SNS COLLEGE OF TECHNOLOGY
(An Autonomous Institution)
COIMBATORE-35
DEPARTMENT OF AEROSPACE ENGINEERING
19ASB204 – Aerospace Propulsion
Unit 3 – Thrust Augmentation

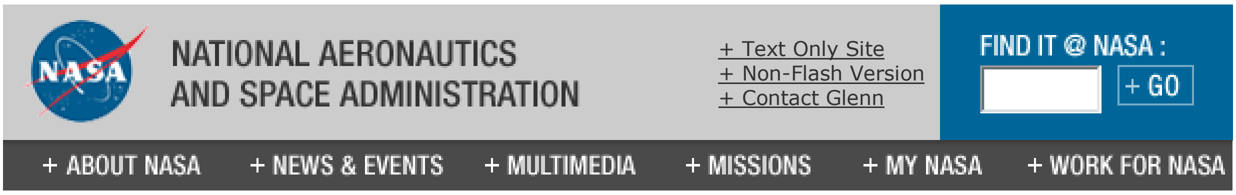
Thrust Augmentation

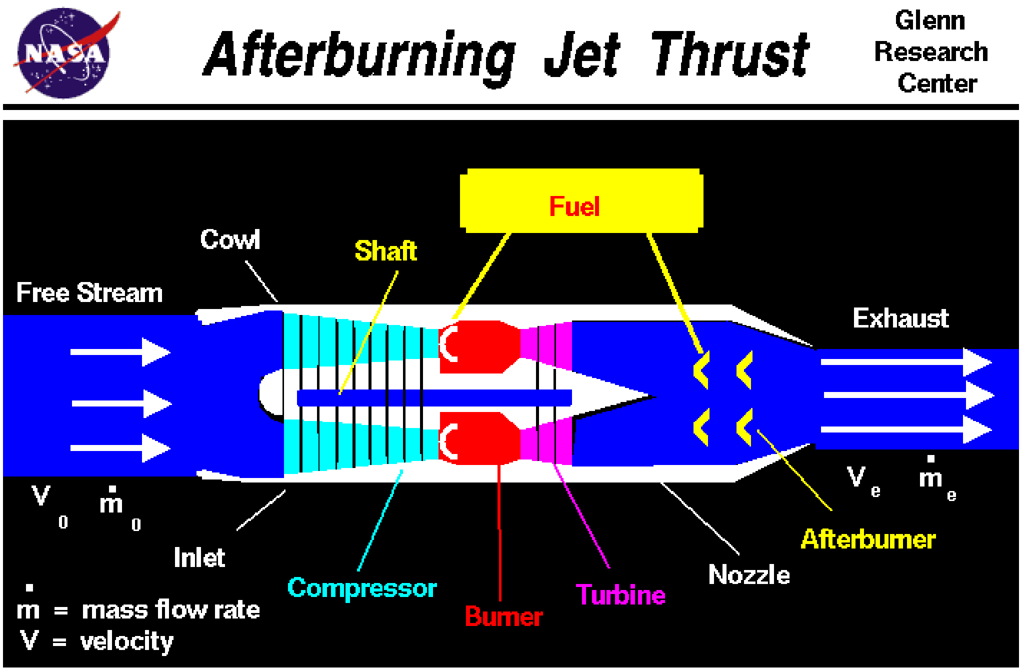
Although the first generation of jet aircraft were entering service, the turbojet had a long way to go before reaching its potential. One of the principal problems was the sluggish acceleration of jet aircraft. This necessitated longer runways for takeoffs and was a hazard in emergency situations and combat.

The National Advisory Committee for Aeronautics (NACA) and industry sought ways to boost thrust for short periods of time. These thrust augmentation measures included the bleedoff of exhaust gases, use of an afterburner and injection of coolants. The variable-area nozzle, which could be expanded or closed during flight, was an essential component of these strategies. The JPSL played a key role in the development of each of these methods.

