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DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORY

Propulsion Technical Memorandum 475

A PRELIMINARY INVESTIGATION INTO THE FEASIBILITY OF USING A SMALL TURBOJET TO PROPEL AN EXPENDABLE HOVERING DECOY

by

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SUMMARY

The of use of a turbojet engine to propel a hovering decoy has been investigated to determine its suitability for this role in terms of operating characteristics, vehicle/engine integration and cost. The thrust and flight endurance were assumed to be 450 N and 5 minutes. As an alternative to purchasing engines from manufacturers, the option of manufacturing such an engine in Australia using off the shelf automotive turbocharger components has been explored

The special characteristics of the turbojet are compared with those of a rocket and some of the broader design considerations needed to adapt the turbojet to this application are discussed.

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1. INTRODUCTION

The current emphasis on increasing the pay load and/or flight duration of stand off weapons has encouraged the development of a whole new generation of small, expendable turbojets which are now being used in such applications as target drones, reconnaissance and surveillance, and cruise missiles.

The present investigation was undertaken as an element of a broader study of enabling technologies for an advanced hovering decoy, intended for a role that demands extended flight time and/or pay load capability which may not be achievable with a solid fuel rocket engine.

In order to proceed with the investigation, in the absence of a firm vehicle specification, a number of assumptions had to be made about the engine/vehicle performance. The assumptions are:

1. Thrust required 450 N.
2. Full thrust will be achieved before the launch of the vehicle or immediately it has left launcher so that it is available to lift the vehicle to its operating height and for manoeuvring.
3. The decoy will be launched from a tube using a mortar charge.
4. Thrust vectoring will be used for manoeuvring.
5. Hovering life approximately five minutes.

2. HOVERING PERFORMANCE OF THE TURBOJET AND SOLID FUEL ROCKET MOTOR

The advantages of the turbojet over the rocket motor are illustrated in Figs. 1 and 2 (reproduced from Ref.1), for a range of payloads and flight durations. This improvement is possible because the oxidant is not carried on-board and because a larger mass flow of propellant is exhausted at a lower nozzle discharge velocity, resulting in a better propulsive efficiency.

The fuel specific impulse of a small turbojet is typically in the range 22000 to 30000 N/(kg/s), much higher than the solid fuel rocket which normally is about 2245 N/(kg/s) (Ref.2). In terms of specific fuel consumption, the conventional measure of gas turbine performance, typical figures for small turbojets and solid fuel rockets are 4×10^{-5} and 4.5×10^{-4} kg/N.s respectively.

3. FEATURES OF AVAILABLE TURBOJETS

3.1 Operation

Figs 3, 4, 5 and 6 show schematically the layout and construction of four expendable turbojet engines developed by TELEDYNE and SUNDSTRAND of US and NOEL PENNY TURBINES of UK.

All four engines use a single stage radial compressor coupled by a single shaft to a radial or axial turbine, the latter used by Teledyne. Rolling contact element bearings are used in all the engines to support the turbine and compressor wheels.

The air enters the compressor axially, which imparts to it kinetic energy, which is converted to pressure energy by the radial diffuser. On leaving the diffuser the air enters the combustor at a pressure of 3.5 to 4.5 atmospheres where its temperature is raised to about 1000 degrees Celsius at constant pressure. The hot gas is then expanded in the turbine which removes the energy required to drive the compressor. The residual pressure energy in the combustion gas is converted to kinetic energy in the exhaust nozzle to propel the vehicle.

It will be noted that each engine has a fixed rated thrust. Where this does not precisely match the vehicle weight, there is scope for uprating or derating the engines. In the case of the former, this may or may not entail reduction in operating life.

3.2 Lubrication

The appropriate method of lubrication of bearings depends on their location in the body of the engine, on the load they carry, the temperature they experience, the speed of rotation and the length of service. Teledyne and Noel Penny have used grease in their designs. Sundstrand have used oil mist lubrication because of the high shaft speed. Of the two methods grease lubrication is the simpler because it dispenses with the scavenge pump, shaft seals, filters, oil tanks and coolers normally required with a circulating oil lubricating system, thereby reducing costs and complexity. Oil mist lubrication is a total loss system in which the oil supplied to the bearings is drawn into the combustor and burned. This method requires an oil tank and oil pump or pressurised oil tank on board.

3.3 Fuel Handling System

In current turbojets used in unmanned vehicle application, the fuel management system is usually electronically controlled by a computer mounted on the air frame or on the engine. A simple fuel handling system is comprised of a fuel pump, an electronically controlled modulating valve to meter fuel flow to the engine, a shut off valve and, depending on the fuel pump delivery pressure and the method of fuelling the combustion chamber, a pressure regulating valve. The fuel pump may be coupled to the shaft of the engine or be driven by an electric motor. Driving the fuel pump electrically has the advantage that it can be used to meter the fuel to the combustor by modulating its speed in response to engine demand. These and other options are discussed in more detail in Ref.3.

3.4 Cranking And Ignition

Three cranking methods are in general use: air impingement, windmilling and pyrotechnic cartridge.

Air impingement is used for ground starts and is achieved by injecting high pressure air at 550 to 700 kPa into the compressor by means of a nozzle in the compressor housing. When the proper rotational speed has been reached, the fuel is ignited using a high energy igniter plug. During this phase of operation, fuel to the turbojet may be supplied from the on-board fuel tank, or by fuel lines coupled to an external source by quick release couplings. During launch, the external fuel lines are released and the turbojet is supplied from the fuel tank on board.

Windmill start is used when the unmanned vehicle is launched by rocket or from an airborne platform such as a jet aircraft. Air is forced into the intake of the engine causing the engine to windmill. Ignition of the fuel is as above.

Pyrotechnic cartridge start is a "one shot" high energy solid grain pyrotechnic cartridge, which is discharged through the turbine to crank the engine and ignite the fuel air mixture. Fig.5 and 6 illustrate the location of the pyrotechnic cartridge on the Noel Penny turbojets.

4. FEATURES OF THE ARL TURBOJET FOR LOCAL MANUFACTURE

The engines described, although intended for use in expendable vehicles, are generally designed for a longer working life than is required for this application, and are built to standards entailing costs which arguably could be reduced.

The feasibility of minimising engine costs, by methods including the use of off-the-shelf automotive turbocharger components in an engine which could be manufactured in Australia, has been investigated in a design study. Fig.7 is a preliminary design lay-out used to obtain the cost estimates. This geometry was selected because it permitted minimum outside diameter, low number of parts, low weight and low production costs.

The engine has been designed around the Garrett-AiResearch industrial turbocharger compressor and turbine wheels, part numbers L497326-4 (408554 DUP 4:1LE) trim "P" and 408649-3 "G" trim 1.7 A/R (Ref.4). These components, mass produced for automotive use, were selected by Garrett-AiResearch for use in an expendable turbojet design of their own, the ETJ131 of 445N thrust, which underwent preliminary development some years ago (Ref.5). The integration of the turbocharger components, other than the rotors, into the ARL design was considered, but it was found to be impractical because of the weight and size penalty these components would impose.

