

Solar-Thermal Engine Testing

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Abstract. A solar-thermal engine serves as a high-temperature solar-radiation absorber, heat exchanger, and rocket nozzle, collecting concentrated solar radiation into an absorber cavity and transferring this energy to a propellant as heat. Propellant gas can be heated to temperatures approaching 4,500 °F and expanded in a rocket nozzle, creating low thrust with a high specific impulse (I_{sp}). The Shooting Star Experiment (SSE) solar-thermal engine is made of 100 percent chemically vapor deposited (CVD) rhenium. The engine "module" consists of an engine assembly, propellant feedline, engine support structure, thermal insulation, and instrumentation. Engine thermal performance tests consist of a series of high-temperature thermal cycles intended to characterize the propulsive performance of the engines and the thermal effectiveness of the engine support structure and insulation system. A silicone-carbide electrical resistance heater, placed inside the inner shell, substitutes for solar radiation and heats the engine. Although the preferred propellant is hydrogen, the propellant used in these tests is gaseous nitrogen. Because rhenium oxidizes at elevated temperatures, the tests are performed in a vacuum chamber. Test data will include transient and steady state temperatures on selected engine surfaces, propellant pressures and flow rates, and engine thrust levels. The engine propellant-feed system is designed to supply GN_2 to the engine at a constant inlet pressure of 60 psia, producing a near-constant thrust of 1.0 lb. Gaseous hydrogen will be used in subsequent tests. The propellant flow rate decreases with increasing propellant temperature, while maintaining constant thrust, increasing engine I_{sp} . In conjunction with analytical models of the heat exchanger, the temperature data will provide insight into the effectiveness of the insulation system, the structural support system, and the overall engine performance. These tests also provide experience on operational aspects of the engine and associated subsystems, and will include independent variation of both steady state heat-exchanger temperature prior to thrust operation and nitrogen inlet pressure (flow rate) during thrust operation. Although the Shooting Star engines were designed as thermal-storage engines to accommodate mission parameters, they are fully capable of operating as scalable, direct-gain engines. Tests are conducted in both operational modes. Engine thrust and propellant flow rate will be measured and thereby I_{sp} . The objective of these tests is to investigate the effectiveness of the solar engine as a heat exchanger and a rocket. Of particular interest is the effectiveness of the support structure as a thermal insulator, the integrity of both the insulation system and the insulation containment system, the overall temperature distribution throughout the engine module, and the thermal power required to sustain steady state fluid temperatures at various flow rates.

BACKGROUND

A solar-thermal propulsion upper stage engine uses concentrated solar energy to heat propellant to very high temperatures and exhausts the propellant through a nozzle to provide thrust. It combines relatively high I_{sp} (upwards to 1,000 s) with moderate thrust levels (1–100 lb) that result in up-to-a-factor-of-two increase in payload capability with commercially acceptable orbit transfer times. The solar-thermal engine serves as a high-temperature solar-radiation receiver, heat exchanger, and thrust nozzle. There are two basic modes of operation: Direct gain and thermal storage, both of which have thermodynamic and operational advantages and disadvantages. The direct-gain approach simultaneously collects and transfers energy to the propellant gas and produces thrust. The thermal-storage concept sequentially collects energy, stores it in a thermal-storage heat exchanger, and then thrusts. Marshall Space Flight Center's (MSFC) Shooting Star Experiment (SSE), restructured in 1998 as a technology development program, has produced valuable hardware and advances in virtually all the critical technology areas relevant to solar propulsion. Two 100-percent rhenium engines have been fabricated in addition to several types of concentrators. One-g mission simulations of full-scale cryogenic-fluid management systems have been successfully tested with subcritical hydrogen.

Although the SSE engines were designed as thermal-storage engines to accommodate mission parameters, they are fully capable of operating as scalable, direct-gain engines. These engines are capable of long life, high-temperature operation (up to 4,500 °F), and are mounted in a designed-for-flight insulating support structure, allowing them to withstand the dynamic launch environment as well as high operating temperatures in space.