Afterburner

The most widely recognized method of boosting thrust is the afterburner, also known as tailpipe burning. Fuel is injected into the hot exhaust gas flowing between the turbine and nozzle. The combustion of the gas expands the airflow as it enters the nozzle, which increases thrust. This type of combustion requires large quantities of fuel so it can only be utilized for short boosts. The concept of combusting excess heat for additional energy is old and not unique to aircraft engines, but it was particularly applicable to the new jet engines since the increased temperatures would not damage the engine components and could be used to increase thrust.





$$\text{Thrust} = F = \dot{m}_e V_e - \dot{m}_0 V_0$$

To move an airplane through the air, thrust is generated by some kind of propulsion system. Most modern fighter aircraft employ an **afterburner** on either a low bypass turbofan or a turbojet. On this page we will discuss some of the fundamentals of an afterburning turbojet .

In order for fighter planes to fly supersonically , they have to overcome a sharp rise in drag near the speed of sound. A simple way to get the necessary thrust is to add an afterburner to a core turbojet. In a basic turbojet, some of the energy of the exhaust from the burner is used to turn the turbine. The afterburner is used to put back some energy by injecting fuel directly into the hot exhaust. On the schematic, you'll notice that the nozzle of the basic turbojet has been extended and there is now a ring of flame holders, colored yellow, in the nozzle. When the afterburner is turned on, additional fuel is injected through the hoops and into the hot exhaust stream of the turbojet. The fuel burns and produces additional thrust, but it doesn't burn as efficiently as it does in the combustion section of the turbojet. You get more thrust, but you burn much more fuel. With the increased temperature of the exhaust, the flow area of the nozzle has to be increased to pass the same mass flow. Therefore, afterburning nozzles must be designed with **variable geometry** and are heavier and more complex than simple turbojet nozzles. When the afterburner is turned off, the engine performs like a basic turbojet. You can investigate nozzle operation with our interactive nozzle simulator.

The nozzle of a turbojet is usually designed to take the exhaust pressure back to free stream pressure. The thrust equation for an afterburning turbojet is then given by the general thrust equation with the pressure-area term set to zero. If the free stream conditions are denoted by a "0" subscript and the exit conditions by an "e" subscript, the thrust **F** is equal to the mass flow rate **m dot** times the velocity **V** at the exit minus the free stream mass flow rate times the velocity.

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F = [m dot * V]e - [m dot * V]0

This equation contains two terms. Aerodynamicists often refer to the first term **(m dot * V)e** as the **gross thrust** since this term is largely associated with conditions in the nozzle. The second term **(m dot * V)0** is called the **ram drag** and is usually associated with conditions in the inlet. For clarity, the engine thrust is then called the **net thrust**. Our thrust equation indicates that net thrust equals gross thrust minus ram drag.

Afterburners are only used on fighter planes and the supersonic airliner, Concorde. The Concorde turns the afterburners off once it gets into cruise. Otherwise, it would run out of fuel before reaching Europe. Afterburners offer a mechanically simple way to augment thrust and are used on both turbojets and turbofans.

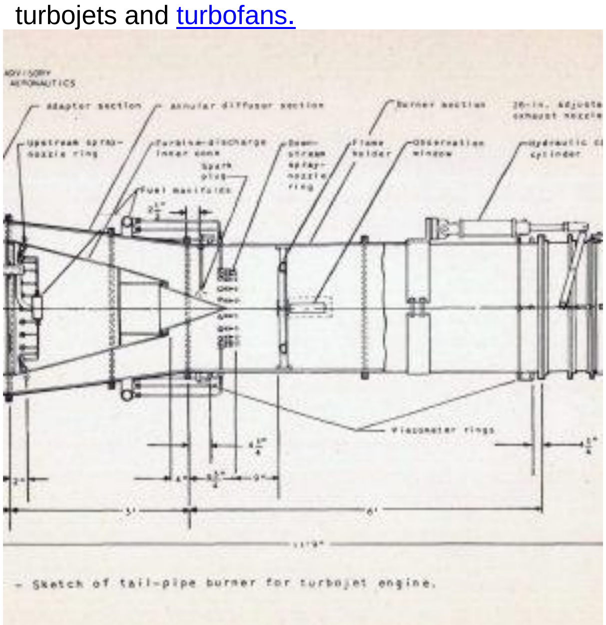
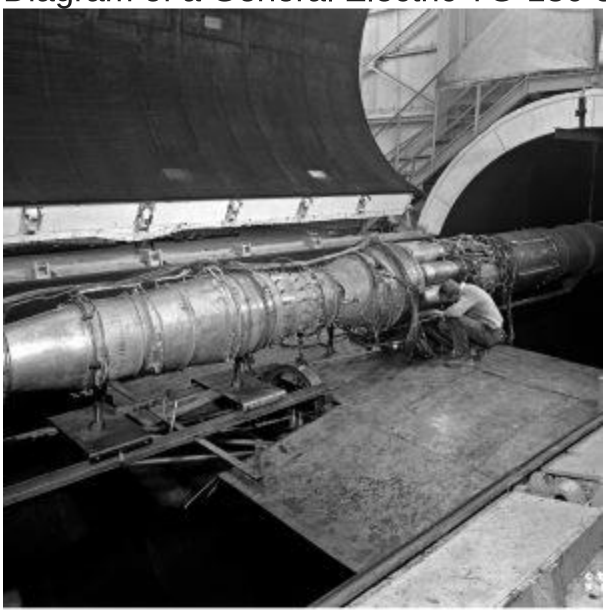