The compressor and turbine are of a radial flow type, assembled back to back and supported by rolling element bearings. The bearings are located in the nose cone of the engine where it is cool, so they can be grease lubricated, thus eliminating the need for an oil lubricating system that requires an oil pump, oil tank and shaft seals.

The fuel/ air mixture is burned in a reverse flow combuster. It is fuelled using pressure atomisers operating at 345 kPa above the compressor delivery pressure. Experience at ARL with the operation of the Couguar turbojet, which has a combustion chamber geometrically similar to the proposed engine, suggests that this may be feasible. Fuel to the atomizers could feasibly be supplied by an automotive electric fuel pump or by a centrifugal pump fitted into the nose cone of the engine and driven by the main-shaft. No attempt has been made to design an engine fuel control system because the final configuration will depend on the number of control functions that need to be performed. This in turn depends on how the engine is started, and how the engine and vehicle will be controlled in flight, matters which are difficult to determine in absence of a vehicle specification.

Provision for driving a 1 kW, 0.7 kg alternator (shown mounted) has been made in the nose cone of the engine by increasing the length of the compressor wheel shaft. The feasibility of setting up a special production run to manufacture 9000 of these components was discussed with the manufacturer. They were optimistic that an agreement could be reached if they were formally approached.

To keep manufacturing costs down, materials for the production of the engine components were selected in consultation with potential manufactures in order to avoid unnecessary and expensive production trials with unfamiliar metals. The materials selected are listed against the components in Fig. 7. Production methods were limited to investment casting of the more complex components and sheet metal forming. The nose cone, compressor diffuser and turbine nozzle are investment cast whilst the exhaust pipe nozzle, combustor and combustor casing are fabricated from sheet metal.

5. TURBOJET COST ESTIMATES

The engine costs are approximate and only suitable for budgeting purposes. Factors influencing the unit price are the type of engine control and fuel system selected (25% of the engine factory cost for a system used on a target drone engine Ref.6), the starting method and the power conditioning/regulation. Although these requirements have been anticipated to some extent and are represented in the cost estimate, full vehicle specification will be necessary for a more detailed estimate.

In order to procure realistic cost estimates from both overseas and local manufacturers, engine cost estimates were requested for 1500 units per year and a total volume of 9000 units.

5.1. Overseas Procurement

Three overseas manufacturers were approached. They were Teledyne and Sundstrand in US and Noel Penny Turbines in UK. Preliminary cost estimates are $A23,000 per unit from Noel Penny Turbines and $A16,000 from Teledyne. No estimate was received from Sundstrand.

The above prices do not include testing or modifications to meet special customer requirements. These will be subject to contract. The engine performance figures presented by the manufacturers in their technical brochures are uninstalled values which are affected by engine/vehicle integration requirements, and therefore, are subject to verification by qualification testing.

5.2. Local Design And Manufacture

The estimated unit cost to manufacture the turbojet engine locally is $A6,500. The price includes 20% contingency: it does not include development cost or the cost of the alternator.

6. PROCUREMENT OPTIONS

There are three procurement options:

1. Overseas purchase

2. Local development and manufacture

3. Local development and manufacture as part of a joint venture with an established manufacturer (this option can be explored when a vehicle program is in place).

The choice of option 2 or 3 would be influenced by the lead time available before the flight of the first prototype, however it has the advantage of establishing a technology base in Australia.

Option 1. is recommended if the lead time is short.

7. TURBOJET/VEHICLE INTEGRATION

Options exist for mounting the engines either on top or the bottom of a hovering vehicle.

The engine mounted on top of the vehicle is shown in Fig.8. Manoeuvring of the vehicle is achieved by deflecting the exhaust gases with the three swivelling vanes. These vanes may also be used to rotate the decoy on its axis. This configuration allows the vane actuators and control hardware to be fully integrated and contained within the body of the vehicle and simplifies the design of the launcher to some extent. However the effect of the hot exhaust gasses, at around 850 degrees Celsius, washing over the payload and other sensing transducers needs to be investigated.

Mounting the engine on the bottom of the vehicle (Fig.9) has the possible advantage that much of the experience gained and the technology used in the development of the flight control of the Winnin rocket powered hovering decoy (Ref.7), may be applicable, thereby reducing the design and development costs. With this configuration the potential problems associated with exhaust gas washing over the body of the decoy are also eliminated. However, a strong skirt surrounding the engine will need to be provided to transmit the launching loads to the frame of the vehicle.

8. THRUST CONTROL AND MANOEUVRING

In applications such as target drones and cruise missiles, thrust is controlled by varying fuel flow. In a hovering application this may not be the most suitable method because the thrust response of the engine to fuel flow changes may be too slow. For example, the Sundstrand TJ-90 turbojet (Fig 4), takes 9.4 seconds to increase thrust from 223 N at 85000 RPM to 470 N at 102000 RPM (Ref.8). A better method may be to operate the engine at full thrust and to modulate the thrust externally to the engine, by spoiling the exhaust jet, to compensate for fuel weight loss and for manoeuvring. Since fuel mass with turbojet propulsion would be a comparatively small proportion of the total, this relatively inefficient means of thrust modulation would probably be acceptable. Gyroscopic forces acting on the vehicle during manoeuvring, due to the compressor and turbine rotors, were found to be insignificant (Ref.1).

9. STARTING THE TURBOJET

The pyrotechnic cartridge start is the most expensive of the three starting methods in general use, however it is the fastest and the most reliable (Ref.9).

Compressed air impingement start, although slower than the pyrotechnic cartridge, can be used to start the turbojet more than once. This method may be suitable if the vehicle is operated in a role where the "system alert" can be initiated sufficiently in advance of the required instant of launch.

Windmill start is not acceptable in this application. The operating height of the vehicle is not sufficient to allow time for the turbojet to accelerate to a shaft speed that can sustain continuous combustion. Ref.10 suggests that rocket boost to Mach numbers of 0.3 to 0.65 is necessary for this method.

The time required for the turbojet to reach full thrust will depend on the method used to crank the engine and on the starting and acceleration schedules of the fuel control system. For example, the Microturbo Couguar 022 turbojet which uses compressed air for cranking, achieves maximum thrust in about 30 seconds from the time the engine starting sequence is initiated. Cranking and ignition is completed in 20 seconds. At the end of 20 seconds the engine is running at about 15000 RPM: another 10 seconds is required to accelerate it to 30000 RPM and maximum thrust (Ref.11). By contrast, the Sundstrand TJ-90 turbojet (Fig 4) can achieve full thrust in about 10 seconds using a 3 second burn time pyrotechnic cartridge for cranking (Ref.8). At the end of 3 seconds the engine is running at about 80000 RPM: another 7 seconds is required to accelerate it to 102000 RPM and maximum thrust. The TJ-90 was developed to power an experimental fibre optic guided missile for defeating hovering helicopters at extended ranges.

