynolds number
- Exit tip clearance

All of these factors vary with the utilization and size of the engine system, and many are