Diagram of a General Electric TG-180 engine with a tailpipe burner.



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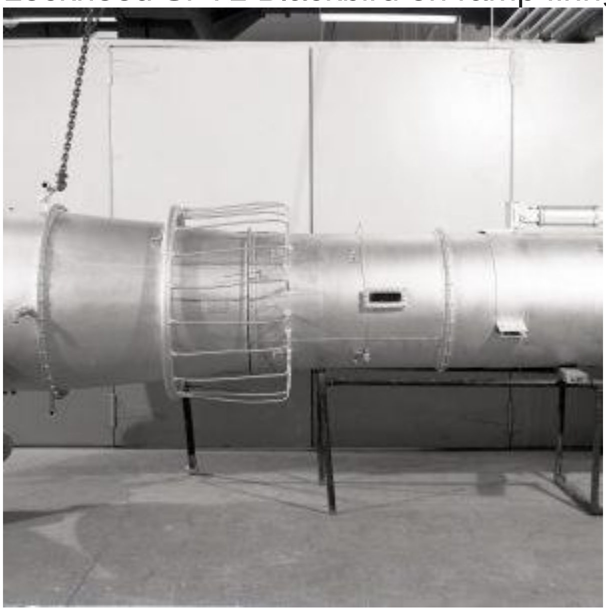
GE TG-180 in the Altitude Wind Tunnel for a series of afterburner studies (1948).

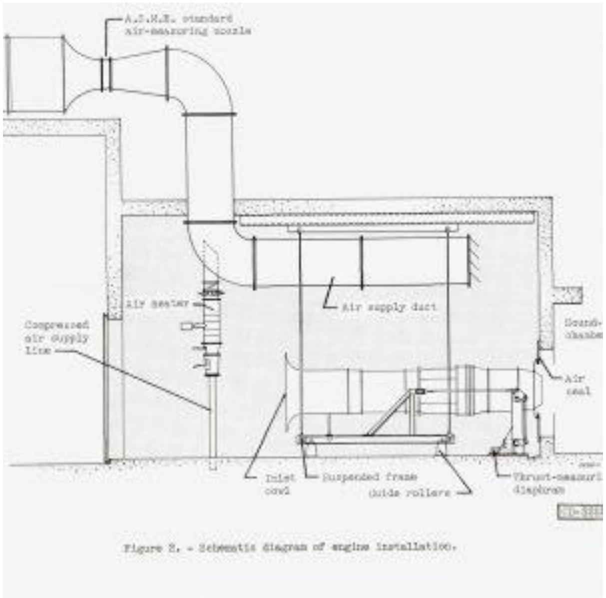
Lockheed Sr-71 Blackbird on ramp firing dual max afterburners (1998).