10. EFFECT OF LAUNCHING ACCELERATION ON THE TURBOJET

The effect of the acceleration during launch on the stability of the compressor air flow, the fuel spray pattern in the combustor and the life of the main shaft bearing supporting the compressor and turbine wheels need to be investigated. Distortion of the air flow at the face of the compressor and/or of the fuel spray pattern in the combustor may cause combustion instability, possibly leading to combustor flameout.

The probability of the main shaft bearings failing under the acceleration load would appear to be very low, based on the experience with the 800 N thrust Couguar 022 turbojet in the Turana target drone (Ref.12). This vehicle was launched using rocket boost which subjected the vehicle to an acceleration of 110 m/s/s for a period of 1.5 seconds with no damage to the bearings.

11. LAUNCHER CONFIGURATION

With the engine mounted on the bottom of the vehicle there would appear to be no alternative but to sit the vehicle on a piston for launching. A schematic drawing of the piston and launching tube is shown in Fig.10. The purpose of the openings in the top skirt of the piston and the launching tube, is to allow the exhaust gases of the turbojet to escape during launching. This is necessary because the turbojet has to be started a finite time before launching, so that full thrust is available to lift the vehicle to its operating height and for manoeuvring. If a gas generator charge, such as a pyrotechnic cartridge is used to propel the piston, the piston needs to be provided with extra length of skirt below the exhaust gas deflector, equal to the piston travel, to retain the launching gas pressure as it moves past the openings in the wall of the launcher. The length of travel of the piston and hence the length of the launcher will depend on the acceleration and the velocity that is chosen for the vehicle when it leaves the launching tube.

With the engine mounted on top of the vehicle a pyrotechnic cartridge could conceivably be used to launch the vehicle if the lower end, which may house part of the payload, can be hardened to act as a piston under which the charge can be ignited. If this is impractical there is the option of sitting the vehicle on a piston. With this engine and vehicle configuration, openings in the piston and launching tube described above would be unnecessary. Also the piston need not have a skirt as deep as the above design.

The piston may be launched with the vehicle and allowed to fall away. Alternatively, it can be retained in the launching tube.

Another possible method of launching the decoy is to use a booster rocket which is allowed to fall away when it is spent. If, due to operational requirements this is not practical, the booster assembly will have to remain onboard at the expense of payload.

12. CONCLUSION

Preliminary indications are that, from a technical aspect, the turbojet engine may be suitable for propelling hovering decoys defending high value marine targets. It offers pay load mass and flight duration capabilities that cannot be matched by the solid fuel rocket motor. However, there may be operational penalties. For example, compared with the rocket motor it is slow to achieve full thrust. This may limit the role of the decoy to defence applications where this delay is not of critical importance.

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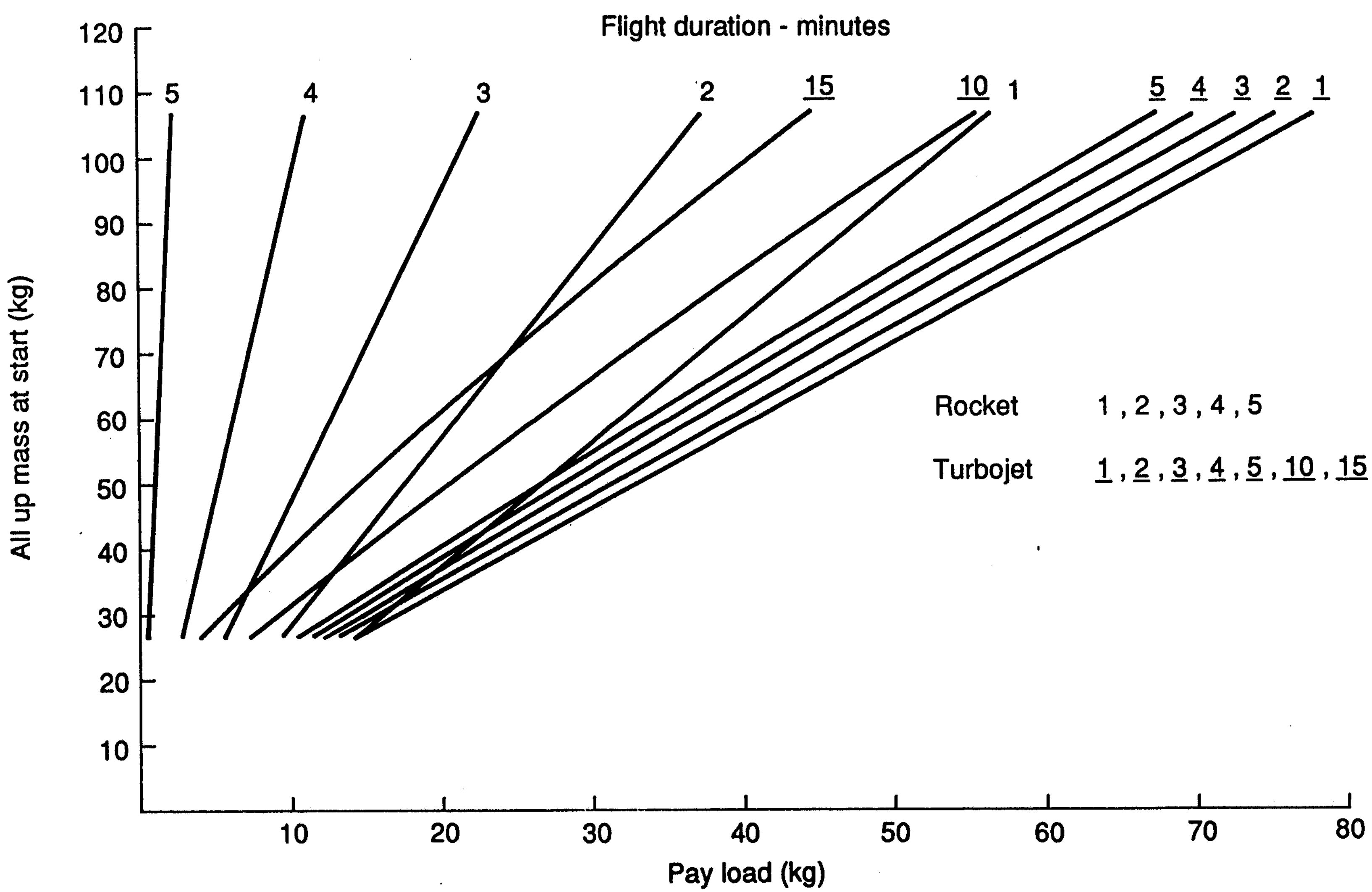