Engine Design Parameters

The solar-thermal engines were intended to support a flight demonstration of a small-scale solar thermal in-space transfer stage. The engine design was based on a 6-ft-diameter on-axis, inflatable polyimide fresnel lenses concentrator. Because of manufacturing limitations on the diameter of the lenses, and thus the available thermal power, the engines were to be of the thermal-storage type in order to produce a measurable level of thrust. The aggressive philosophy of the Shooting Star program forced key engine design parameters (i.e., propellant selection, spot power, spot size, thrust level) decisions to be made while other components, such as the concentrator, flight support platform, and even the launch vehicle were still undefined. Every effort was made to maintain a reasonable match between other components and subsystems and engine performance. Tables 1 and 2 show the engine performance goals and reference configuration, respectively.

TABLE 1. Engine Performance Goals (Thermal Storage Mode).

Operating temperature (°F)	3,000
Engine inlet pressure (psi)	60
Prop. (GN ₂) flow rate (lb/h)	20–60
Thrust @ 60 lb/h (lb)	≈1
Thrust Duration (s)	30
I_{sp} @ 3,000 °F (s)	N2: 200 H2: 800
I_{sp} @ 4,000 °F (s)	N2: 230 H2: 860
Weight (lb)	≈20

TABLE 2. Reference Configuration.

Spot diameter (in)	1.5
Spot power (W)	1,500
Aperture diameter (in)	1.7
Absorber cavity length/diameter ratio	4
Nozzle	
Throat diameter (in)	0.128
Area ratio	245:1

Engine Description

In total, three solar engines were built for the SSE program. One Inconel 718 engine simulator and two 100-percent rhenium engines. The Inconel engine was originally intended as a mass simulator to be used in vibration tests of various engine support structures. It was ultimately converted to a low-temperature (2,000 °F) thermal simulator using a carbon foam heat exchanger and instrumented to thermally map the propellant flow field through the foam. The two all-rhenium engines were fabricated using CVD (Williams, 1999) and consist of an inner absorber cavity, heat exchanger, outer shell and nozzle, engine support structure, and propellant inlet tube. The inner absorber cavity, outer shell/nozzle, and the 0.25-in-diameter propellant inlet tube are made of 100-percent dense CVD rhenium. The heat exchanger and primary-engine support structure are 10 percent and 20 percent dense CVD rhenium foam, respectively. The components are shown in figure 1. The two engines differ only in the configuration of the foam support structure. Both engines are shown in figure 2. Tests were performed on the “wagon wheel” configuration only.

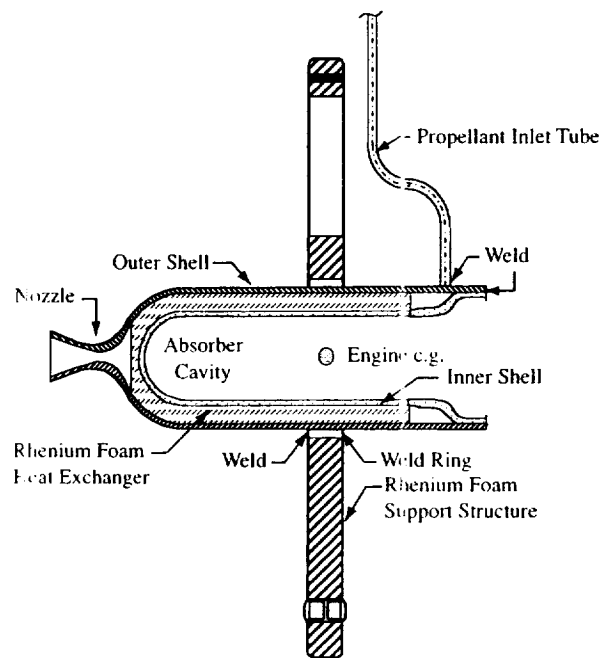


FIGURE 1. Engine Schematic (Wagon Wheel).

