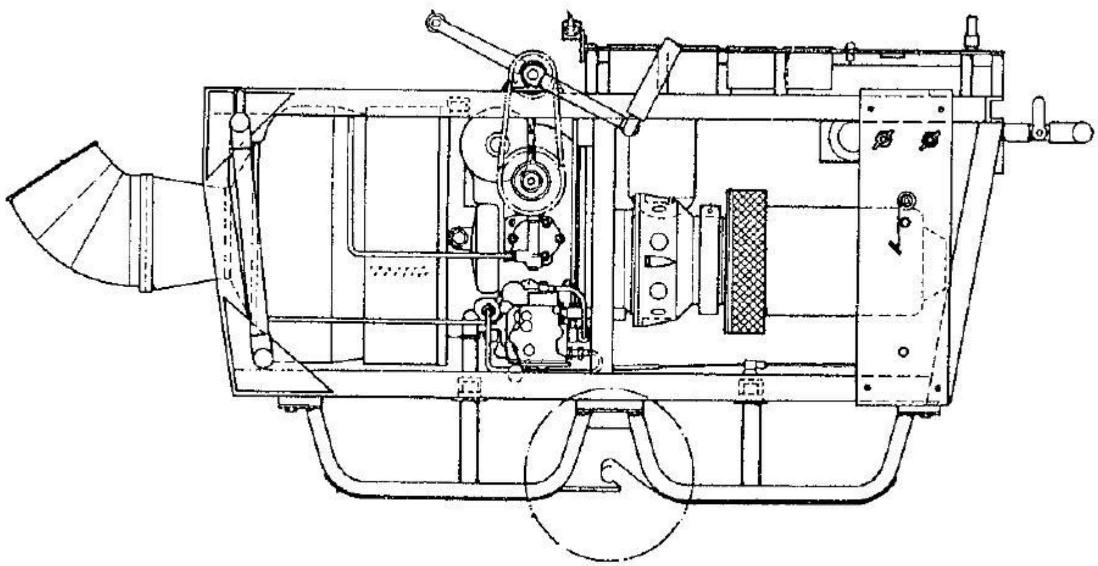
Chapter 5

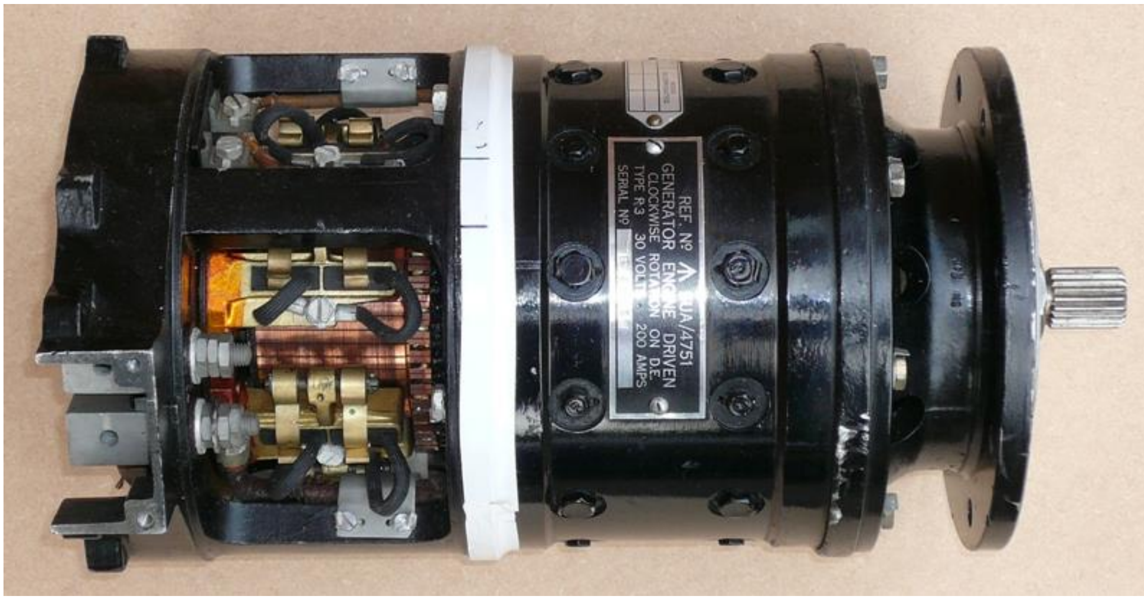
Driven Equipment



Small gas turbines are employed to drive a various differing load and to provide various services that are normally part of an aircraft installation. Small gas turbines may also be used to provide ground-based services, these are usually compressed air or electrical power. Mechanical loads take different forms, also in the case of an engine that supplies compressed air directly from its turning compressor, the compressor itself is the load placed upon the engine.

DC generators

A small gas turbine may be used to drive a DC generator. DC generators of aircraft type are normally highly specified producing a high output power for their size and weight. The generator is driven by the engine via a reduction gearbox at a speed usually between 4,000 and 8,000 rpm. Up to 900A at 28V is possible from a DC generator driven by a small gas turbine.



Typical aircraft DC generator gas turbine driven

Most aircraft DC generators unlike automotive style generators (Actually alternators) do not incorporate built in regulator control boxes. A DC generator is normally connected to an external regulator control box that ensures the unit excites on start up, the output DC voltage is kept constant over a relatively wide rpm range (2-1 range) and electrical load range.

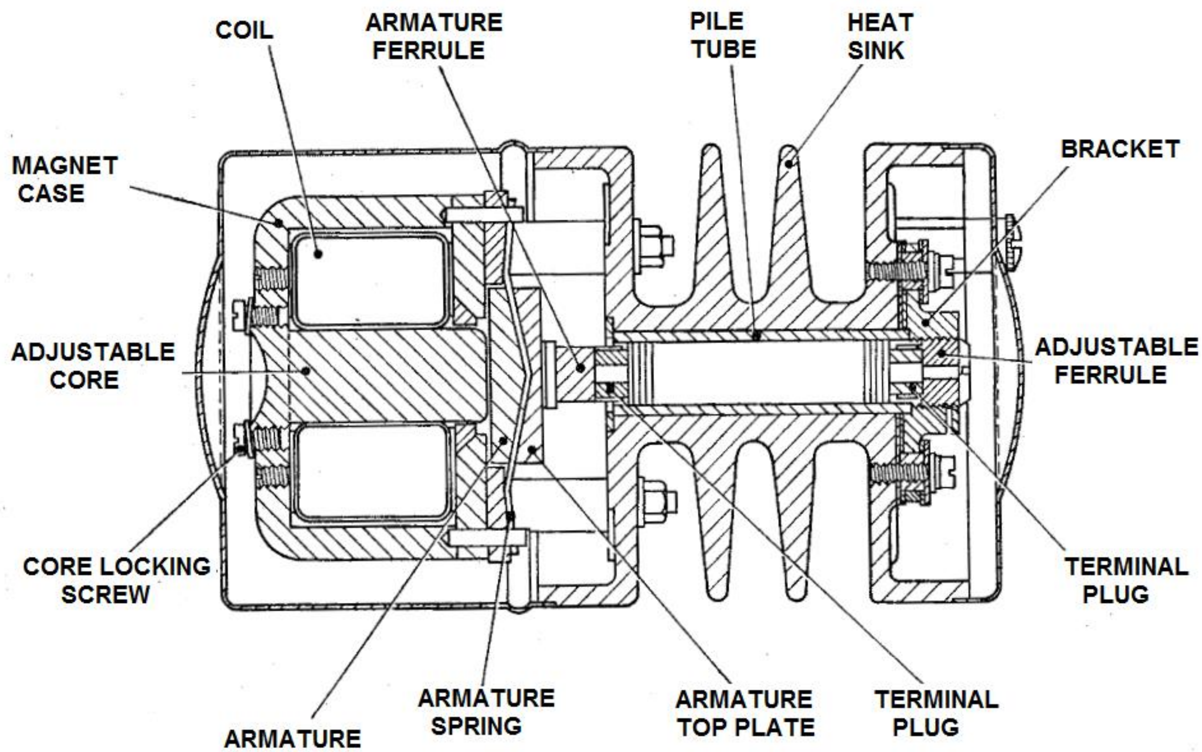
Carbon pile regulators

In order that it can supply a constant output voltage over a range of rotational speeds and loads a DC generator is required to have a regulation system in place. This is normally achieved by varying the field current or “Excitation” current supplied to the generator as it runs.

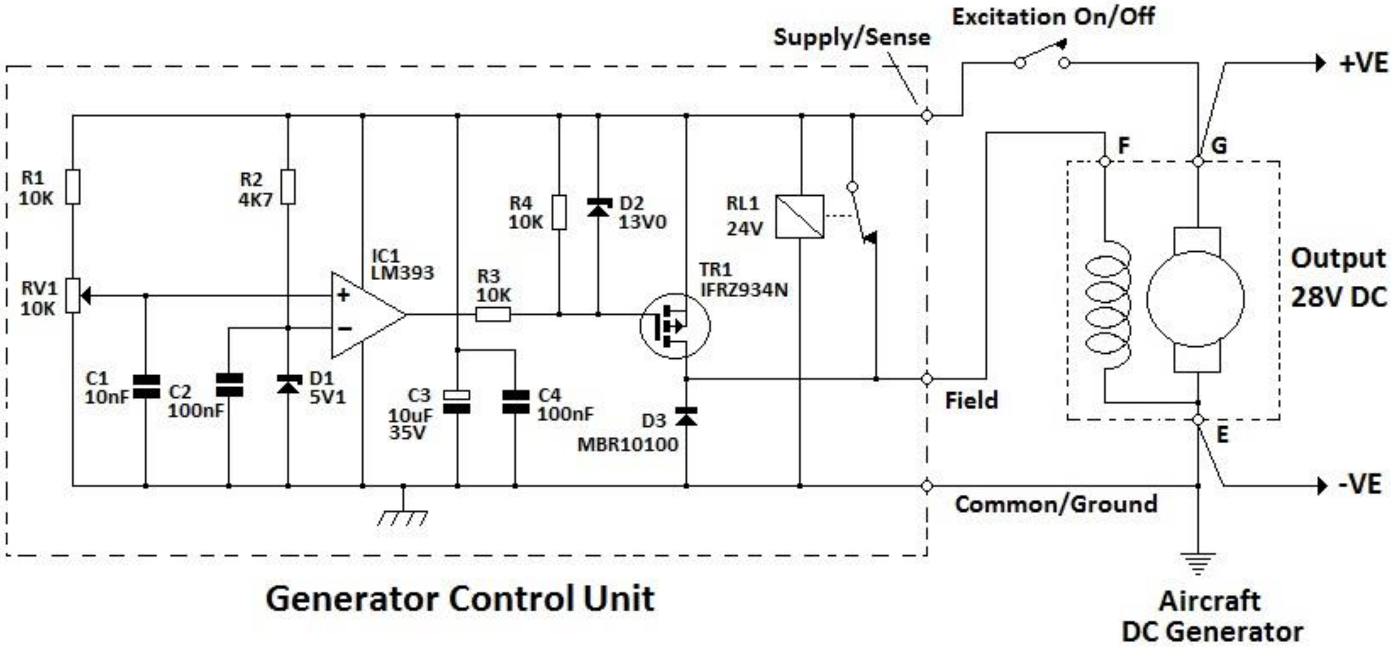
A common system employed in older aircraft operating gas turbine driven generators was to use a device known as a carbon pile regulator unit. The regulator unit consists of a series of carbon discs arrange in a pile that is able to provide a varying resistance. A variable mechanical pressure is applied to the pile by use of a spring biased solenoid. The current in the coil can control the resistance of the pile. A circuit is arranged in such a way as to use the generator output voltage to feed the solenoid which in turn varied the excitation current fed back to the generator via the carbon pile. This system forms a simple feedback regulating circuit that keeps the generator output constant within practical limits.

Aircraft carbon pile regulators are precision built mechanical units that are adjusted to match a particular model of DC generator.

Carbon pile mechanical regulator



Section diagram of carbon pile regulator



Simple DC generator control unit

The diagram shows a simple DC generator control/regulator circuit. The circuit is suitable for use with aircraft type DC generators up to 500A capacity and may be used to replace obsolete carbon-pile type field current regulators.