FIGURE 1. ALL UP MASS vs PAY LOAD COMPARISON OF ROCKET AND TURBOJET (REF. 1)

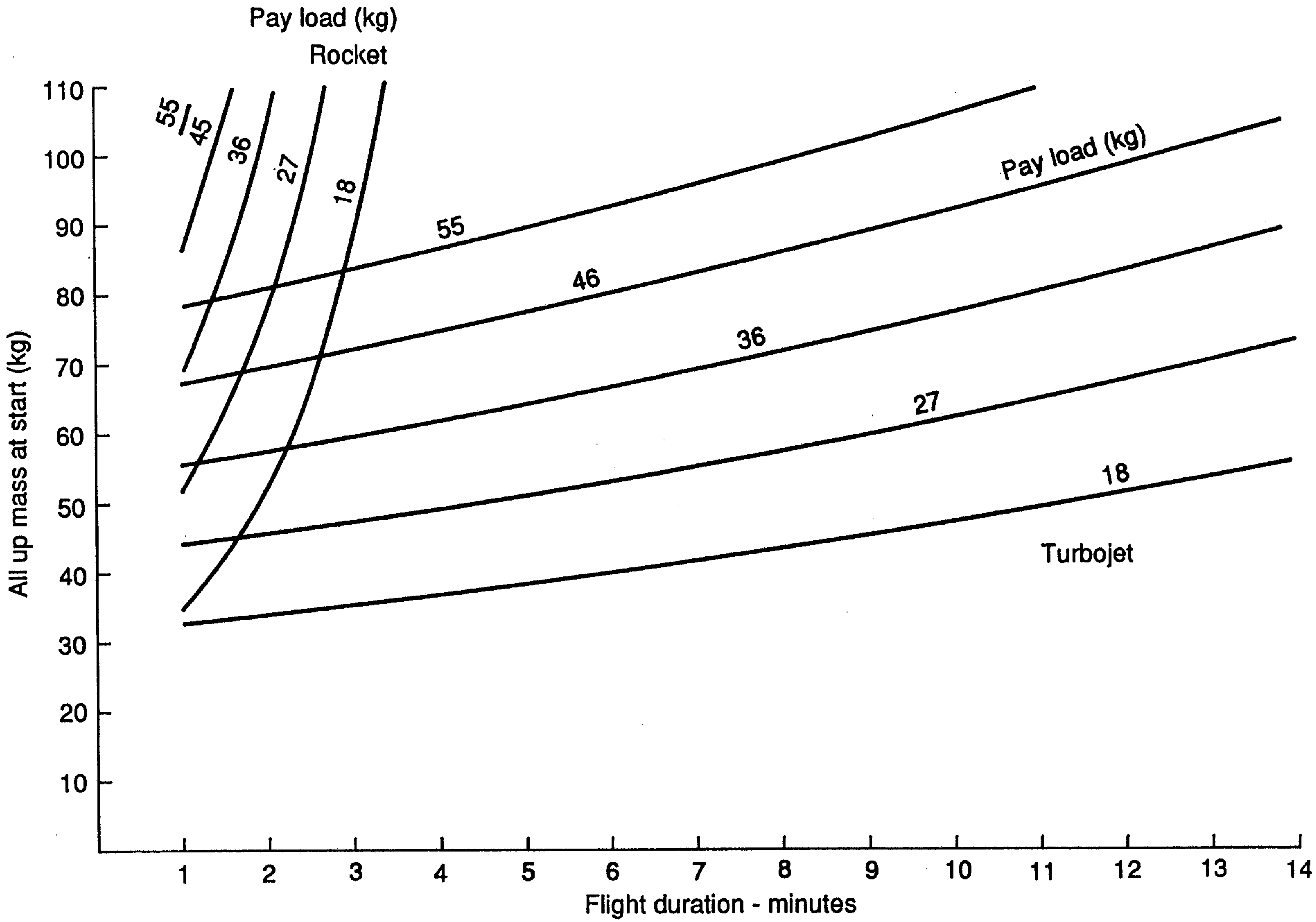
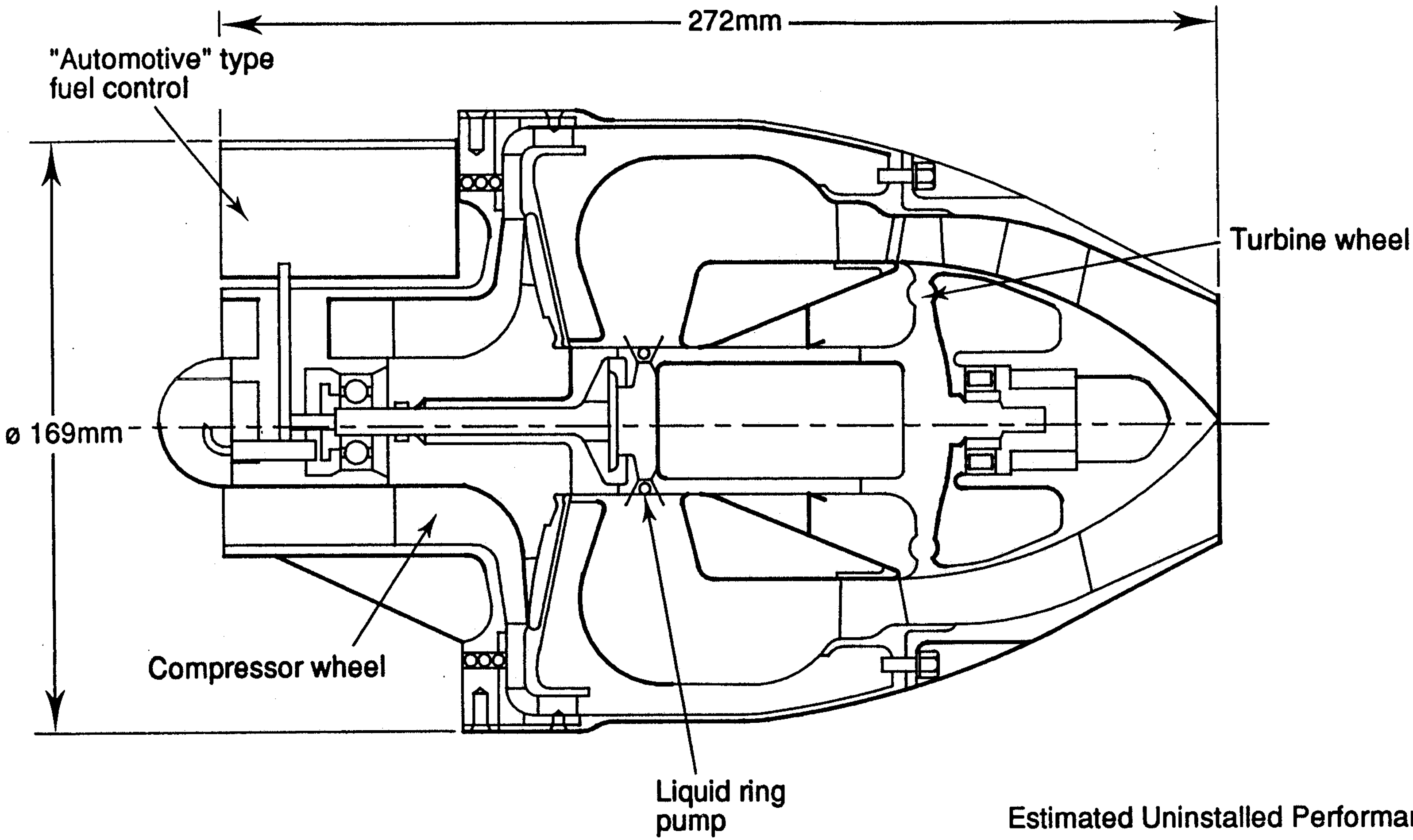