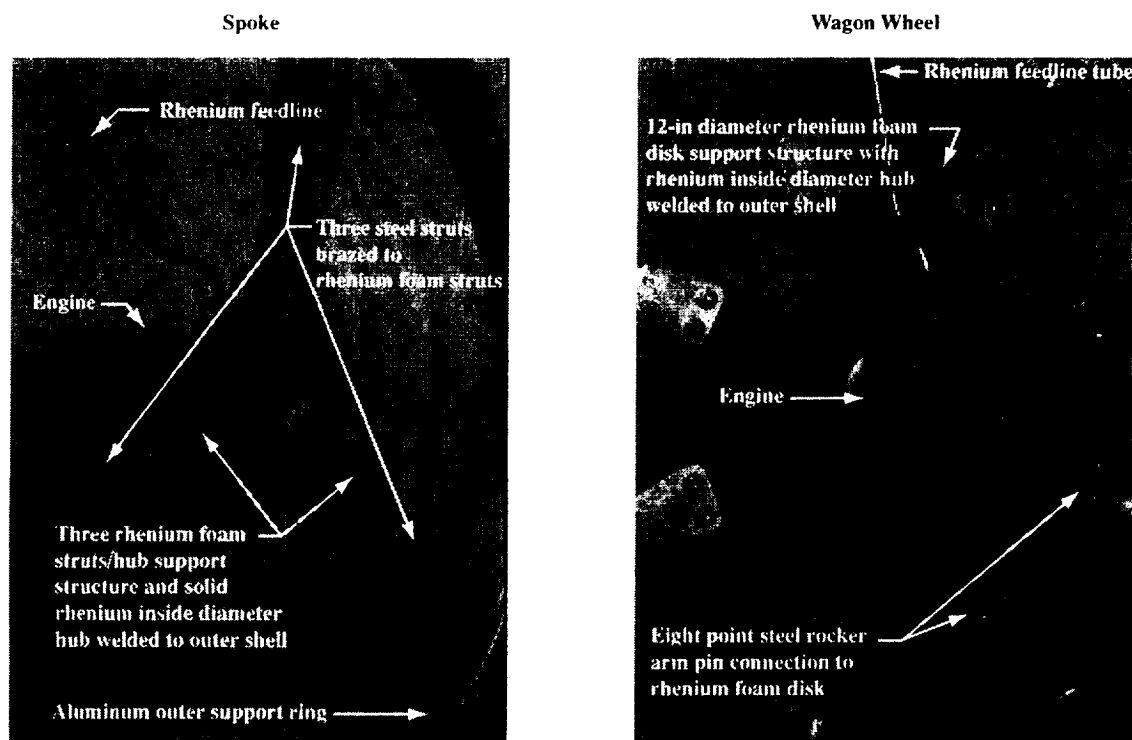


FIGURE 2. Shooting Star Solar-Thermal Engines.

Engine

The all-rhenium engines consist of an inner-shell absorber cavity, thermal-storage heat exchanger, outer shell, and nozzle. The absorber cavity is a 1.7-inch-inside diameter, 6-in-long cylinder, closed on one end. The thermal-storage heat exchanger material is fabricated from reticulated carbon foam coated with rhenium by CVD. This material configuration provides thermal-energy storage mass and a high surface area to volume ratio for heat transfer. A foam porosity of 45 pores/in is expected to produce uniform flow through the heat exchanger with pressure drops <5 psi. The engine outer shell is also CVD rhenium and provides the closure for the propellant flow path, structural support attachments, nozzle, feedline, and instrumentation interfaces. The feedline is a 0.25-inch-outside diameter rhenium tube \approx 10-in long, bent to absorb thermal expansion, and is connected to the supply system with a standard AN fitting. The feed system is designed to supply GN₂ to the engine at a constant inlet pressure of 60 psi, producing a near constant thrust of 1.0 lb. The propellant flow rate decreases with increasing engine temperature from \approx 60 lb/h to 20 lb/h, which increases engine I_{sp} .

Engine Support Structure

The two engines and their support structures as shown in figure 2 are supported by 20-percent dense rhenium foam, similar to the heat exchanger foam. The rhenium foam spokes are brazed to stainless steel struts. The struts attach to the outer support ring by a bolt and Belleville washers that allow the spokes and struts to expand due to the thermal environment.