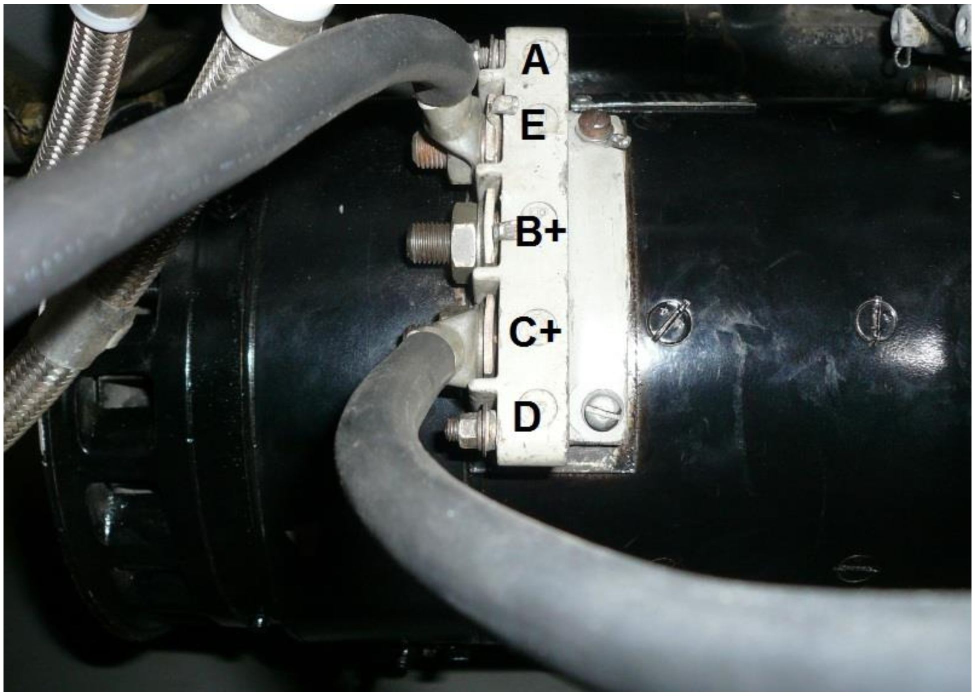
The circuit is a switch-mode type regulator. The IC1 comparator senses the generator output voltage and compares it to a fixed voltage reference set by the zener diode D1. When the voltage is below the reference the transistor turns on the supply of excitation current to the generator field coil. When the output voltage exceeds the reference the field current is switch off and the output voltage drops. The circuit oscillates about the reference point, creating a square wave action. Due to the large inductance of the generator field coil the oscillation is smoothed out and the generator output remains almost constant. The circuit time constant is set by the field coil inductance and is found to oscillate around 100 KHz in frequency.

D2 and D3 protect the switching transistor from back-e.m.f. transients, and prevent excursions outside the power supply rails. The relay RL1 is used to ensure the generator initially excites as the generator come up to speed. When not powered the relay connects the field winding directly from the generator output. Residual magnetism creates a small voltage that quickly builds up, the relay then opens, and the regulator circuit come into operation.

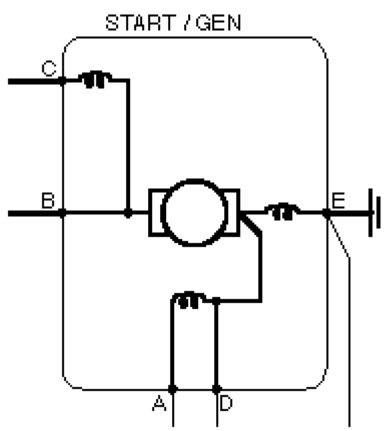
Simple DC generator control regulator unit

In critical applications it is recommended that the circuit be used with a over voltage protection device in case of short circuit failure of the switching transistor.

A problem sometimes encountered with DC generators is caused by the brush gear. Due to a high current output, the brush gear contained in the generator is heavily spring loaded producing a machine that is stiff to rotate. During the starting phase of the gas turbine, the engine may experience difficulty in accelerating under the load placed upon it by the generator friction. The gas turbine produces only low torque (but rising with rpm) until it reaches almost full speed, during this phase it may overheat if loaded by the generator. If centrifugal clutch is fitted between the engine and the generator, it will allow the engine to start off load and idle before accelerating to running speed and accepting the load of the generator.



Typical starter generator connections (Lycoming T53)



A	**Generator field +ve input**
B	**Generator Output +ve**
C	**Start +ve (Use for starting)**
D	**Generator field Sense+ve**
E	**Ground -ve Battery (Use for starting)**

Air portable 500A 28V DC generator set (Rover 1S60)

Generator set control panel

Portable 500A 28V DC generator set (Hand-started BMW/MAN 6012)

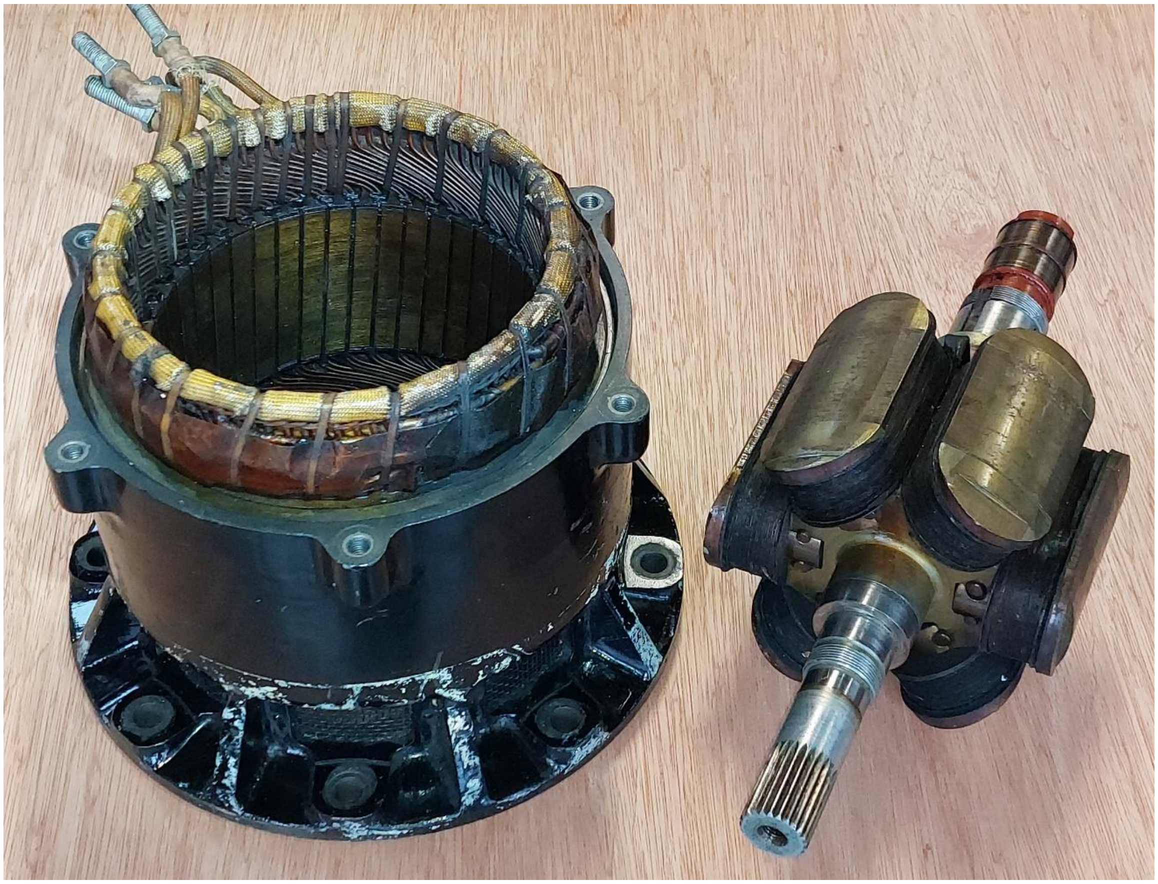
AC generators

One advantage of a gas turbine running at constant speed is that it is suitable for driving an AC generator or alternator, this arrangement will produce an electrical output at a constant frequency. An AC generator is driven by the gas turbine through a reduction gearbox, the speed at which the generator spins and the number of magnetic poles contained in it, will determine the output frequency. Generators originating from aircraft will normally provide a 110/208V output at 400 Hz, for this reason they are required to spin fast at 6,000 rpm, 8,000 or even 12,000 rpm depending on the number of poles. Generators providing a 50 Hz supply for ground-based applications normally turn at a slower 3,000 rpm (60 Hz for 3600 rpm).

30 KVa 400Hz brushless alternator

Generators of up to 60 KW capacity are common, high output types may require an external air supply for cooling. A blower that may be shared with the engine oil cooler can be used to supply air to the generator.

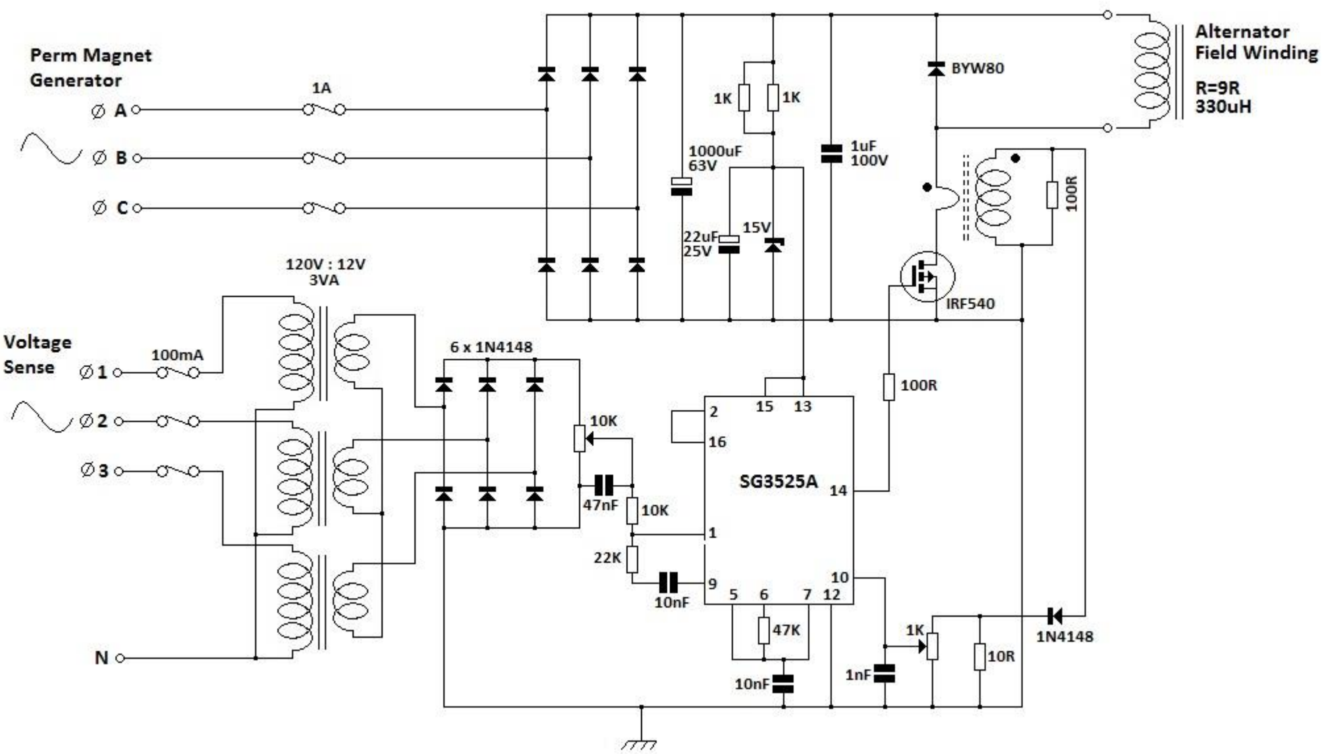
AC generators do not employ heavy brush gear and so are very free to turn. Provided that the machine is electrically isolated during the start up phase of the gas turbine, no load is presented to it.



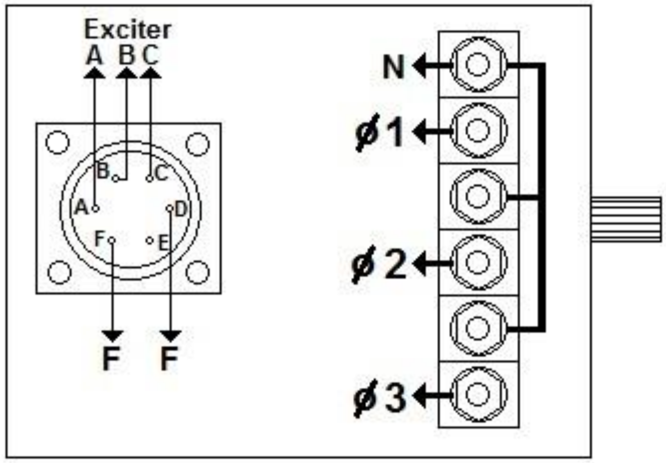
Rotax AC generator

Pictured above, the stator and rotor of an aircraft generator from the 1960s. This unit is a 6-pole slip-ring type three phase unit rated at 30KVa. This generator made by Rotax Aircraft electrical equipment would have been fitted to a small gas turbine such as the Rover 1S60 unit and known as an “airborne auxiliary power unit”. The six-pole rotor (rotating field) can clearly be seen with the slip ring contacts at the end of the shaft. The stator windings are would with distributed pole pieces similar to squirrel cage induction motor practice.

