Development of T-100 Multipurpose Small Power Unit

JAMES C. NAPIER
Program Manager, Technology Programs
Sundstrand Power Systems
San Diego, CA 92122

ABSTRACT

The T-100 Multipurpose Small Power Unit (MPSPU) is a small gas turbine power unit technology demonstrator. Funding has been provided by the U.S. Army for development and test demonstration of this unit. The T-100 integrates emerging component technologies into a single power unit. The technology is targeted for use in airborne, vehicular, and ground auxiliary power applications. Three power levels will be demonstrated with a family of engines derived from the baseline 50-horsepower (HP) unit and include a modified 75-HP unit and two advanced technology versions of the Uprated 100-HP unit.

The T-100 MPSPU program approach was to develop advanced component concepts with analyses and rig tests to determine total system performance in the MPSPU power units. The results of this process are summarized here. Component rig tests included the inlet protection system, compressor stage, combustor, and turbine stage. These rig tests demonstrated advances in component capabilities for small turbomachinery. Power unit testing has demonstrated achievable levels in specific fuel consumption (SFC) and overall performance for a gas turbine power unit in this class.

INTRODUCTION

The T-100 Multipurpose Small Power Unit (MPSPU) was developed by Sundstrand Power Systems under contract to the U.S. Army Aviation Applied Technology Directorate (References 1 and 2). The T-100 is a small gas turbine engine with power capability from 50 to 100 shaft horsepower (SHP). The program intent is to use the T-100 as a technology demonstrator for the latest small gas turbine turbomachinery component technologies. The MPSPU program has provided the basis for an improved generation of small gas turbine engines, which have a great potential for improvement, since significant funding has not previously been applied to developing this class of turbomachinery compared to larger turbine engines.

The advancements brought about by this program will apply to future Army requirements for airborne, mobile vehicle and ground power applications. Advances include lower specific fuel consumption, improved durability, more self diagnostics capability, better reliability and maintainability, and reduced initial and life cycle costs. The concept of deriving from a baseline unit a family of power units with variable power capability with minimal change was also shown.

The T-100 MPSPU power unit consisting of power module, gear reduction drive and accessories is shown in Figure 1.

Fig. 1. T-100 MPSPU Multipurpose Small Power Unit

The T-100 MPSPU is capable of change in maximum power rating from 50 SHP to 75 SHP at sea level standard day with only a change in turbine nozzle area. Further modification to the hot section with advanced-ceramic or all metallic component designs extends power capability to 100 SHP (Reference 3). Specific fuel consumption...
consumption (SFC) is targeted at 0.75 lb/HP·hr for the 50 SHP point, with improvements expected at the higher power levels since power increases are achieved by increasing the turbine inlet temperature (TIT). These SFC levels compared to other gas turbines in Figure 2 represent a significant advancement over previous turbines in this very low power class. Since SFC is improved primarily through higher component efficiencies and increased pressure ratio, significant technological advances were required to overcome the negative effects of small physical size that in the past have caused higher relative seal and blade leakages in addition to the negative downscaling effects on component efficiencies.

The T-100 MPSPU program includes advanced development of baseline (50 Hp), modified (75 Hp) and uprated (100 Hp) units. This program showed feasibility of the T-100 MPSPU small power unit family concept. Program goals and specific Sundstrand goals are as follows:

- Demonstrate significant performance improvements over existing power units in the 50 SHP (37.3 kilowatt) class.
- The T-100 MPSPU design goal is to provide an SFC of 0.750 lb/HP·hr (0.456 Kg/kW·hr) at the 50 SHP design point.
- Validate the concept of deriving a family of power units from a baseline T-100 MPSPU with design provisions to increase the continuous power rating with minimum changes in configuration and hardware.
- The T-100 MPSPU will provide 75 SHP with only one component change within the power module and with an advanced hot end component version (Ref.3) 100 SHP can be achieved with only three component changes.
- Provide reliability and durability improvements over existing power units.
- The T-100 MPSPU baseline and modified units are designed for mean time between removals (MTBR) of 3000 hours minimum, a design life of 6500 hours and a low-cycle fatigue (LCF) life of over 19,000 cycles.
- Show by analysis a reduced design-to-unit production cost (DTUPC) compared with existing power units. The goal for the T-100 MPSPU is a factory cost of $15,700 (1986 dollars) for the 1000th power module with a production rate of 150 per month for twelve years.