The wagon wheel support structure is a 12-in-diameter rhenium foam disk 0.7-in thick. The disk has a solid rhenium weld ring at the center hub of the disk. The engine assembly is welded to the foam disk at the center of gravity (c.g.) of the assembly. The wagon wheel/engine assembly is attached to the outer support ring by eight rocker arm/clevis attachments.

Instrumentation

Instrumentation consists of type C and K thermocouples, pressure sensors, flow meter, and strain gauges. Type C thermocouples were routed along the engine outer shell inside of ceramic tubes and were attached by molybdenum wire and high-temperature graphite adhesive. Figure 3 shows the thermocouple attachment scheme.

Thermal Control System

The thermal control system for the wagon wheel configuration consists of graphite-felt insulation wrapped around the engine and tied with molybdenum wire. There is no flightlike thermal insulation design for the wagon wheel. It is insulated as simply as possible but sufficiently to allow the engine to be heated to the desired temperature. The graphite felt insulation system is shown in figure 4.



FIGURE 3. Thermocouple Attachment Scheme.

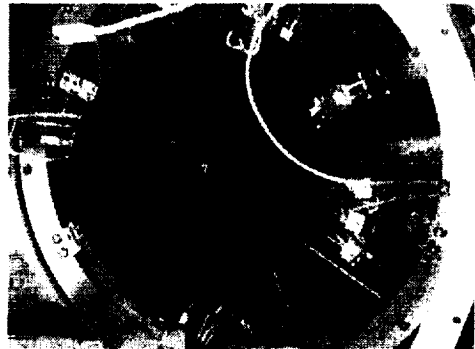


FIGURE 4. Wagon Wheel Graphite Insulation System.

Material Considerations

A limited amount of material and component testing supported the engine development. Ceramic tubes were instrumented and tested at the solar facility at the University of Alabama in Huntsville to help determine the optimum cavity length-to-diameter ratio. Although rhenium is expensive to fabricate and machine, it was selected as the engine material because it has a high melting point (5,400 °F), high strength at elevated temperatures, is inert to hot hydrogen, is weldable, and significantly, has no ductile-to-brittle transition temperature, allowing innumerable thermal cycles. Tantalum sheaths and ceramic tubes were used as thermocouple insulators, tungsten and molybdenum wire for some attachments, and graphite felt as engine thermal insulation. Samples of various combinations of these materials were tested for metallurgical and chemical reactions. Samples in contact with each other were heated in vacuum to $\approx 3,000$ °F. There was no evidence of extensive attack on the rhenium material except for minute carbide formation.

TEST RESULTS

Parametric variations on engine temperature, propellant inlet pressure, and run duration were conducted. Nine tests were performed on the Inconel engine simulator and 23 tests were conducted on the rhenium wagon wheel. The engine performed largely as predicted. Thrust as a function of inlet pressure was within 20 percent of predicted values, reasonably accounted for by connections to the engine module; i.e., plumbing and instrumentation lines. A schematic of the wagon wheel test configuration is shown in figure 5, and figure 6 is a photograph of the test article installed in the 15-ft vacuum chamber at Test Stand 300 at MSFC.

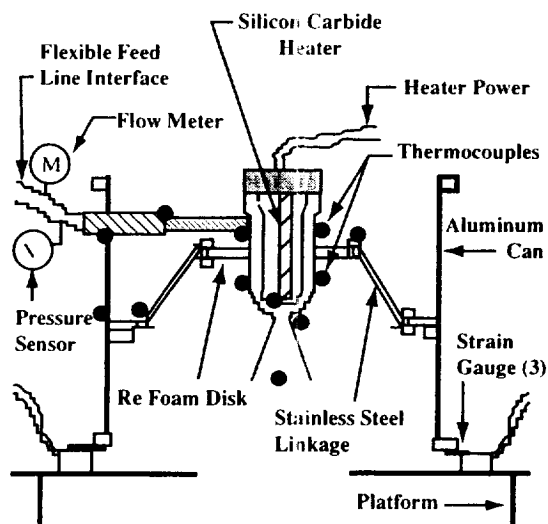


FIGURE 5. Wagon Wheel Test Configuration.