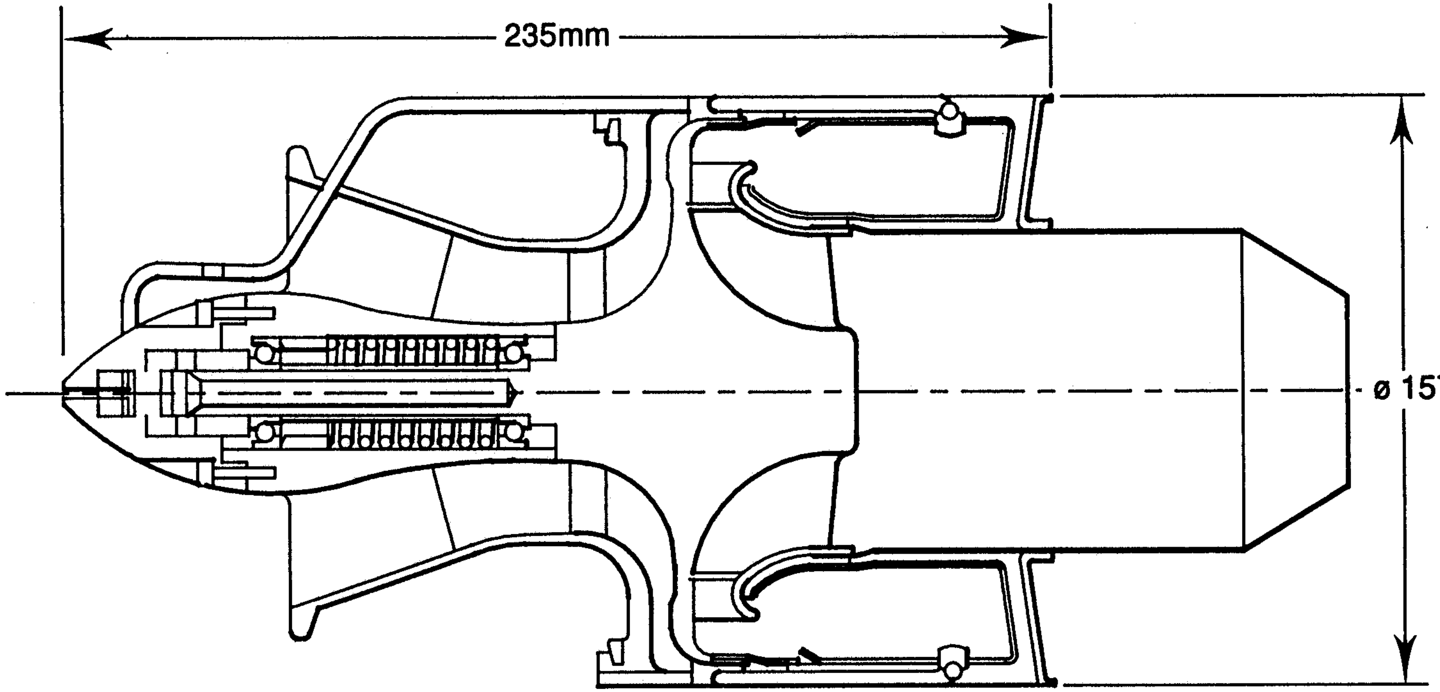
FIGURE 2. ALL UP MASS vs FLIGHT DURATION COMPARISON OF ROCKET AND TURBOJET (REF. 1)



Estimated Uninstalled Performance At Sea Level

Maximum Thrust	400	N
Air Flow	0.59	kg/s
Specific Fuel Consumption	3.6×10^{-5}	kg/N.s
Engine Speed	89000	R.P.M.
Exhaust Gas Temperature	1160	°K
Weight Dry	8.60	kg
Fuel	JP_4;JP_5;JP_8;JP_10	