An extensive level of analytical and component rig development work was completed during the design phase. Rig testing of an inlet protection system, compressor stage, combustor and turbine stage have been completed. These component tests are discussed in this paper. The T-100 MPSPU development program is now in the integrated power unit test phase. Initial power unit test results are also discussed herein.

POWER MODULE DESIGN

The T-100 MPSPU family of engines result from a “clean sheet of paper” design approach utilizing latest proven component advances integrated into a single power unit. The power module includes:

Fig. 2. SMALL ENGINE COMPARATIVE PERFORMANCE (Ref. 1)
- An integral but removable low profile inlet protection system, with simple bleed-ejector driven scavenge flow.
- A high efficiency, high pressure ratio single stage centrifugal compressor section with pipe diffuser.
- A compact annular tangential swirl combustor.
- An improved high efficiency durable single stage radial turbine.
- A single shaft overhung rotor assembly with pre-loaded angular contact ball bearings.

A cross section of the power module is shown in Figure 3. A description of the preliminary design optimization process is given in Reference 4.

Aerothermodynamic performance of the T-100 was optimized based upon small single stage centrifugal compressor and radial inflow turbine attainable efficiencies as a function of specific speed and size. The optimization procedure is described in Reference 4 and resulted in the selection of nominal sea level standard performance parameters. Estimated performance for sea level standard day for the baseline and modified ratings is shown in Figure 4.

The gearbox includes a 12,000 RPM main output pad and a variety of spare pad options. An electronic hydromechanical fuel control with integral fuel pump and permanent magnet generator (PMG) allow fully independent self-sustaining operation. The PMG also provides “black start” capability for the power unit, i.e., only hydraulic energy (no electric power) is required to initiate start. The power unit includes interchangeable hydraulic or electric starters. A brassboard full authority electronic digital control is used to control power unit start and operation, provide overspeed and overtemperature protection, life usage indications, fault isolation and self-diagnosis.

The primary purpose of the PMG is to provide independent electric power for the power unit. The PMG speed was selected at 24,000 RPM to give 400 Hz AC power directly (without conditioning). The PMG can provide up to 1.5 KW continuous...
These results show performance after a number of refinements to the basic design were made.

![Graph showing fuel flow vs power for baseline and modified ratings.](image)

**Fig. 4. T-100 ESTIMATED PERFORMANCE, SEA LEVEL STANDARD DAY**

electric power. Its high power density results from the high magnetic flux obtained from Samarium Cobalt magnets.

**INLET PROTECTION SYSTEM**

Air enters power unit through the radial inflow inertial inlet particle separator (Figure 3). The separator operates by aerodynamic inertial separation of particles entrained in the airflow. The inlet airstream negotiates a high “G” turn at the transition from axial to radial flow just prior to entering the compressor. Inertia causes the airborne particles to continue in the axial direction for capture by the scavenge collector system around the inlet housing. Proper aerodynamic design minimizes losses to the inlet flow dynamic head and results in less than 1.5% inlet depression, which is included in overall power unit performance.

Rig test of the inlet protection system was accomplished with a full scale prototype. Airflow was provided by a facility driven ejector system, and scavenge ejector flow was provided by an external air supply. Results of the rig tests are shown in Figure 5.

![Graph showing separation efficiency vs scavange flow for C-spec sand and AC coarse sand.](image)

**Fig. 5. INLET PROTECTION SYSTEM PERFORMANCE**

The net separation efficiencies are shown in Figure 5 for C-spec (Mil-E-5007 C) sand with mean particle size of about 200 microns, and AC coarse sand with mean particle size of about 32 microns. The effect of varying scavenge flow and the scavenge flow generated from compressor discharge flow are shown.