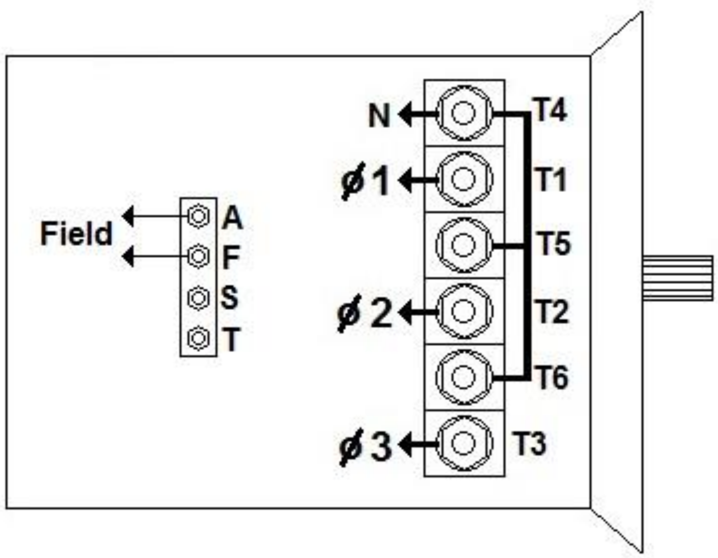
Many types of AC generators consist of a "brushless" design. Here energy is initially produced by a small permanent magnet generator mounted on the same shaft within the generator housing. This produces electricity to "Excite" a stator field winding that then transfers energy to a rotor field winding which intern couples to an output winding. The energy is transferred magnetically from the stator to the rotor and so brushes are not needed. The rotor also incorporates a rectifier unit as a DC current is required to excite the rotor.



Experimental AC generator regulator circuit.



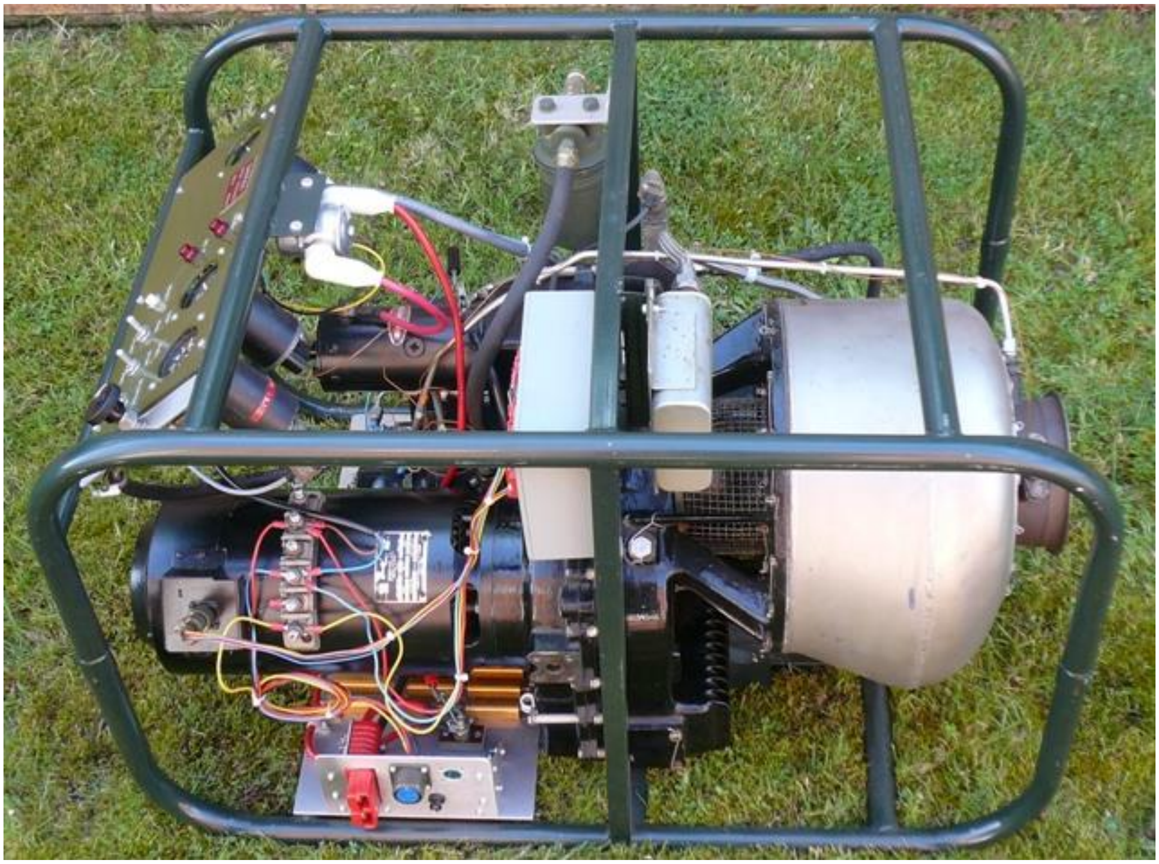
Bendix 25KVa 400Hz brushless alternator connections



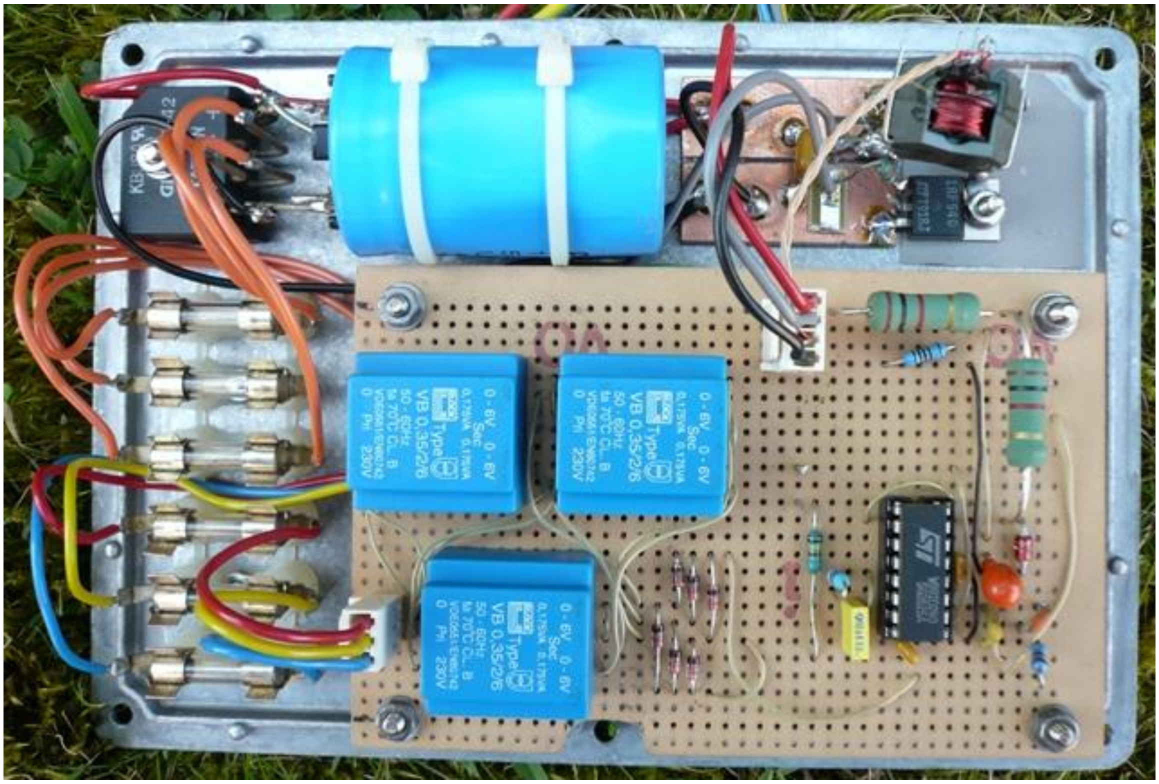
Plessey 30KVa 400Hz brushless alternator connections

When operating a gas turbine driven generator, care should always be exercised to ensure that during starting and stopping all electrical load is removed. When starting a gas turbine, the engine rpm should be allowed to stabilize, and the exhaust temperature settle before exciting the generator and connecting it to a load. As more electrical load is applied to the generator, the mechanical load on the gas turbine will increase, this will manifest itself as an increase in exhaust temperature. The exhaust temperature should always be watched so that the engine is not overloaded. Except in an emergency, a gas turbine should always be run off load for a few minutes to allow the temperatures to drop before it is shut down.

AC Generators may be used to provide a speed-sensing signal for instrumentation. A constant speed engine/generator should provide a 400Hz frequency signal that may be re-calibrated to indicate 100% engine speed. A frequency in excess of 420 Hz indicates the engine is running fast.



Portable 25 KVa gas turbine driven generator set

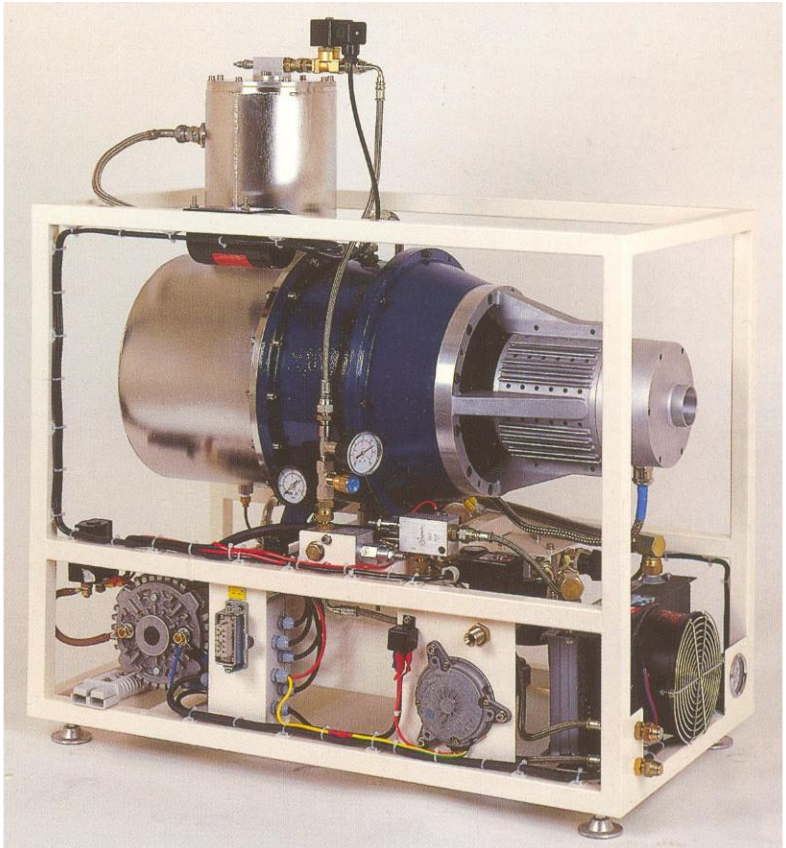


Experimental generator regulator unit

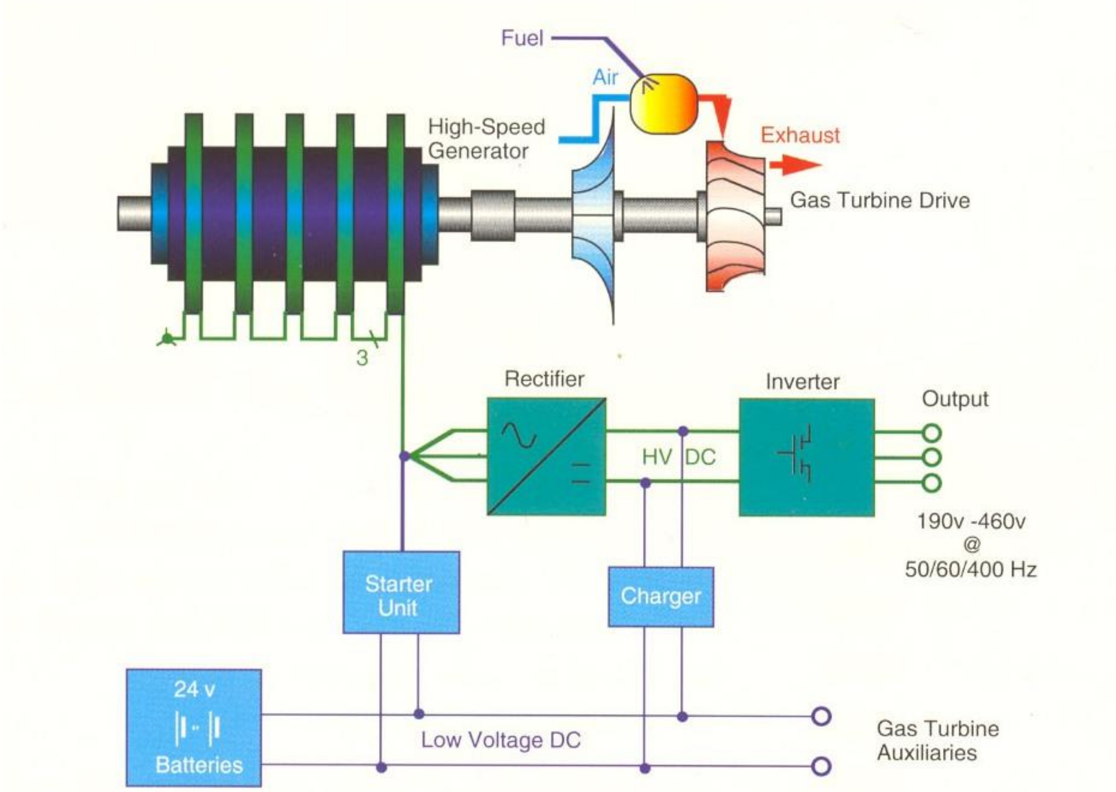
Gen-set operating under light load (3 Phase)

Direct drive generators

Special types of electrical generators exist that are capable of being directly coupled to a gas turbine engine shaft. Specially constructed generators are built to withstand the high forces generated when the rotor is rotated at the same speed (> 50,000 rpm) as the engine compressor. A permanent magnet alternator consisting of a reinforced rotor (Often with Carbon Fiber) turning inside a output winding assembly will provide a high current high frequency electrical supply. The high frequency supply is not suitable for direct connection to a load so sophisticated electronics are employed to convert the generator output to a useable voltage and frequency. Typical outputs from such a system are 240V 50Hz, 60 Hz or 400 Hz.