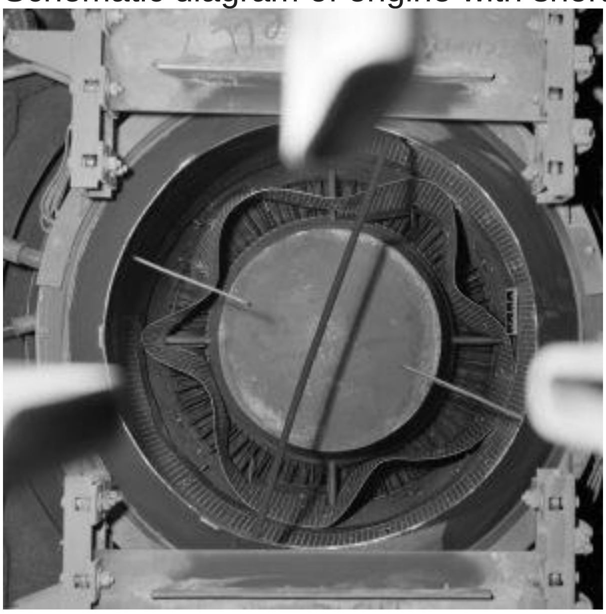
A mechanic inspects an afterburner for a General Electric TG-180 in Cell 4.

In the early 1950s, the military asked the NACA to study the use of shorter afterburners to boost thrust during takeoff for new long-range bomber and transport jet aircraft without increasing weight or pressure losses in the engine that would limit the range. The shorter afterburners required the truncating of the diffuser and combustor sections. In 1952, NACA researchers analyzed different diffuser modifications and tested the most promising on a General Electric TG-190 engine in

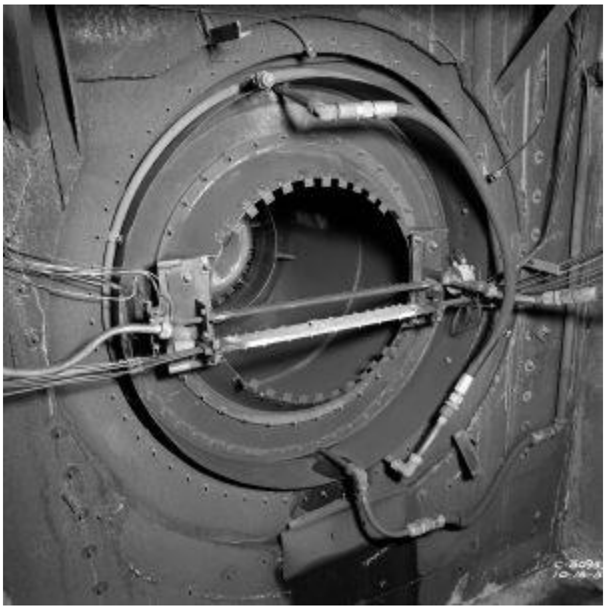
Cell 6 of the JPSL. They continued to modify and retest the diffusers until they were able to define the minimum effective diffuser length. They then sought to shorten the combustion area to further decrease the overall size of the afterburner. A series of tests in the JPSL determined that a 36-inch chamber produced the best results.



Schematic diagram of engine with shortened afterburner in Cell 6 (1954).



Distorted screech liner installed on a short afteburner for a TG-190 engine (1955).



Exit of a short afterburner on a GE TG-190 emerging from Cell 6.

Variable-Area Nozzles

Jet engines expel their hot combustion gas into the atmosphere through a tubular nozzle, which produces thrust. Nozzles whose diameter can be adjusted during flight, known as variable-area nozzles, offered one of the best options for rapidly adjusting the thrust of a jet engine without changing engine speed. Variable-area nozzles are necessary for the use of afterburners and improve engine efficiency during normal cruising situations. Afterburner ignition produces hotter exhaust gases, which requires a larger nozzle. The variable-area nozzle is opened wide to accommodate the resultant large gas flow. This wide diameter, however, would be inefficient when the exhaust temperatures are lower during normal flight, so the variable-area nozzle is then closed.