This curve illustrates that maximum separation of C-spec sand occurs with about 10% scavenge flow which can be generated with 1.7% of compressor discharge flow driving the scavenge ejector. Separation efficiency of over 94% was demonstrated in rig tests. Separation efficiency increased with increasing scavenge flow with AC coarse sand and is about 75% at 10% scavenge flow. Separation of the C-spec sand was assigned higher priority in development of the separator since these larger particles cause much more erosion per ingested weight than AC coarse sand.

**CENTRIFUGAL COMPRESSOR**

A major technical risk item in this program was considered to be the aerodynamic performance of the small high pressure ratio centrifugal compressor stage. A good basis for the compressor stage behavior was available from a recently tested compressor with a significantly larger physical size than the T-100 MPSPU. At the T-100 MPSPU size of roughly 4 inches (102 mm), it was predicted that design point adiabatic efficiency could be achieved at 6:1 pressure ratio. To verify this prediction, this compressor impeller was scaled down to the T-100 MPSPU size; the diffuser was reshaped to match the 6:1 pressure ratio with a simpler configuration. In a high speed turbodrive facility the prototype test compressor stage demonstrated 5% adiabatic efficiency margin at 6:1 pressure ratio within 3% of the design speed, effectively verifying the scaling projections. Surge margin in these
tests exceeded 8%. A more complete performance discussion of the prototype compressor is provided in Reference 4.

Following successful testing of the prototype compressor, minor design revisions to the impeller eye were made to permit installation in the MPSPU powerhead. The final engine design compressor was retested in the turbodrive rig complete with a simulated integral particle separator inlet at speeds and pressures inclusive of the T–100 MPSPU design point.

Results from the turbodrive rig test of the final engine design compressor are shown in Figure 6. The 78% design point efficiency was exceeded by 0.5%, and the design pressure ratio was exceeded by approximately 1%.

![Figure 6. T–100 MPSPU COMPRESSOR STAGE PERFORMANCE IN TURBO DRIVE RIG TEST](https://example.com/figure6)

ANNULAR COMBUSTOR

A principal problem of very small gas turbine annular combustors is fuel injection. To minimize reliability problems of small orifices, small scale viscosity effects, and small combustor dimensions that increase the need for small fuel droplets, fuel injector design dominates the approach combustor design. With an MPSPU ignition fuel flow of about 4 lb/hr at 15,000 feet altitude and 10 percent engine speed, with a combustor pressure drop of 0.8–inch water, the fuel injection design problems are formidable, especially using a viscous non-volatile diesel oil in cold Arctic conditions.

The injector design problem is simplified considerably with a can combustor. The single fuel injector of the can combustor provides a reasonably practical means of fuel atomization at these very low fuel flows. An annular combustor would require ten or more fuel injectors using conventional design techniques. However, with a solution to the multi–point fuel injection problem, an annular combustor offers many advantages over a can combustor. These include:

- Minimal space, weight and cost
- Maximum volume
- Minimal pressure loss
- Superior outlet temperature distribution
- Lower wall temperatures
- Higher airflow uprating capability
- More symmetrical loads
- Better hot end accessibility for inspection
- Improved outlet radial temperature gradient control
- Higher turbine temperature growth capability

With a conventional annular combustor, once the dome height and diameter are established, little margin exists for reducing the number of fuel injectors. In the T–100 ‘Sidewinder’ annular combustor, a trade–off between combustor length and the number of fuel injectors was made possible by injecting the fuel in a unique tangential manner. The jets of fuel and flame were visually observed in atmospheric rig testing to extend over 80 percent of the combustor circumference. The evaporation path length was thereby significantly increased and this extended fuel evaporation zone provides exceptional fuel evaporation despite poor fuel atomization. In the T–100 MPSPU combustor rig, using diesel fuel at 10 percent engine speed and with 0.8–inch water combustor pressure drop, stable combustion was achieved without any observable fuel atomization. The exceptional pattern factor achieved in pressure rig test of the combustor is shown in Figure 7. This capability of thorough circumferential mixing of fuel and air was demonstrated in the MPSPU combustor rig by plugging of two of the four diametrically opposed injectors and still achieving the pattern factor goal.