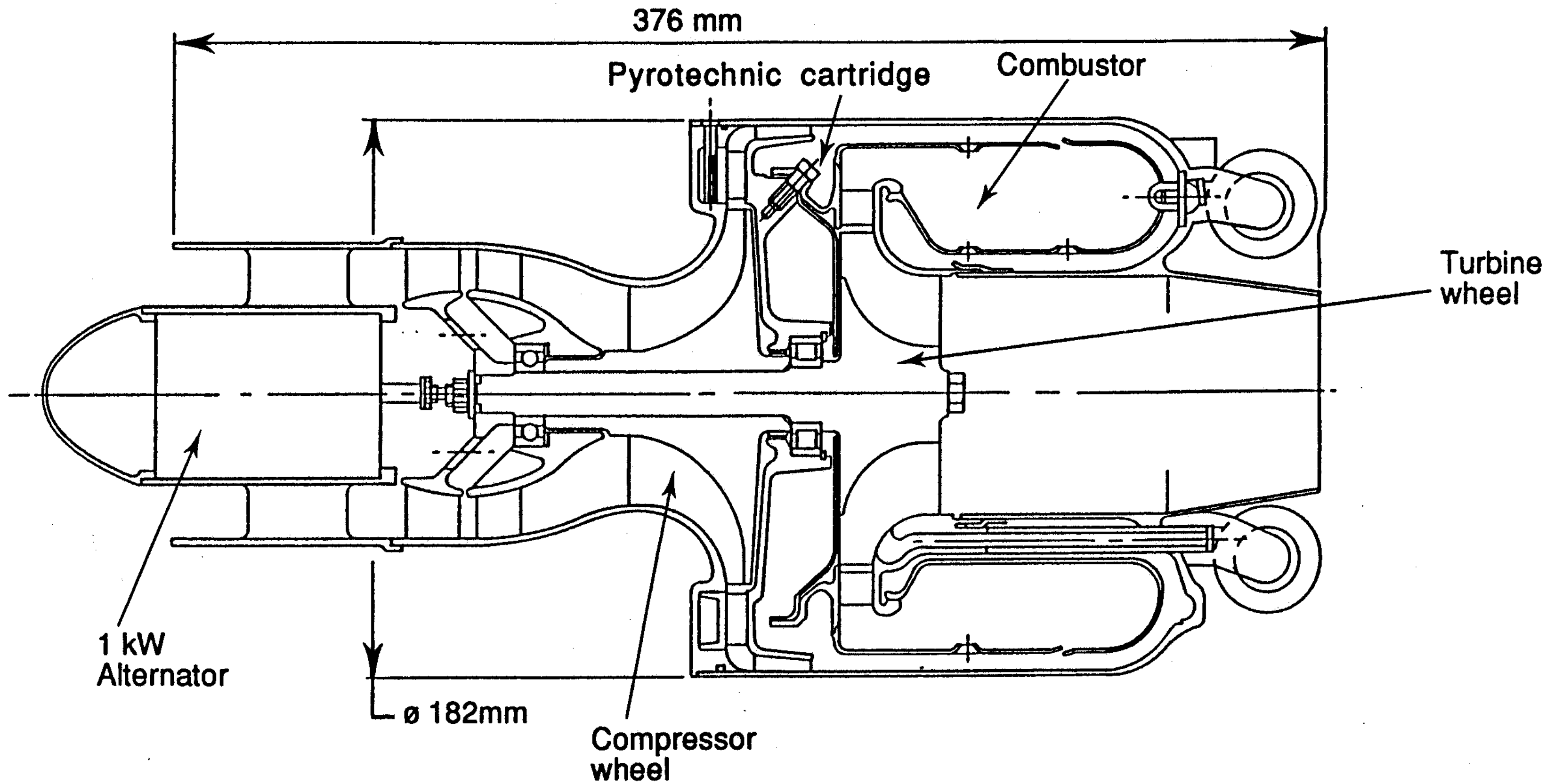
FIGURE 3. TELEDYNE CAE MODEL 305-7E



Estimated Uninstalled Performance At Sea Level

Maximum Thrust	476	N
Air Flow	0.69	kg/s
Specific Fuel Consumption	3.8×10^{-5}	kg/N.s
Engine Speed	102000	R.P.M.
Exhaust Gas Temperature	not available	
Weight Dry	4.80	kg
Fuel	JP_4;JP_5;JP_10	

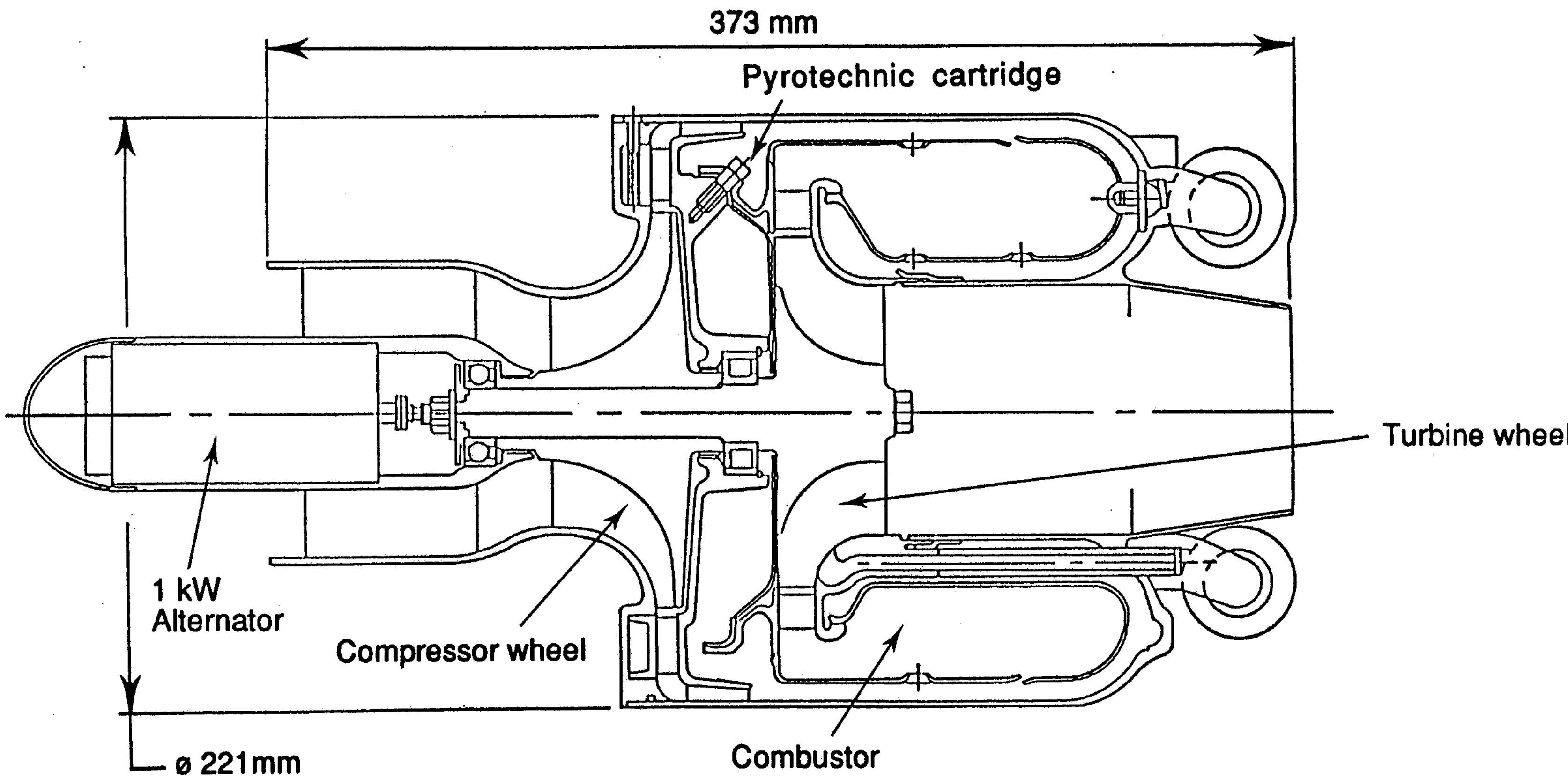
FIGURE 4. SUNDSTRAND MODEL TJ-90



Estimated Uninstalled Performance At Sea Level

Maximum Thrust	445	N
Air Flow	0.74	kg/s
Specific Fuel Consumption	3.3×10^{-5}	kg/N.s
Engine Speed	86600	R.P.M.
Exhaust Gas Temperature	1046	°K
Weight Dry	9.50	kg (without alternator)
Fuel	JP_4;JP_5	