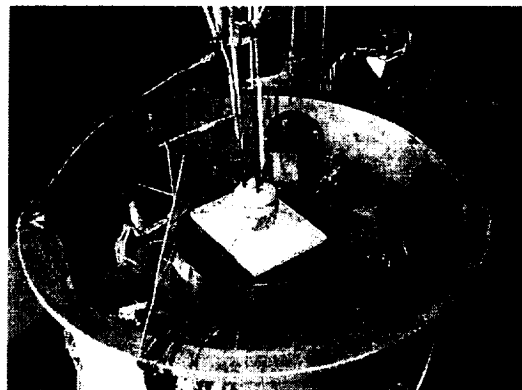


FIGURE 6. Test Article in 15-ft Vacuum Chamber.

Thrust Measurement

A simple thrust measuring apparatus was devised using cantilevered beams and strain gauges. The engine module was placed on the three beams so as to thrust in the vertical down direction. The strain gauges measured the difference in weight of the module when thrusting and not thrusting. The assembled engine module test article weighted ≈ 60 lb. Although this simple approach proved reasonably accurate and reliable, there were inherent errors in the device. The propellant tube was connected with a 0.5-in.-flexible hose, eliminating a significant amount of constraint on the module, but not all. There was an electrical power line and ≈ 35 thermocouple connections. These connections ultimately affected

the module's center of gravity as well as the measured thrust level. The thrust is, therefore, higher than the measured values. Theoretical I_{sp} values suggest the thrust is actually about 20 percent higher than measured. The cantilevered strain gauges were calibrated using hanging weights of 5, 10, and 20 lb. The center of gravity of the engine module, prior to final integration into the vacuum chamber, was determined and adjusted to coincide with the centerline of the nozzle throat. Figure 7 shows measured strain gauge values for an inlet pressure of 91 psia, producing a total measured thrust of 1.7 lb. Figure 8 shows measured thrust as a function of propellant inlet pressure.

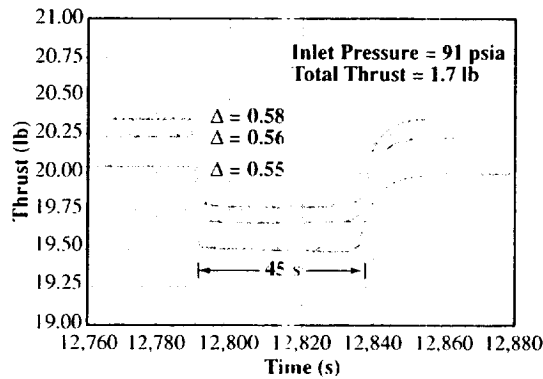


FIGURE 7. Strain Gauge Thrust Measurement.

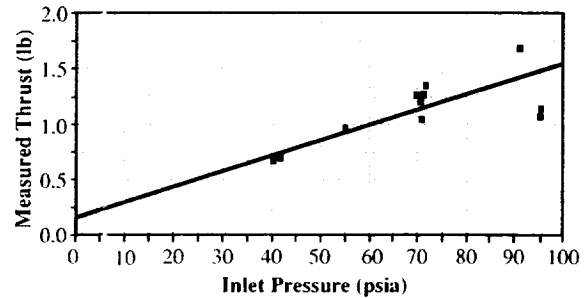


FIGURE 8. Measured Thrust as a Function of Propellant Inlet Pressure.

Temperature Profile

Temperature profiles throughout the engine insulation system proved acceptable to secondary material temperature limits. Figure 9 shows the heat up transient of selected locations on the engine and throughout the support structure and insulation system with no propellant flow. The heat up transient is ≈ 3.6 h from room temperature to a maximum temperature of $\approx 2,750$ °F inside the absorber cavity. Figure 10 shows the maximum steady state temperature at the same locations with a heater power of 1,000 W.