A Fourier analysis of the temperature distribution suggests that reducing the number of fuel injectors by one–half may be a feasible future goal for the T–100 MPSPU. This injector demonstration also simulated a very high altitude start, where manifold head effects caused all the fuel to go through the bottom fuel injector. Air blast injection of fuel provided exceptional flame performance and an ultra low pattern factor at design conditions with minimum fuel injectors. The concept seems an attractive means of improving on current practice for both large and small combustors, while avoiding the complexities, cost and reliability problems of more conventional fuel injectors.

RADIAL INFLOW TURBINE

Key parameters upon which turbine efficiency depends are tip speed, exit kinetic energy (Mach number) and tip clearance. Figure 8 shows how the MPSPU turbine design compares with universal charts for small radial inflow turbines. As shown, the chosen configuration is close to the maximum efficiency island.

Turbine rig testing of the T–100 single–stage radial inflow was conducted in a high speed turbodrive facility of the type described in Reference 6, where the turbine output was absorbed by a
**Mathematical Expressions:**

\[ \text{PF} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{mean}} - T_2} = 0.087 \]

**Textual Content:**

- 38 circumferential T/C's
- \#2 diesel oil
- 6:1 pressure ratio
- Circumferential 1/C's

**Diagrams and Tables:**

| Harmonic | Amplitude | Harmonic | Amplitude | Harmonic | Amplitude |
|----------|-----------|----------|-----------|----------|-----------|
| 1        | 30.609    | 8        | 15.295    | 15       | 3.837     |
| 2        | 17.159    | 9        | 38.514    | 16       | 25.257    |
| 3        | 17.202    | 10       | 16.336    | 17       | 10.700    |
| 4        | 7.501     | 11       | 10.947    | 18       | 19.337    |
| 5        | 5.338     | 12       | 7.614     | 19       | 0.158     |
| 6        | 9.658     | 13       | 6.261     |          |           |
| 7        | 13.853    | 14       | 10.937    |          |           |
| 14       | 10.937    |          |           |          |           |
| 15       | 3.837     |          |           |          |           |
| 16       | 25.257    |          |           |          |           |
| 17       | 10.700    |          |           |          |           |
| 18       | 19.337    |          |           |          |           |
| 19       | 0.158     |          |           |          |           |

**Figures:**

**Fig. 7. T-100 MPSPU Combustor Pattern Factor at 1500 °F TIT**

**Fig. 8. T-100 MPSPU Turbine Stage Design - Point vs. Attainable Efficiency Levels**

Single-stage centrifugal compressor with inlet throttling. Warm pressurized facility air at approximately 500°F was supplied to the simulated combustor and expanded through the nozzle and rotor to the exhaust. An exhaust ejector was used for turbine calibration of the higher pressure ratios.

The turbine test rig was used to complete tests of three turbine geometry configurations involving clearance changes, nozzle throat area variations, and exducer flow traversing. Results for the optimized geometry are shown in Figure 9. Total to static efficiency was approximately one half percentage point short of the goal.

Detailed analysis of the turbine geometry showed that low cycle fatigue life of the design is over 19,000 cycles for the baseline MPSPU rating. Analysis and holographic vibration testing verifies that no coincident blade or other turbine wheel resonances interfere with operating speeds which could reduce high cycle fatigue life of the design.

Future development of the T-100 turbine component is progressing towards a high temperature advanced alloy/cooled hot section and an alternate design version with ceramic turbine wheel and nozzle. More detail on these variants is given in...
The inlet protection system provides improved durability where airborne solids can be entrained in inlet air. This is an important factor in helicopter installations where wash from the rotor can entrain sand and dust into inlet air. Lack of provision for separation of these particles can severely limit the life of the compressor stage and turbine nozzle.

Other reliability improvements are realized by the dual element speed pick-up and the dual element exhaust gas temperature (EGT) thermocouples. Each of these sensors is linked to the control system to provide fault warning, but the power unit will continue to operate after failure of one of two elements.