Experimental direct-drive gas turbine generator



System diagram of a direct drive gen-set

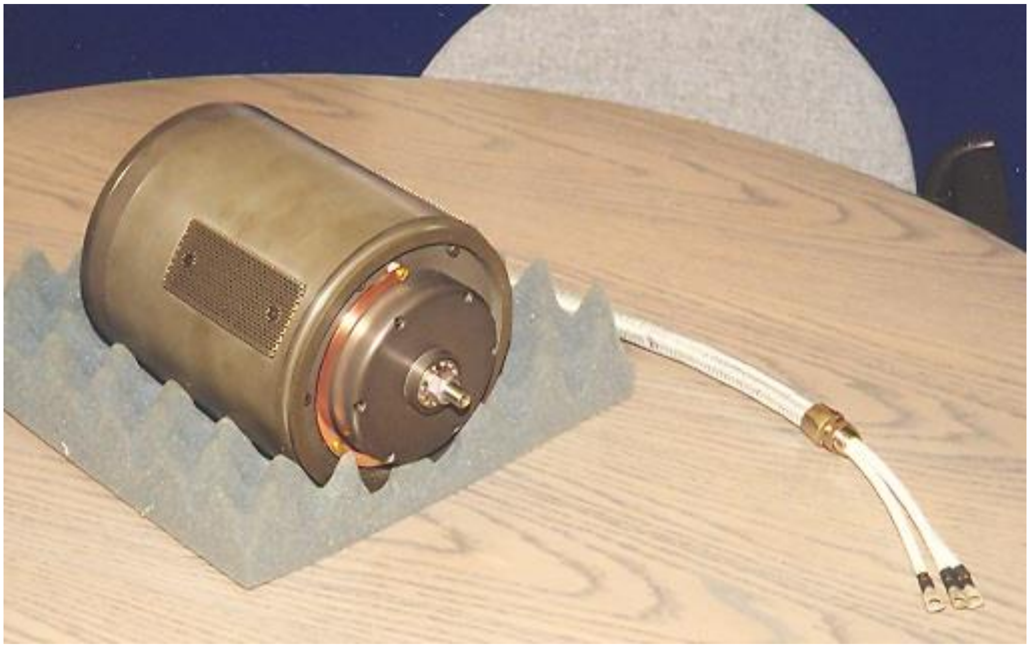
High speed alternator

Automotive gas turbine with direct-drive alternator and recuperator

(Volvo VT40)

Prototype gas turbine hybrid car (Volvo)

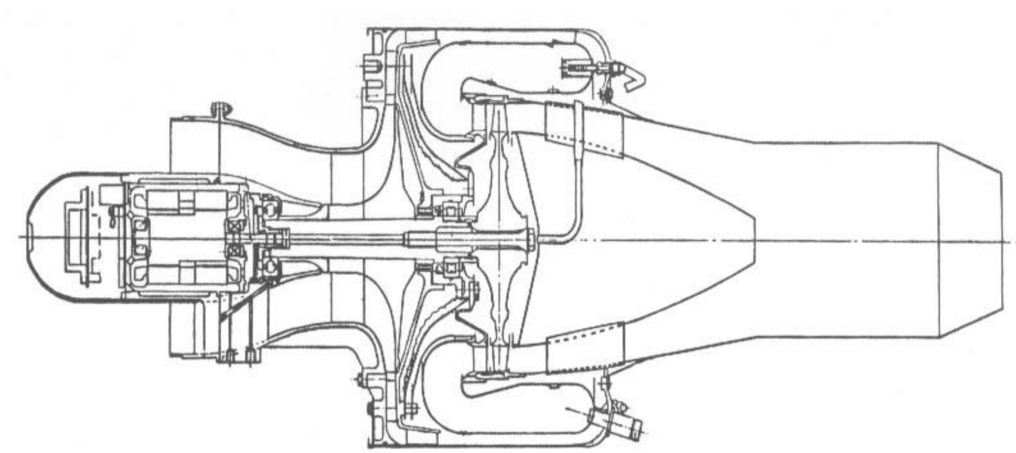
High speed direct drive generator set with 50Hz output (Turbogenset)



High speed alternator (Turbogenset)

NPT301 alternator

A number of small turbo-jet engines intended for missile and small aircraft propulsion employ direct-driven high-speed alternators to provide a source of electrical power. Usually, a small permanent magnet alternator is fitted in the center of the compressor air intake area to form an intake nose or bullet. Compressor air rushing past or over the alternator will serve to cool it.



High speed alternator fitted to turbojet engine (NPT301)

Engines designs that employ external electric motor driven accessories require a driven alternator so that the engine installation is fully self-supporting requiring external electrical power only for starting.

High speed alternator components (stator and rotor)

Governor behavior

A typical gas turbine that is used to drive an electrical generator will be required to run at constant speed regardless of the load placed upon it by the generator. It is the function of the engine fuel control system to govern the engine speed and ensure it does not vary under load.

A characteristic of mechanical and some electronic speed governor systems is known as "Droop". Normally as load is applied to the engine the speed drops by a small amount, the governing system admits more fuel and the system stabilizes at a new point. This phenomenon is known as Governor Droop. Droop may be compensated for in several ways. In mechanical systems sufficient gain (Sensitivity) must be used to minimize droop without introducing instability. Electronic actuators and similar devises may be used to augment the governing process and compensate for droop by trimming the governor datum to negate the droop in rpm as load is applied.

GPT30 governor trim.

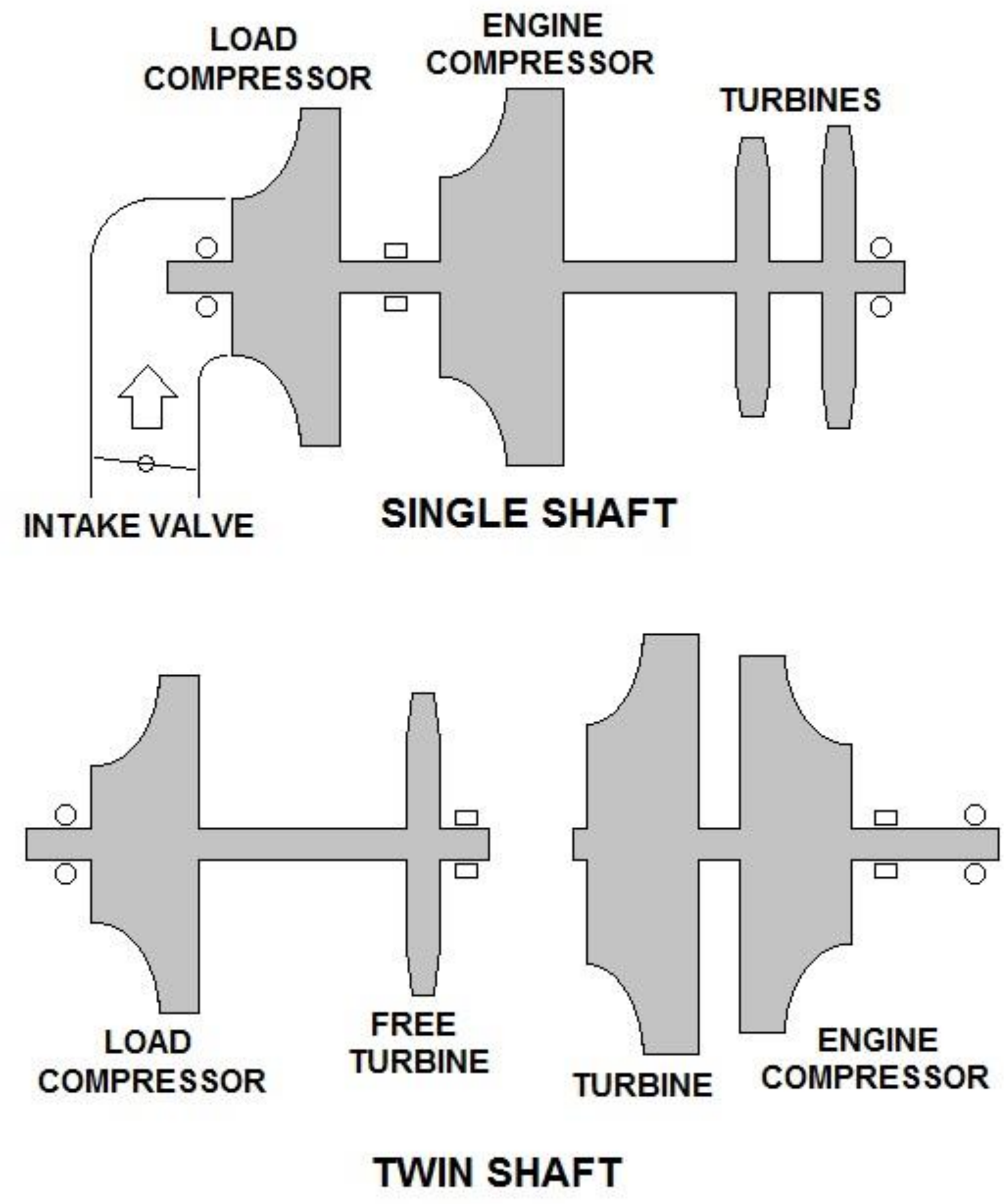
The Garrett GTP30 small gas turbine employs a hydro-mechanical control system to govern the engine at constant speed. This control system is fitted with a special electrical actuator that under the control of a small electrical signal may be used to "trim" the governed rpm up and down by just a few percent.

Engines fitted with an all-electronic governor system may also employ methods to reduce or even eliminate rpm droop under load. With an electronic system it is possible to detect the electrical load applied to the generator (by using current transformers in the output cables, hall-effect current sensors and an amplifier feedback system) and operate a feed-forward system to shift the governor datum upwards to compensate for increasing load.

Two thirds of the power developed by a typical single shaft gas turbine is used to drive its own internal compressor. This means a running engine is already heavily loaded and so the additional load placed upon it by driven equipment is relatively light in comparison. For this reason, rpm variations due to load and droop are inherently smaller than when compared to other types of prime mover.

Load compressors

It is possible to use a gas turbine engine as a air compressor by bleeding a portion of air from its compressor whilst it's running. With a suitable sized compressor considerable airflow is available at moderate pressure. It is also possible to use a gas turbine engine to drive a "load" or "separate" compressor unit, usually a single stage centrifugal compressor.



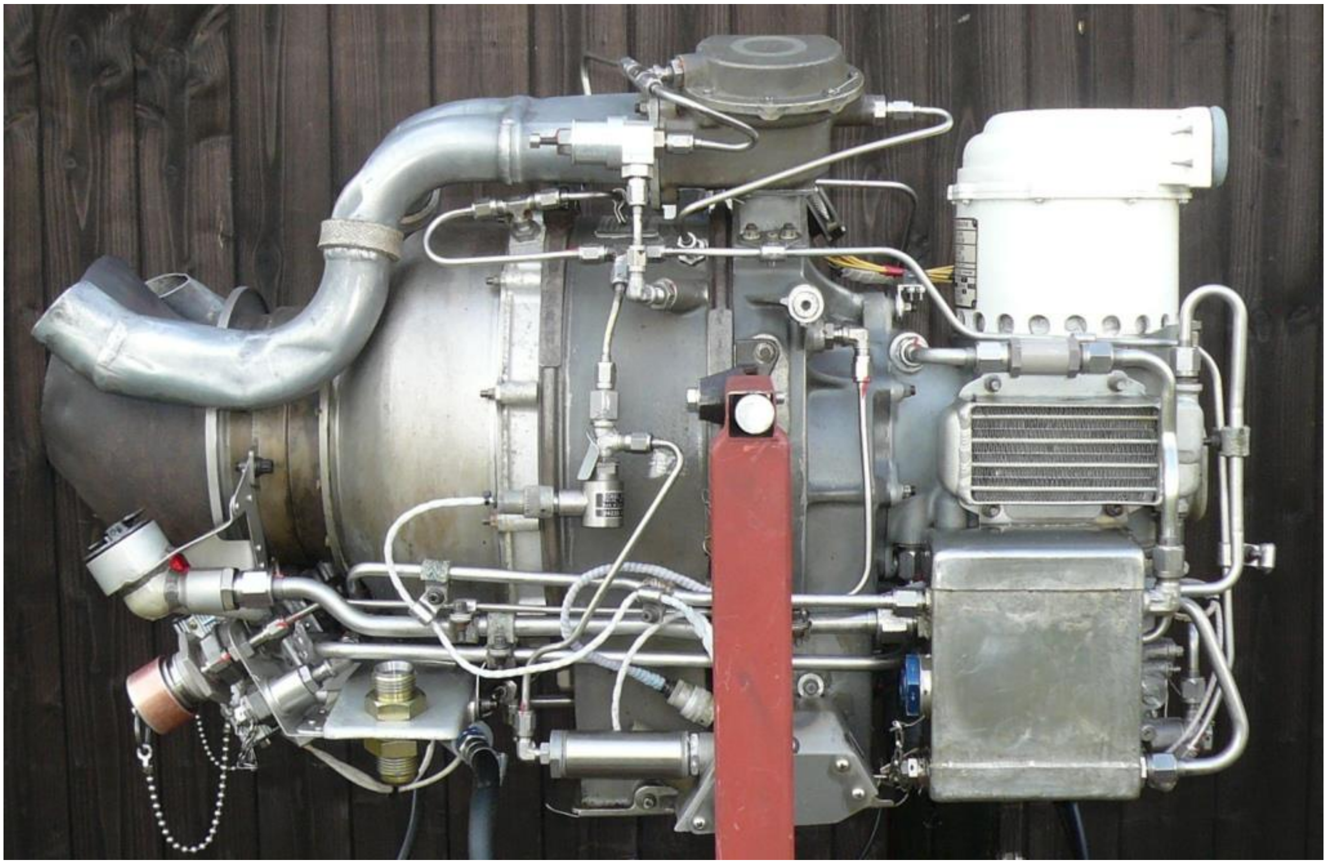
Load compressors; single shaft and twin shaft gas turbine driven

The diagram illustrates two typical engine configurations whereby a load compressor is driven by the gas turbine engine.