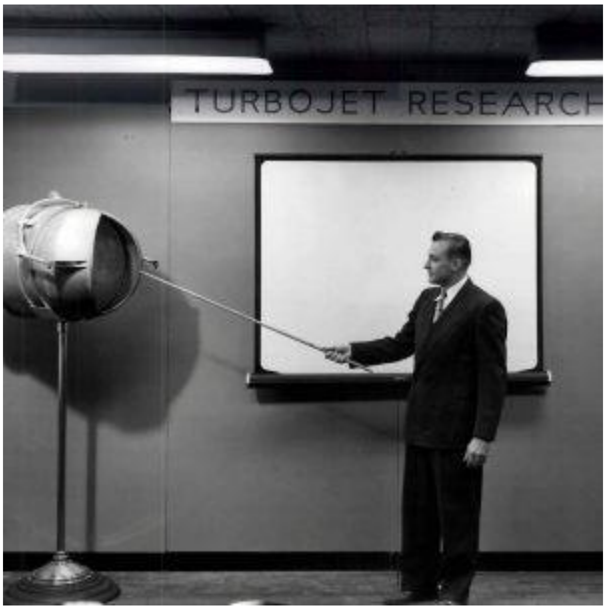
In 1943, AERL engineers designed an early clamshell-type nozzle in which two spherical flaps could be opened during afterburner operation. Researchers immediately began testing it on a General Electric I-16 engine at the JPSL. The nozzle was operated in the open and closed positions at various engine speeds. The researchers compared the data with that from similar tests of the engine in its original configuration and concluded that the adjustable nozzle performed as efficiently at a normal fixed-diameter nozzle, while providing more control.

Over the next five years, researchers tested variations of the variable-area nozzle on different turbojet models both at the JPSL and in the AWT. Although the nozzle designs were too dissimilar to compare the performance of one configuration against another, it was concluded that the overall performance was limited when the alignment of the flaps was uneven. This allowed the engine's normal exhaust gas to leak out.

The use of variable-area nozzles was introduced into aircraft in the late 1940s and soon became standard on all jet engines. The clamshell designs were replaced by nozzles with four flaps that formed a square opening when closed. This reduced pressure losses but caused aerodynamic drag. The problem was resolved with the development of iris-shaped nozzles that retained the nozzles' oval shape when closed.

Images:

Variable-area nozzle designed for General Electric's TG-180 engine tested in the JPSL (1948).



Researcher Martin Saari explains variable area nozzles at the 1948 NACA Inspection.

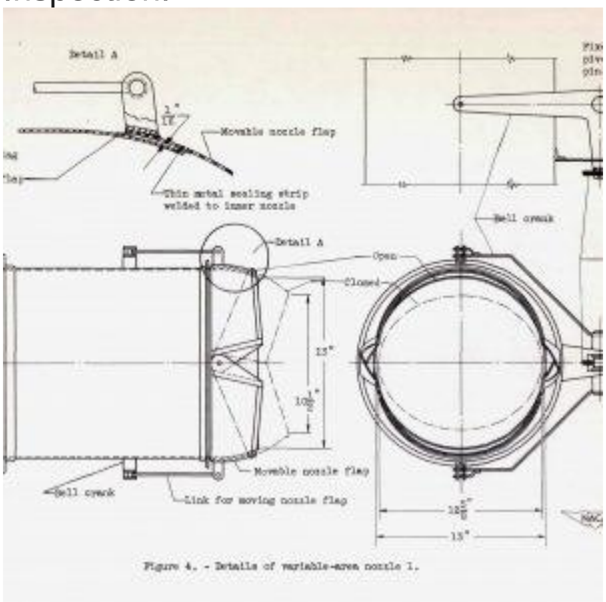


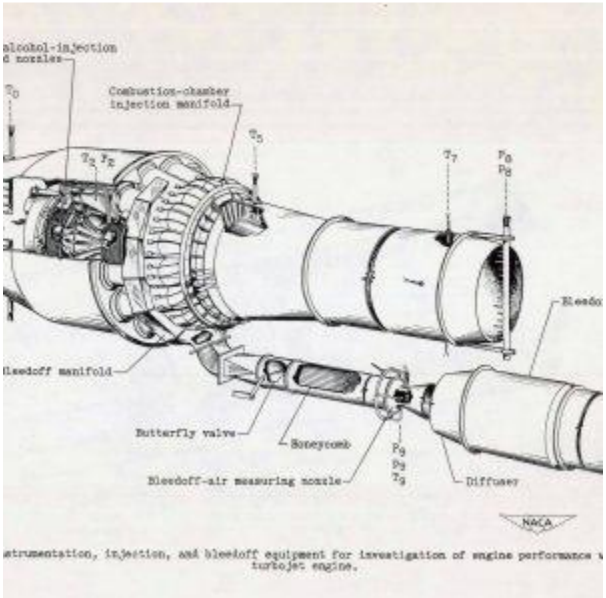
Diagram of clamshell-type variable-area nozzle for I-16 engine tested in the JPSL.