The overall T-100 reliability expected for the power module is further enhanced by design simplicity and low parts count.

INTEGRATED COMPONENT PERFORMANCE

The integrated power unit tests provide the means to demonstrate the performance of individual components as assembled into the turbine power module. The test program for the power unit includes 580 hours of running time. Development tests are in progress to refine the design to meet performance goals for each of the four configurations of the T-100 power module which include: baseline (50 SHP); modified (75 SHP); and two uprated (100 SHP) configurations (ceramic and all metallic with tri-alloy turbine wheel and cooled nozzle).

The major program goals for test of these power module included:

- baseline unit
  - SFC of 0.75 lb/HP-hr at 50 SHP with turbine rotor inlet temperature (TRIT) less than 1490°F
  - 10 hour sand ingestion test with less than 10% performance loss with 265 milligrams per cubic meter concentration
  - 300 starts with electric starter/300 starts with hydraulic starter
  - cold fuel start demonstration
- modified unit
  - 75 SHP with TRIT less than 1840°F
- uprated units
  - 100 SHP

The test program also includes tests and demonstrations for durability, contingency power, noise, exhaust emissions, and maintainability.

Specific fuel consumption of 0.75 lb/SHP-hr is most difficult to meet at the baseline 50 SHP rating since only a modest 1490°F TRIT is required to achieve this power for this unit. A summary of performance cycle model results are compared below with 1)
component performance design goals 2) component performance achieved in rig tests and 3) component performance achieved to date in the integrated baseline power unit.

![Component Performance Table]

- **Power (SHP)**: Design Goal = 50, Rig Test = 50, Integrated into Power Unit = 51.5
- **Speed (RPM)**: 106,588
- **Net inlet flow (lb/sec)**: 0.732, 0.740, 0.780
- **TRIT (°F)**: 1442, 1442, 1490
- **SFC (lb/SHP-hr)**: 0.724, 0.731, 0.832
- **IPS inlet loss (%)**: 1.5, 1.5, 1.5
- **IPS Bleed (%)**: 1.0, 1.0, 1.7
- **Pressure Ratio t-s**: 6.05, 6.10, 6.34
- **Compressor Effic. t-s**: 78.0, 78.5, 78.7
- **Compressor press loss (%)**: 4.0, 4.0, 4.0
- **Turbine Effic. t-s (%)**: 86.9, 86.4, 82.6
- **Leakage (%)**: 1.0, 1.0, 1.0

Integrated power unit performance is less than the calculated sum of individual rig test performance since turbine stage efficiency is reduced. Plans to improve turbine stage performance include reduced clearances facilitated by use of abrasives on the turbine wheel and abradable material on the seal plate heat shield. The turbine nozzle surface finish will also be improved.

Gearbox losses are more than initially assumed and account for an increase in integrated unit SFC of 0.02 lb/SHP-hr.

More than 228 hours of engine testing have been completed. Over 50 hours of durability demonstration have been conducted on the 50 hp unit. Gaseous emissions, smoke and noise tests have also been completed.

Demonstration of the modified 75 SHP unit has been completed with TRIT of 1839°F. Hot end components show very good durability after continuous operation at this TRIT. These results illustrate the benefit of the very low pattern factor possible with the 'Sidewinder' combustor.

Over 400 electric starts and 147 hydraulic starts have been achieved. One electric starter failure occurred after 352 starts on that particular unit.

Integrated component performance has verified rig test results for the compressor. The 'sidewinder' combustor has demonstrated its effectiveness in extending hot section durability due to low inherent pattern factor. Confirmation of rig test results in integrated component performance engine test of the inlet particle separator and turbine stage have not been completed to date.

**ACKNOWLEDGEMENTS**

The author thanks the U. S. ARMY Aviation Applied Technology Directorate and his colleagues at Sundstrand Power Systems for permission to publish the results of the T-100 MPSPU program. The efforts of technical contributors at Sundstrand Power Systems and Pratt & Whitney are recognized.

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