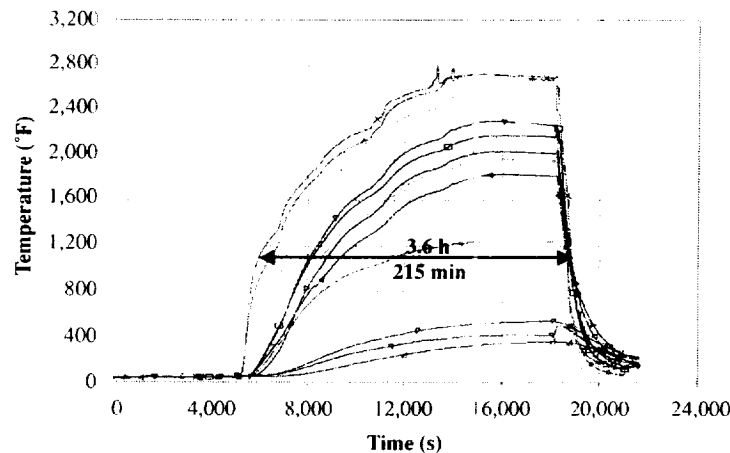


FIGURE 9. Transient Temperature Profile.

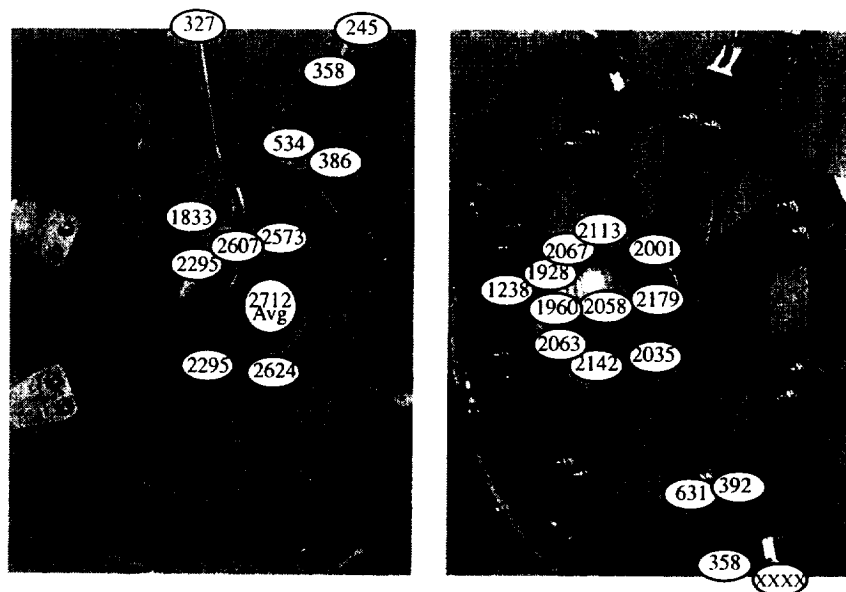


FIGURE 10. Wagon Wheel Thermocouple Locations and Steady State Temperatures (°F) = 1,000 W Heater Power.

Engine Performance

A maximum I_{sp} of 150 s was recorded with nitrogen as the propellant, at an exit temperature of 1,760 °F. This corresponds to an equivalent hydrogen I_{sp} of ≈630 s. Figure 11 shows the I_{sp} as a function of temperature for three different propellant gases, as well as the measured values using nitrogen. The engine-operating principle (constant inlet pressure produces constant thrust over all temperatures, while propellant temperature determines propellant flow rate) was verified and the relevant parameters are shown in figure 12. The drift and slight instability in the thrust data are attributed to the temperature increase of the strain gauges as the engine heats. The maximum engine absorber cavity temperature recorded was 3,100 °F and was limited by the silicon-carbide electrical heater. Analytical comparisons with measured test data are an ongoing effort.