A tailpipe with variable-area nozzle for a General Electric TG-180 in the JPSL (1946).

Bleedoff Air

Turbines are the critical element in jet engines, which is why they are sometimes referred to as gas turbine engines. Turbine materials can only withstand so much heat, so not all of the air flow is combusted as it passes through the engine. In 1944, AERL researchers theorized that jet engine thrust could be increased by bleeding off some of this excess high-pressure air as it leaves compressor so it could be burned separately in an auxiliary nozzle. It was necessary to inject water into the inlet to replace the removed air. The water turns to steam and maintains the engine performance, while an auxiliary jet provides extra thrust.

In April 1945, AERL researchers tested the system on a General Electric I-16 in the JPSL. Although the bleedoff system required large quantities of water, it did increase thrust as predicted. They then continued the investigation using the more powerful I-40 engine to test various modifications. Although the engine's primary thrust decreased during bleedoff, the auxiliary combustor more than made up for the loss. The researchers noted, however, that the engine had to be operated within strict parameters for the bleedoff to be successful.



Instrumentation, water injectios, and gas bleedoff equipment for test of GE I-40 engine.

A mechanic works on a General Electric I-40 engine installed in Cell No. 3 of the JPSL (1946).

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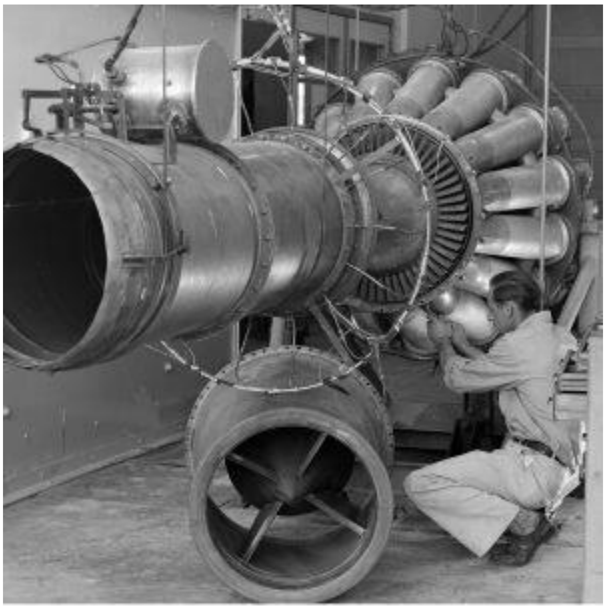
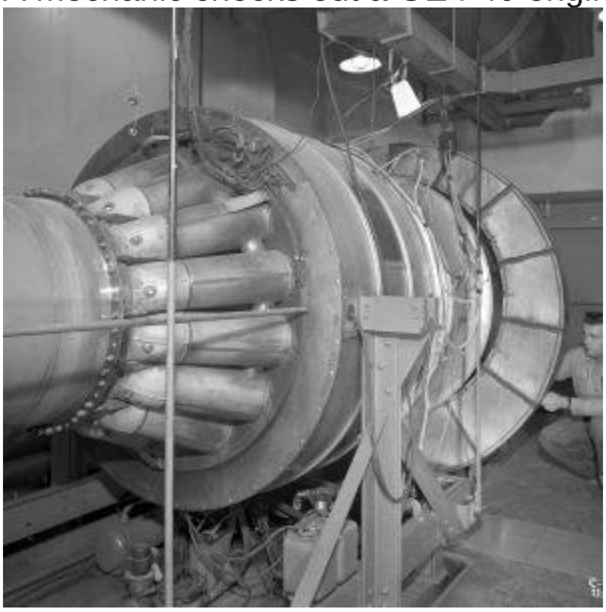


A mechanic checks out a GE I-40 engine equiped with a tailpipe burner (1946).



GE I-40 engine with adjustable exhaust nozzle and bleedback equipment in Cell 2 (1948).