A single shaft gas turbine engine may drive a suitable sized (to absorb sufficient energy to provide the wanted mass flow and pressure without exceeding the engine's rating) compressor unit that is connected directly to the engine compressor shaft. The engine runs at high speed and with the aid of a governor system maintains a constant rpm regardless of compressor load. To start and accelerate the engine to governed speed a shut off valve is placed in the load compressor air inlet duct. The valve is closed during starting and prevents air flow into the compressor, this "Stalls" the compressor and prevents it from absorbing significant power from the engine shaft. A stalled compressor simply rotates freely and without performing work on the stagnant air flow within it's housing. When air flow is required the inlet valve is opened and the compressors operates. Additional air discharge regulating valves and dump outlets may be required to allow intermediate flow rates to be drawn from the load compressor and on-off transients managed to prevent unwanted surging.

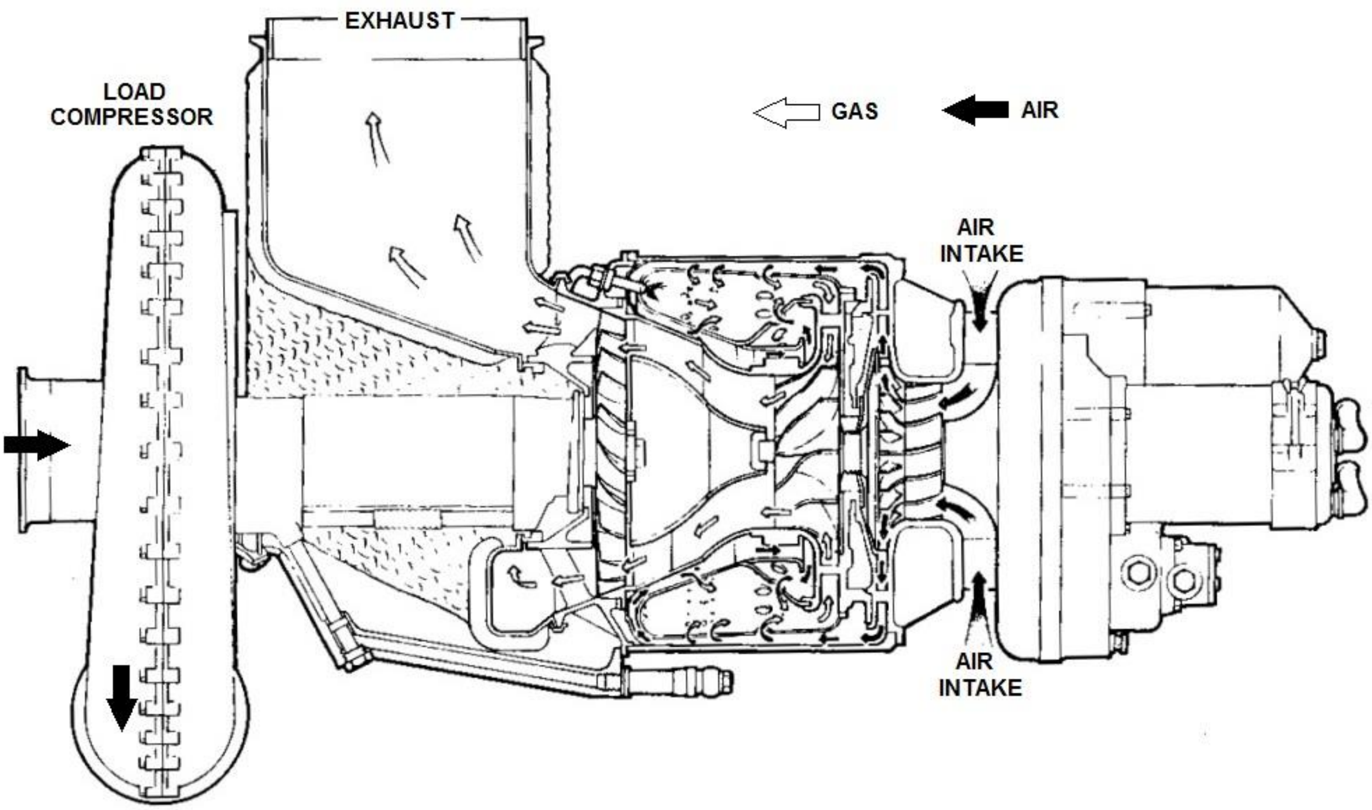
A twin shaft gas turbine engine may be used to drive a load compressor unit that is carried on a shaft driven by the free power-turbine. In this case the "Gas Generator" section of the plant may be started normally and run up to governed speed. As the starting process takes place, the free turbine and load compressor will accelerate to working rpm with no interaction with the gas generator. Care is needed to ensure that with this type of installation that the load compressor is not allowed to stall or operate outside its delivery range (pressure and mass flow) as there is the possibility it will over-speed when insufficient energy is absorbed by it. A separate governor or over-speed cut out device may be required to protect the installation from this condition.

The American built Williams WR27 APU is an example of a unit where a load compressor is driven on a common shaft with the gas generator. For starting an intake flap valve blocks the air flow and an airframe mounted delivery valve is also closed at the compressor outlet. Air is delivered from the unit when the intake and delivery valves open. An additional gearbox drives the engine accessories and a small 400Hz 5Kw alternator.

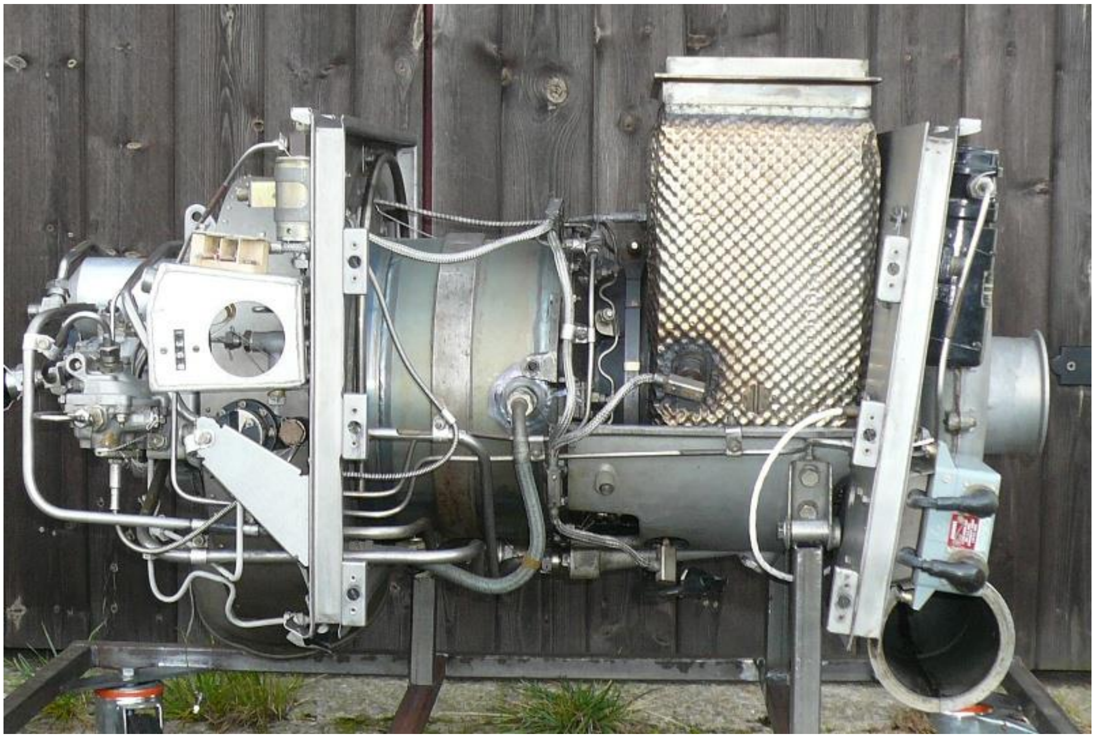


Single-shaft gas turbine engine with separate driven compressor (Williams WR27 APU)

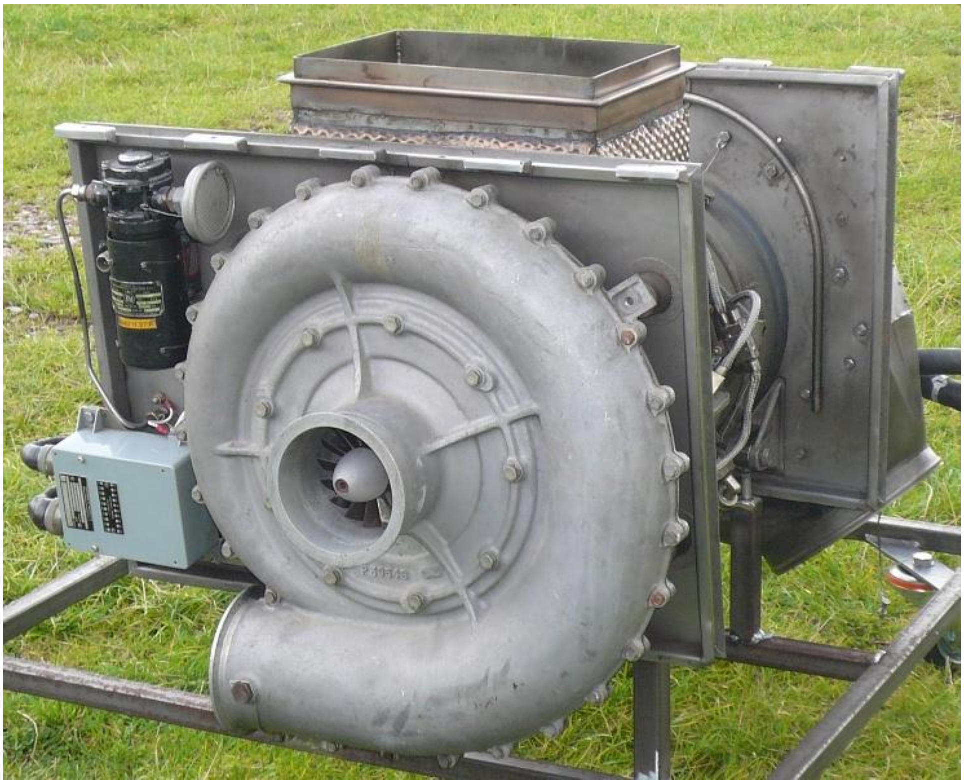
A British twin-shaft APU built by Rover Gas Turbines featured a separate load compressor capable of providing approximately 1.53 LBs/sec at 46 PSI of air mass flow for aircraft engine starting.