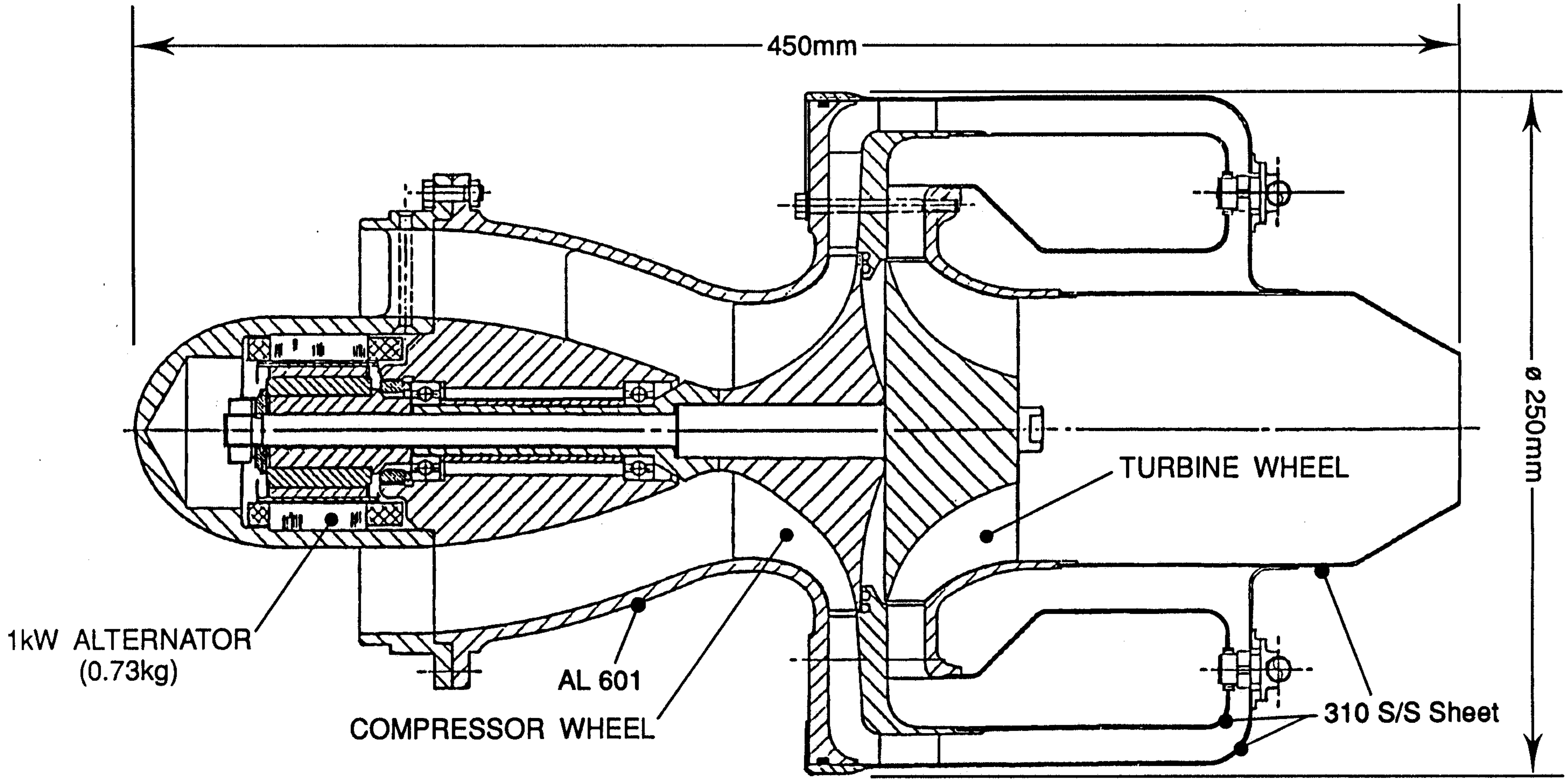
FIGURE 5. NOEL PENNY TURBINES MODEL 425



Estimated Uninstalled Performance At Sea Level

Maximum Thrust	445	N
Air Flow	0.73	kg/s
Specific Fuel Consumption	3.6×10^{-5}	kg/N.s
Engine Speed	85700	R.P.M.
Exhaust Gas Temperature	1105	°K
Weight Dry	13.0	kg (without alternator)
Fuel	JP_4;JP_5	

FIGURE 6. NOEL PENNY TURBINES MODEL 426



Estimated Uninstalled Performance At Sea Level

Maximum Thrust	450	N
Air Flow	1.2	kg/s
Specific Fuel Consumption	4.5×10^{-5}	kg/N.s
Engine Speed	69000	R.P.M.
Exhaust Gas Temperature	1100	°K
Weight Dry	14.0	kg (without alternator)
Fuel	JP_4	