Water Injection

One of the oldest methods of thrust augmentation is the injection of a water and alcohol mixture into the inlet. Water, which is used for economical purposes, is mixed with alcohol to prevent freezing. The liquid evaporates and cools the inlet airflow before it reaches the compressor. The brief temperature reduction allows the compressor to handle larger quantities of air to be used for combustion, which results in greater thrust. The weight of the nozzles, tanks and pumps required for the system must be taken into account, however. In 1944, AERL researchers incorporated the injection system into a General Electric I-16 and tested it with water, water and alcohol, kerosene, and carbon dioxide at the JPSL. Each of the refrigerants except kerosene increased thrust by over 35 percent. The investigation continued in 1945 using the larger I-40 engine. Subsequent flight tests of the injection system on a Bell P-59A demonstrated a 21-percent increase in thrust and a reduction in the distance required for takeoff.

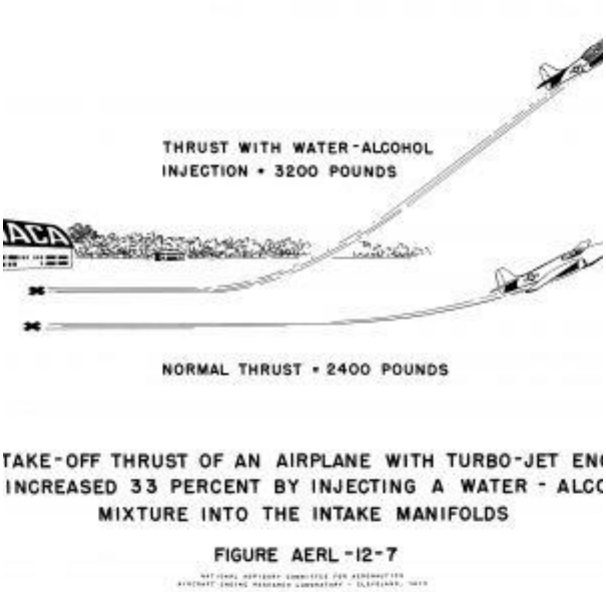
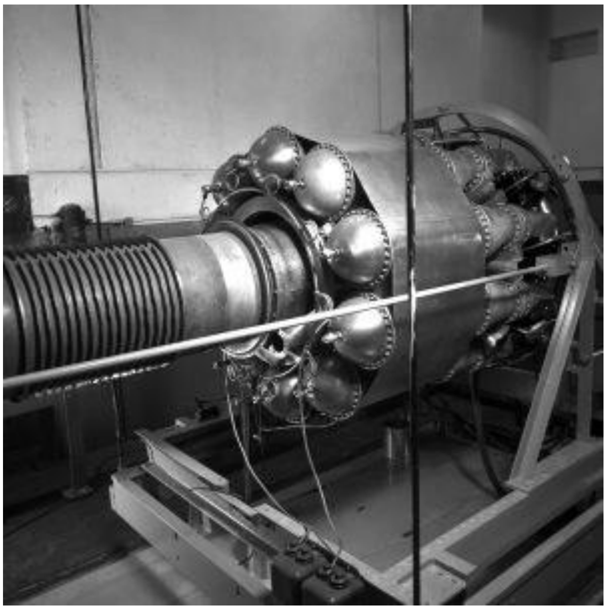


Chart from budget submission showing increase in takeoff thrust by injecting a water/alcohol mixture into the engine (1948).



A General Electric I-16 engine installed in Cell 2 for water injection testing in June 1946.

A mechanic checks out a GE I-40 engine equipped with a tailpipe burner (1946).

A B-52 Stratofortress takes off using a water/alcohol injection system (2017).

Tests of the liquid injection system on engines with axial-flow compressors, however, did not produce the same results as with the centrifugal engines. Researchers found that the greater distance between the inlet injection and the compressor limited its effectiveness. They decided to redesign the system to spray the coolant directly into the compressor stages, not the inlet. This new system was first successfully attempted on a General Electric TG-180 in Cell 6 of the JPSL. In 1950, the investigators decided to combine the liquid injection with an afterburner in a TG-180. These runs revealed that the liquid caused combustion instability and limited the performance of the afterburner. They then decided to inject the coolant into the inlet, compressor stages and combustion chamber simultaneously. Follow-up tests using a TG-190 engine tried injecting coolant into the inlet, compressor stages and combustion chamber simultaneously. The effort improved the thrust by nearly 40 percent. In addition, it was determined that unlike centrifugal engines, the axial-flow engines received the most benefit from a low injection rate.