A twin-shaft gas turbine compressor unit (Rover AAPP MK10501)

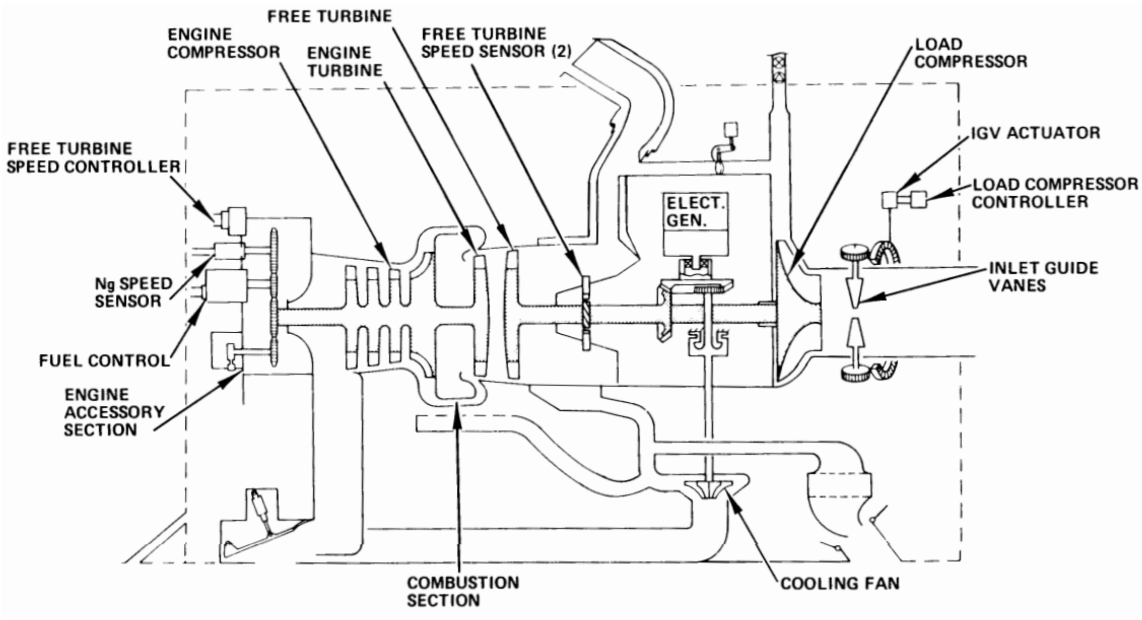


Rover (Lucas Aerospace) AAPP MK1051

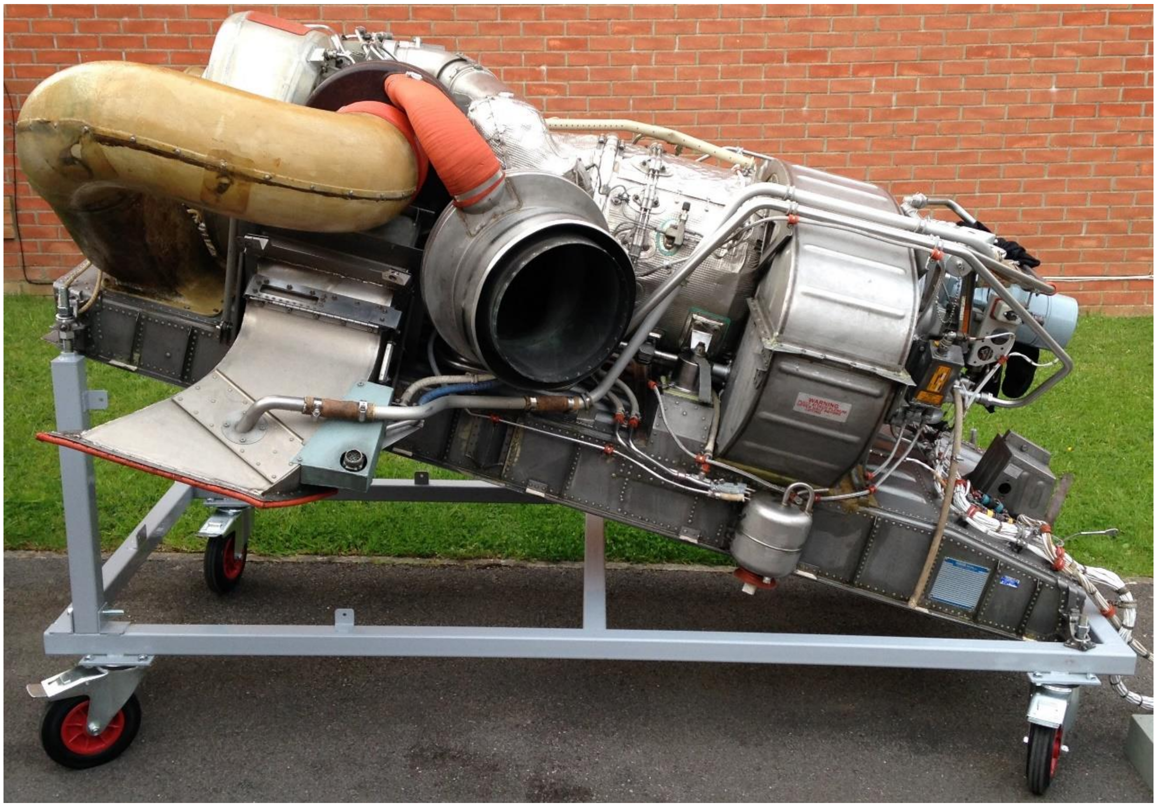


Engine driven centrifugal compressor unit (Twin Shaft)

Another notable twin shaft gas turbine was produced by Pratt and Whitney. The PT6 engine was adapted for use as an APU for use on board the Lockheed Tristar L1011 aircraft. Designated the ST6L73 and rated at some 500HP it drove a centrifugal load compressor and an alternator. An electronic governing system was used to hold the load compressor at a constant speed regardless of load.

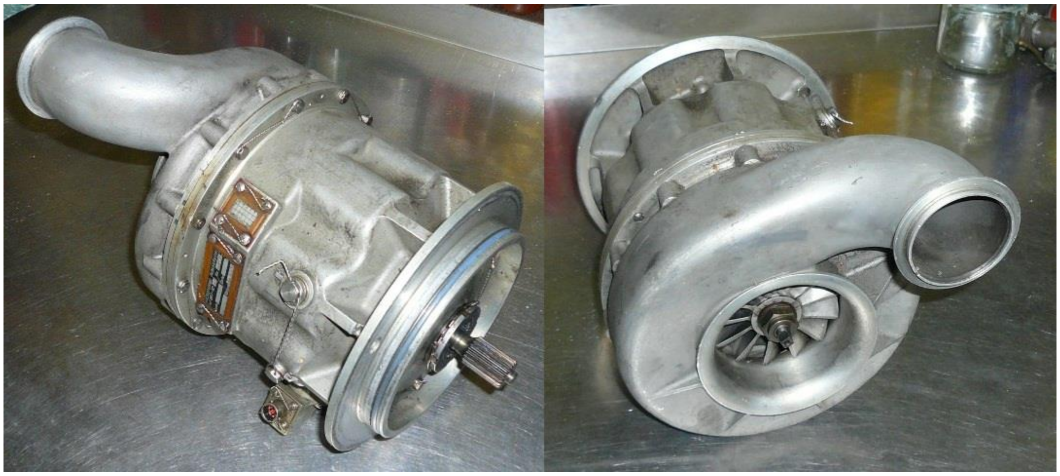


Schematic showing the layout of the ST6L73 APU

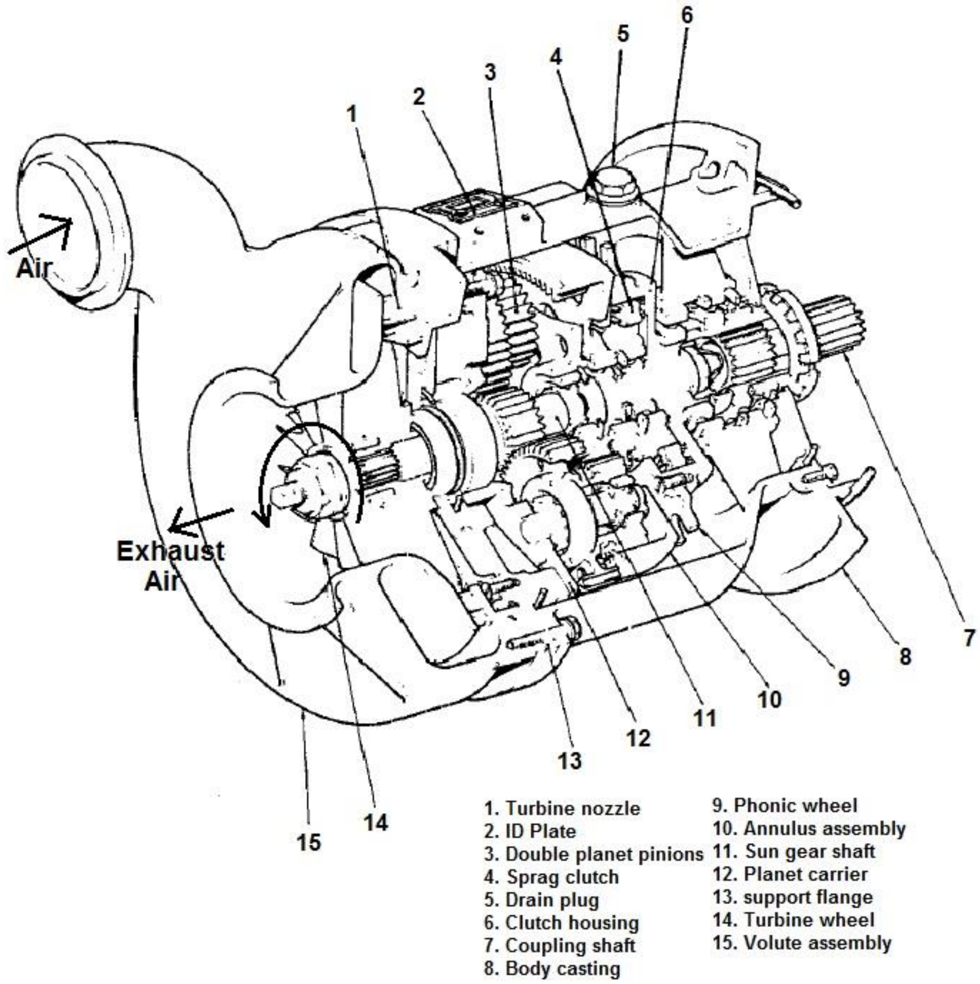


Pratt and Whitney PT6 (ST6L73) derived twin shaft unit driving a load compressor

Air motors (starters)



LP air driven starter turbine unit (Microturbo)



Air turbine motor unit (Microturbo air-starter)

A common unit found in jet aircraft is the air starter unit. An air starter is used as a power starter motor for starting aircraft propulsion engines. Low pressure air is supplied to the starter from a small gas turbine (APU) with a compressor air bleed.

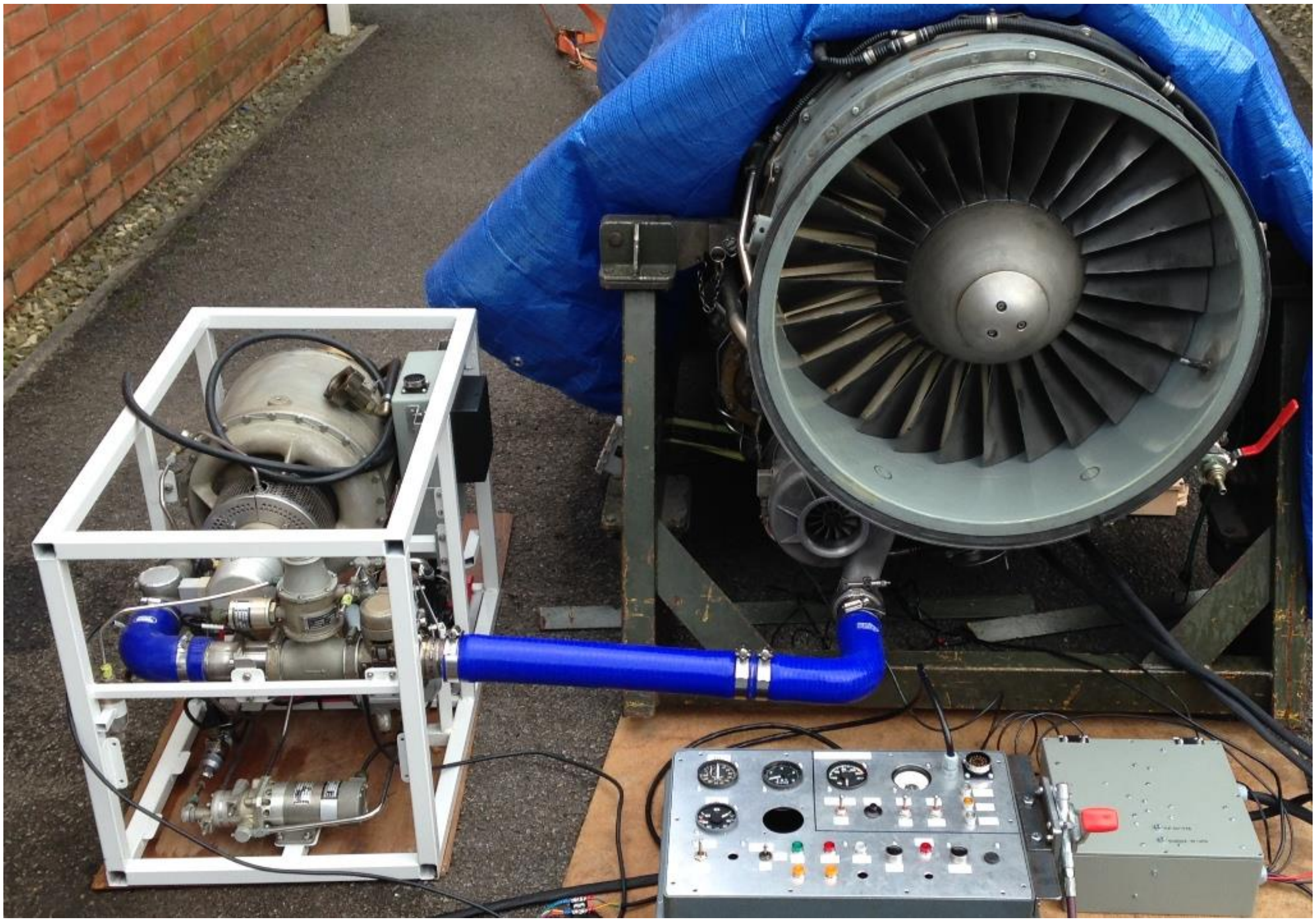
An air starter unit consists of a small radial or axial flow turbine wheel that drives through a reduction gearbox to provide an output shaft speed in the region of 3000-6000 rpm. Normally a one or two stage epicyclic reduction gearbox is used that includes an over-running clutch device such as a sprag clutch. The starter operates in a similar fashion to an electric starter motor, that is it cranks the aircraft prolusion engine and when it becomes self-sustaining the unit is cut off.