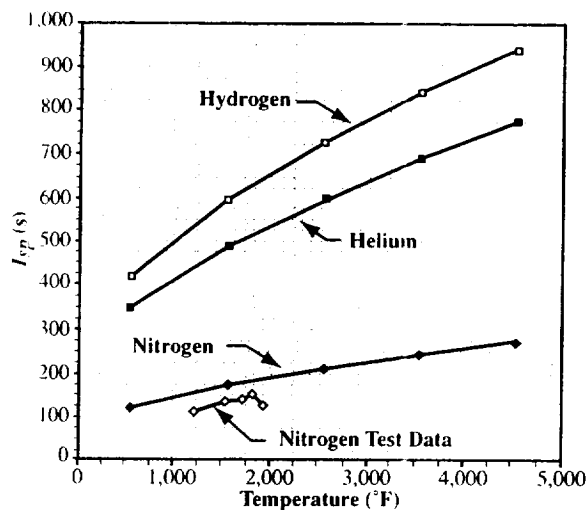


FIGURE 11. I_{sp} Versus Temperature.

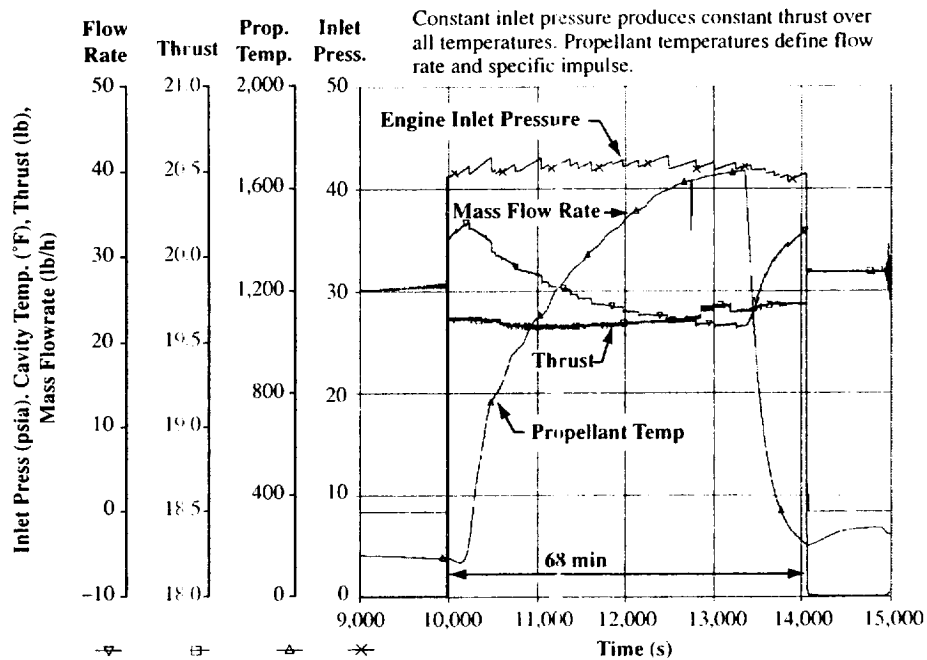


FIGURE 12. Solar-Thermal Engine Operating Principle.

Summary

Comprehensive documentation of the development and testing of these solar-thermal engines is beyond the scope of a single paper. The wagon wheel configuration was the only engine tested. The spoke engine remains pristine. The wagon wheel performed largely as expected and experienced no discernable damage. Both engines are available for high-temperature (>4,000 °F) on-Sun tests using hydrogen as the propellant. Both engines have flightlike support structures and are capable of withstanding dynamic launch loads as well as high temperature on-orbit operation. Pending funding, additional tests will include high-rate thermal cycling and vibration tests. Analytical modeling and correlation with test data are ongoing efforts.

UNIT CONVERSIONS

1 pascal (N/m²) = 1.4504×10^{-4} lb/in²
 1 newton (N) = 0.22481 lb

1 degree kelvin (K) = $\frac{5}{9}$ (°F + 459.67)
 1 meter (m) = 39.37 in = 3.2808 ft

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Williams, B.E., Fortini, A.J., Toffias, R.H., Duffy, A.J., and Tucker, S., "CVD Rhenium Engines for Solar-Thermal Propulsion Systems," in *Procedures for Renewable and Advanced Energy Systems for the 21st Century*, ASME International, New York, 1999.