FIGURE 7. SCHEMATIC OF A.R.L. TURBOJET

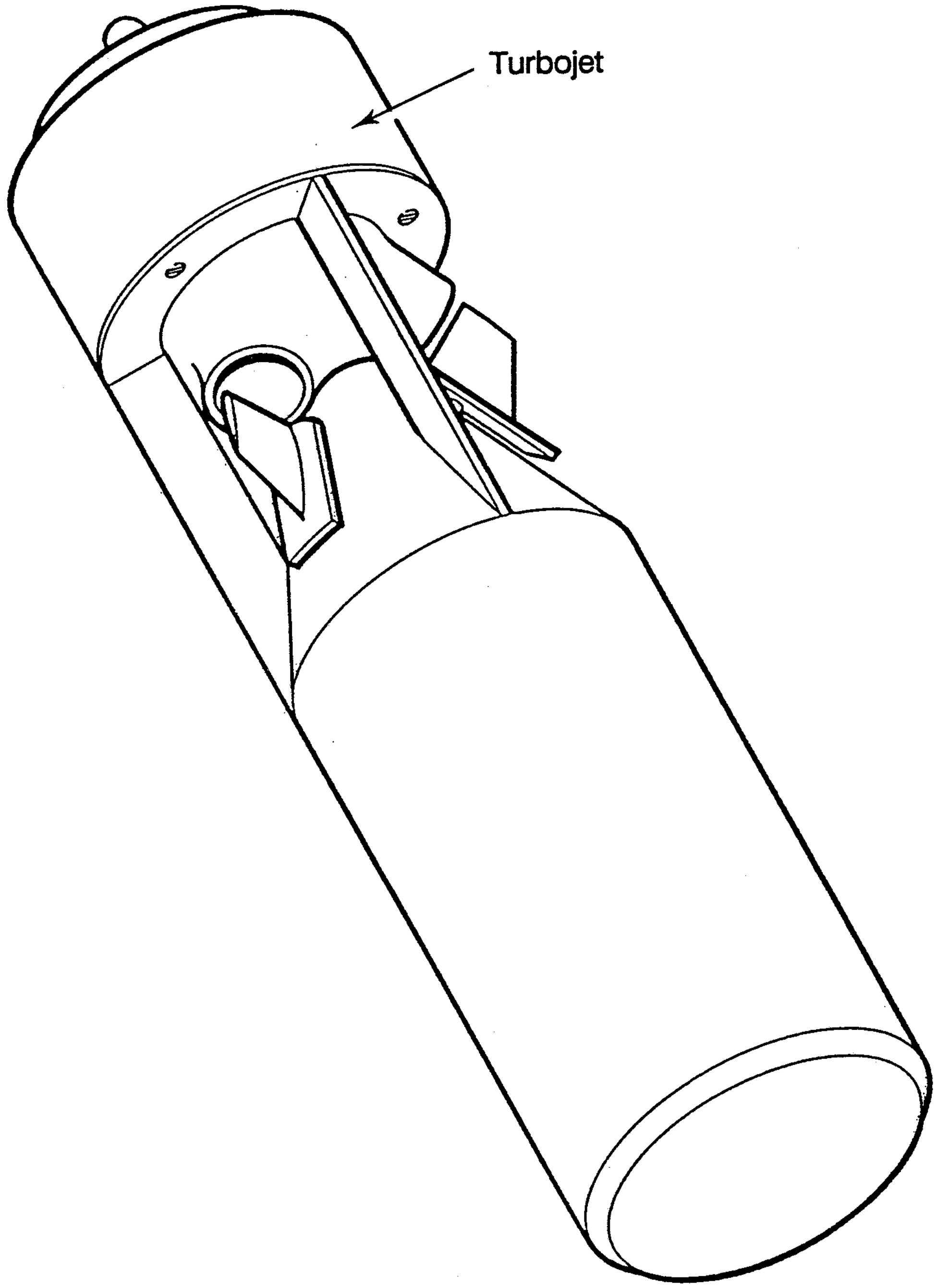


FIGURE 8. POSSIBLE CONFIGURATION OF DECOY WITH TURBOJET MOUNTED ON THE TOP

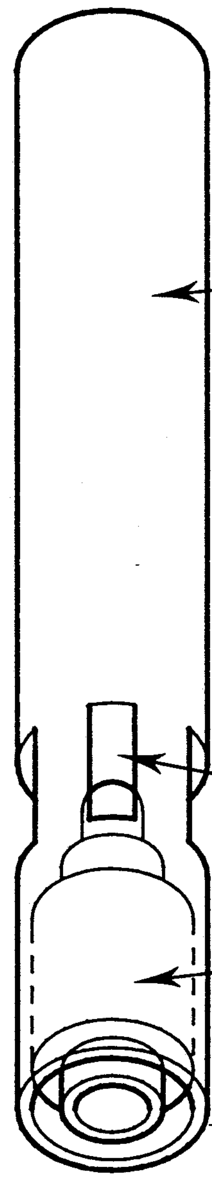


FIGURE 9. POSSIBLE CONFIGURATION OF DECOY WITH TURBOJET MOUNTED ON THE BOTTOM

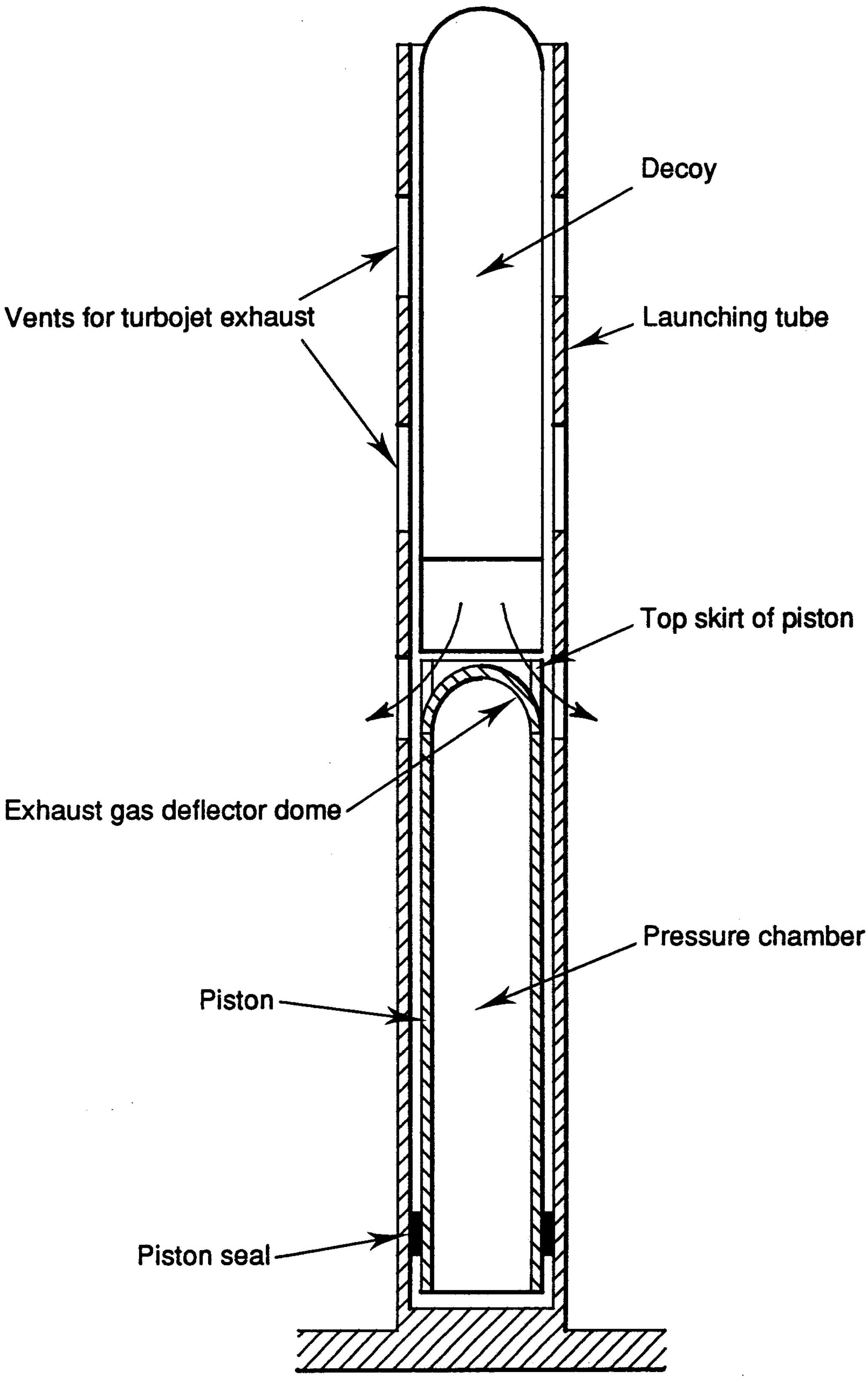


FIGURE 10. SCHEMATIC DETAILS OF LAUNCHER AND PISTON THAT MAY BE NECESSARY TO LAUNCH A DECOY WITH THE ENGINE MOUNTED ON THE BOTTOM

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