Air is ducted into the air starter unit through a volute or plenum and impinges on the turbine wheel through a nozzle assembly. The unit may be considered a small gas turbine engine that is supplied with an external gas (Air) supply. The air supply is of moderate pressure in the region of 40 PSI, a typical mass flow into a starter unit capable of 25 BHP is 0.4kg/sec. The turbine and gearbox bearings are splash lubricated by an integral oil reservoir. Synthetic turbine oil is often placed in this type of unit. Compressed air that is bled from a running gas turbine is heated by the compression, the temperature of the air may lie between 100-180 degrees C.

Air start units are often fitted with a speed detection device so that the air supply may be cut off when the unit exceeds a given speed. This may be achieved by a mechanical centrifugal switch or an electronic reluctance speed probe feeding a detector circuit.

An air-start unit is usually built for intermittent duty. It’s likely that continuous operation would require additional lubrication circulation or even oil cooling.

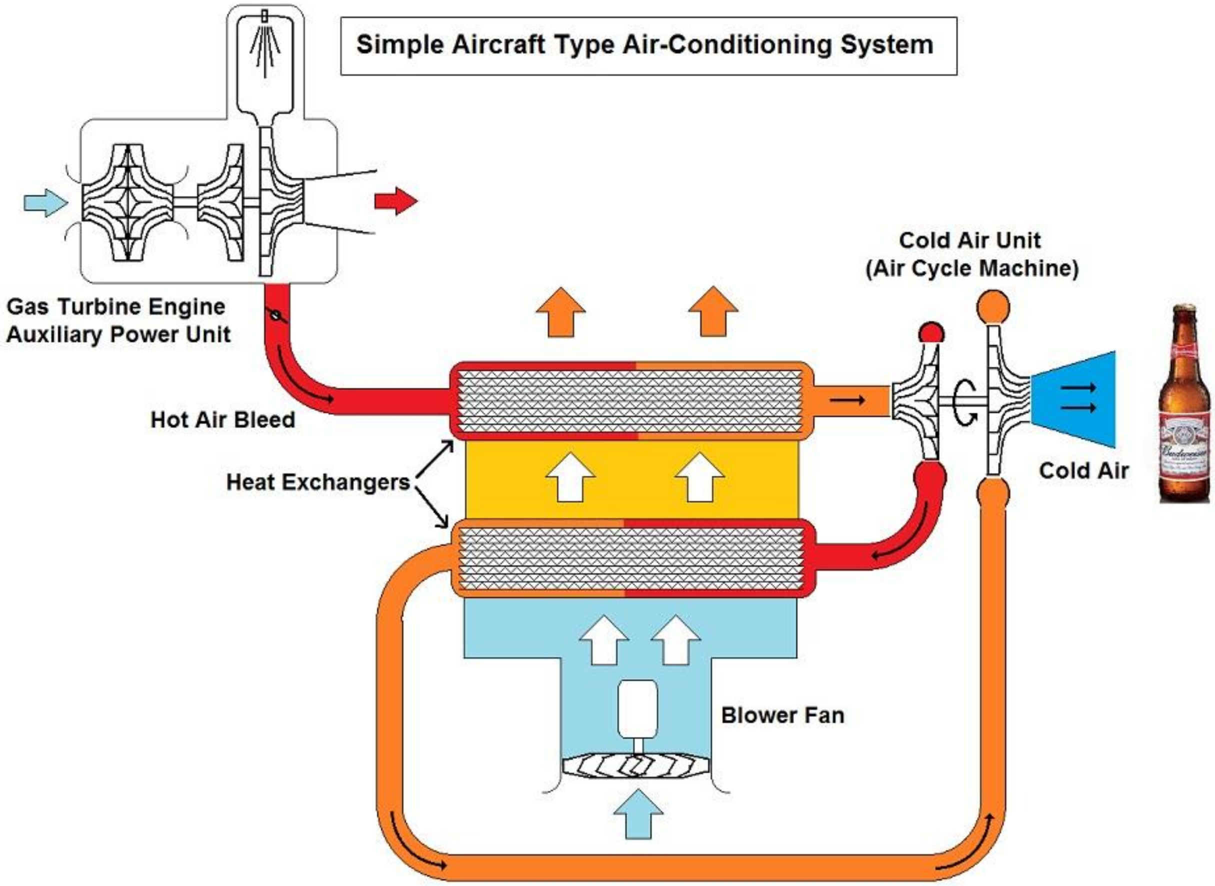
Danger: ***Care is needed when operating Air Starters; The unit should not be allowed to exceed its maximum rated speed or catastrophic failure may result. The unit should not be operated without mechanical load and in the case of starting a larger propulsion engine, the unit should be cut out before it can run away as the engine self-sustains.***



Installed air motor (starter) mounted on an engine and fed from an APU

Air Cycle Machine

Most large aircraft all adopt a similar system for pressurization and air conditioning of the cabin, this includes many military jet aircraft too. A device known as a "cold air unit" or "air cycle machine" is used to provide a source of chilled air onboard an aircraft. Instead of a liquid refrigerant, aircraft systems use the air itself as the cooling medium and the temperature drop comes from expanding the air in a turbine that is loaded and proving work.



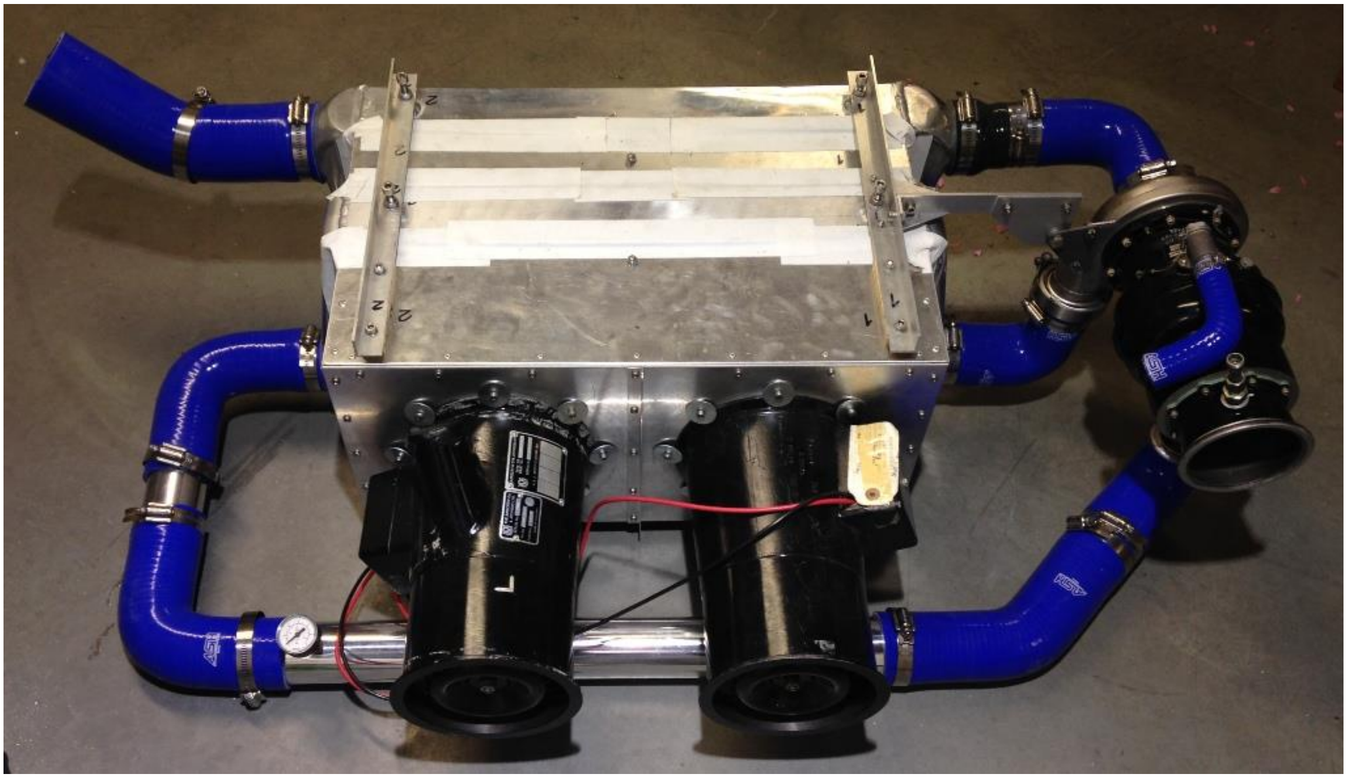
A simple air cycle system may be constructed as follows. Air is bled from a running gas turbine engine and is consequently hot and under pressure. This air is fed in to a heat exchanger type matrix that is cooled by atmospheric air provided by a heavy duty electric blower. The cooled air is passed to a centrifugal compressor unit where it is further compressed becoming heated a second time. A second heat exchanger matrix again cooled by atmospheric air, reduces the temperature after compression. The feed of air is now passed into an expansion turbine that is driving the centrifugal compressor. Here the air expands and gives up energy in the form of heat and work whilst driving the turbine. The load on the turbine is provided the compressor. The air emerging from the turbine has been cooled to below freezing point and is suitable for use cooling aircraft systems and the cabin air supply.

A special device is formed by the combination of the compressor and expansion turbine and is known as a "cold air unit" CAU or "air cycle machine" ACM. This device resembling a turbo-charger (but will not function as one it will not withstand the temperatures!) operates with its own self contained oil supply and operates for many thousands of hours at high rpm.

In practice onboard an aircraft the system is more complex and will feature a control system, many valves and further system components including a water separator. Condensation forms in the chilled air and is removed by the separator. Water collected by the separator may then be used to further enhance cooling when passed over the heat exchangers to provide some evaporative assistance to the atmospheric cooling air.

A demonstration system may be constructed by utilizing a surplus CAU unit and two automotive intercoolers. Restricted bleed air must be provided to ensure the system is not over-pressurized as hoses may blow off and the CAU damaged.

From a hot running gas turbine, the very same hot air becomes icy cold a stark demonstration of thermodynamics at work! The combination of a bleed air gas turbine and the CAU system forms a very inefficient beer cooler!

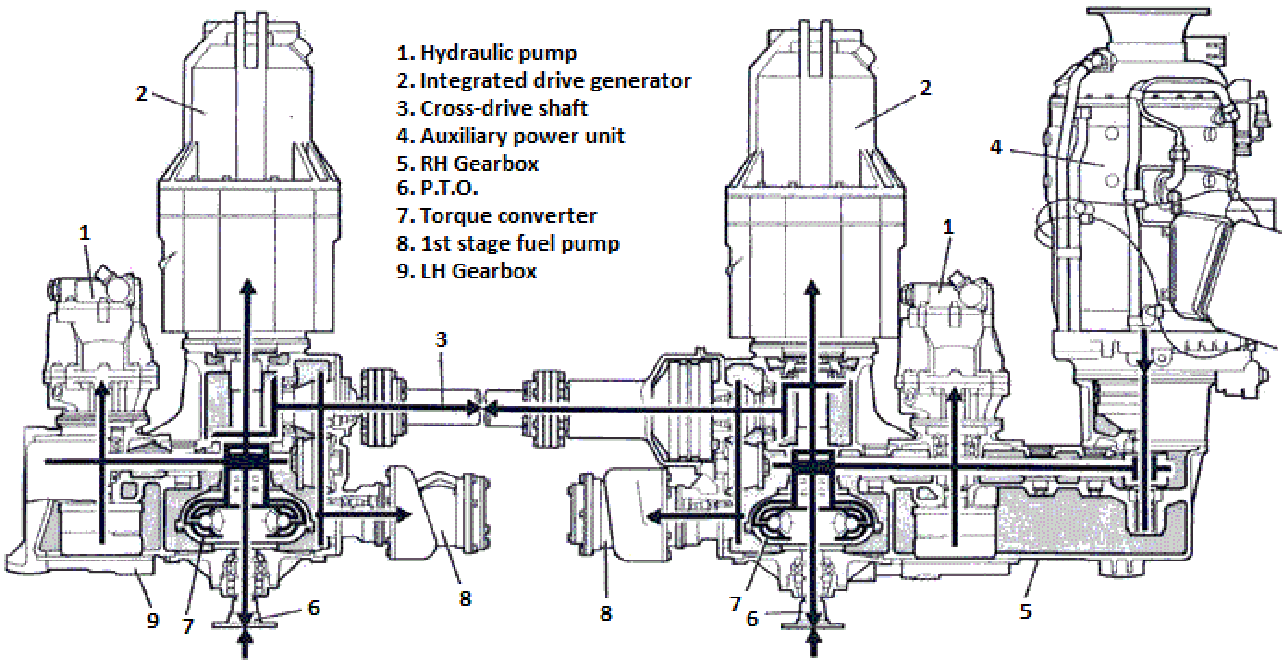


Air cycle cooling pack built with automotive intercoolers

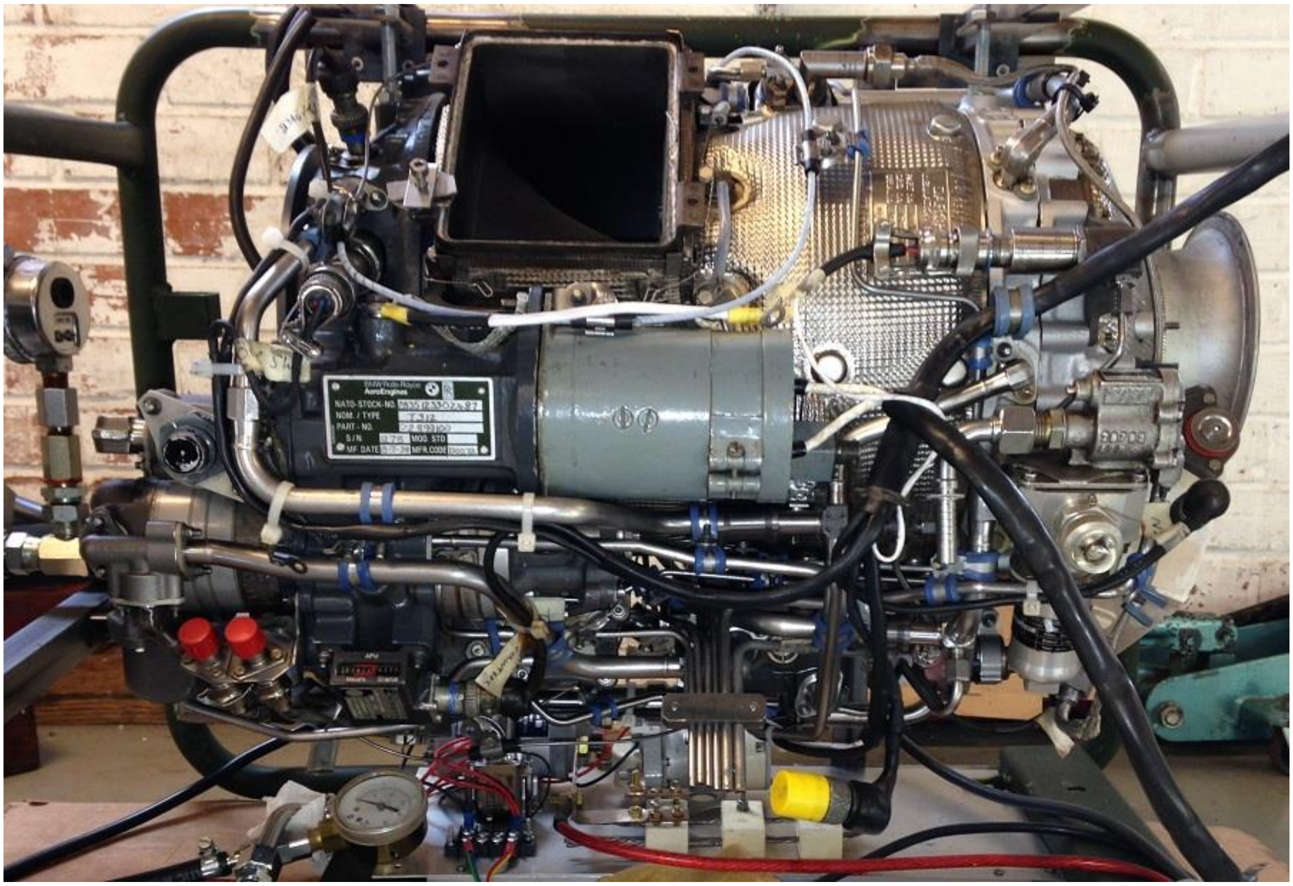
A Cold Air Unit (CAU) Air Cycle Machine

Aircraft secondary power system (S.P.S.)

The British flown Tournado aircraft is fitted with an innovative power distribution system. A small single shaft gas turbine APU is used to provide power for aircraft systems and also engine starting. The APU is used to mechanically drive the main engine accessory gearboxes so that when the engines are not in operation accessories such as hydraulic pumps and AC generators may be utilized. The T312 unit develops some 150HP, mounted on one accessory gearbox the unit is able to pass power to the main engines via torque converter units.

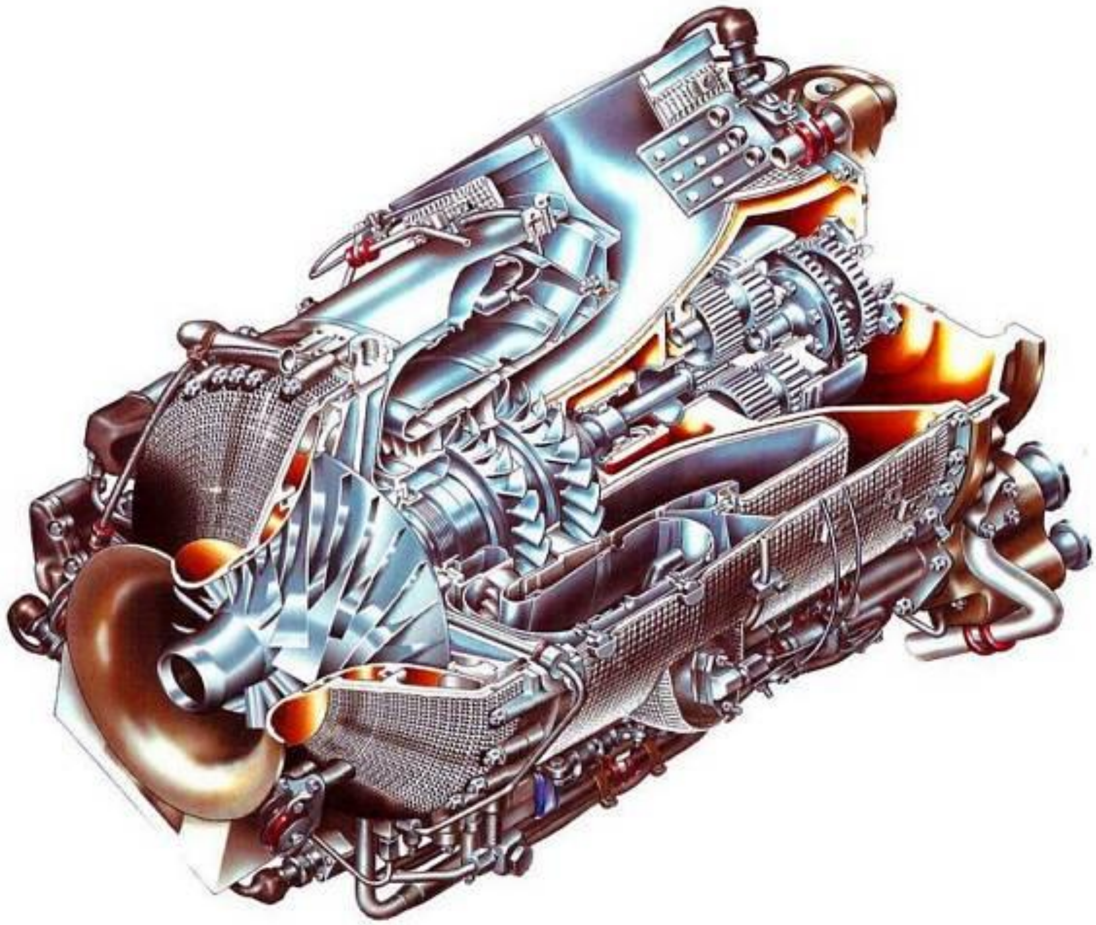


Secondary power system layout (KHD T312)



German built KHD T312 single shaft engine

Small Gas Turbines by Ian F Bennett



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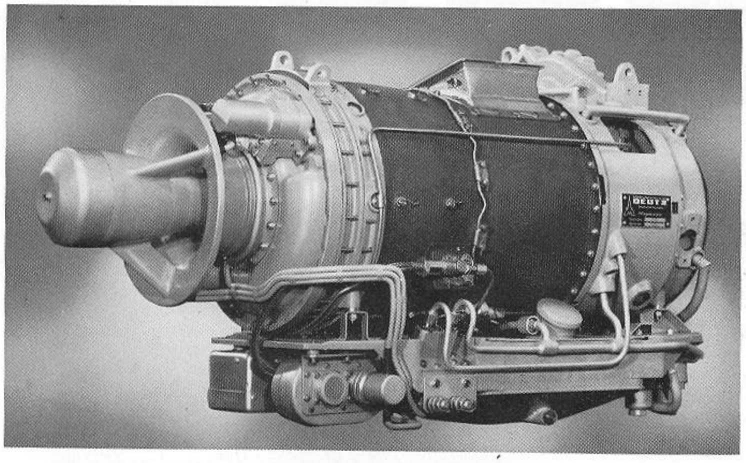
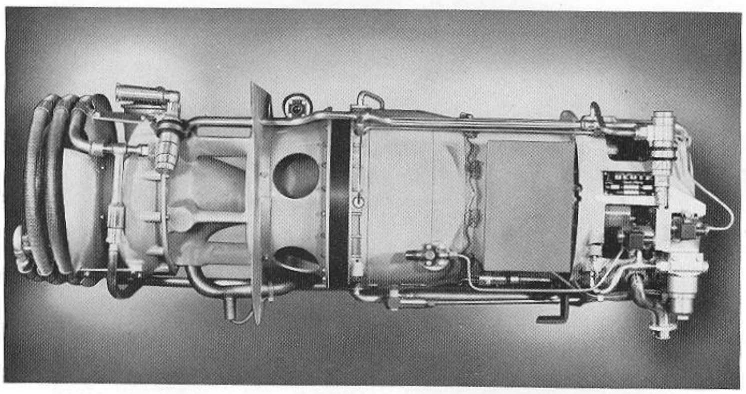
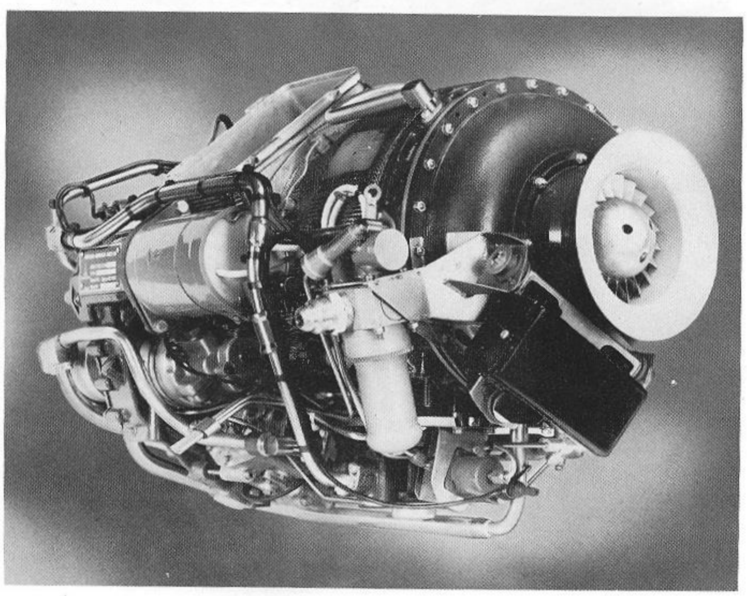
KHD T312 (MK2) cut away view

Gas Turbines · Air Supply Units · Auxiliary Power Units







The auxiliary gas turbine T 112 has been designed such that the accessories (governor, pumps, starter) are fitted in front of and behind the turbine. This has resulted in a turbine of extremely small diameter.

Bleed air at varying volumes can be tapped off behind the compressor. Controlling is done with the aid of a ring valve set up behind the guide-vane ring of the radial compressor. This arrangement permits taking off full shaft power or full bleed air or a combination of the two of any desired ratio. This unit and its means of power output are made use of on board of aircrafts during flights. Therefore, all tests for flight clearance have been carried out.

T 212

The auxiliary gas turbine T 212 is a genuine compressor. It is made use of particularly for compressing air required for jet propulsion of the propeller tips. In order to deliver the large air volumes at a compression ratio of 2.8 necessary for this duty, a radial compressor has been coupled to the turbine direct without providing for an intermediate gear. Also in this case one of the most important design criteria has been an as small front cross-section area as possible. This means that the limited installation space available for this application of the unit, i. e. with regard to its diameter, has been considered.

T 312

The auxiliary gas turbine constitutes the most powerful type of this series. It permits the selection of full shaft output or full air supply or a combination of both. The output of the turbine is fed into a secondary power system over a reduction gear arranged at the exhaust-gas end. In order to arrive at as small gas turbine dimensions as possible, all accessories have been mounted radially to the turbine. Compared with this type, the gas turbine T 112 described above, is by about 50% longer.