NASA Contractor Report 187095

Thermal Storage Advanced Thruster System (TSATS) Experimental Program

M. Frank Rose and Michael E. Lisano, II
Auburn University
Auburn, Alabama

April 1991

Prepared for
Lewis Research Center
Under Grant NAG3-1155

NASA
National Aeronautics and
Space Administration

Thermal Storage Advanced Thruster System (TSATS) Experimental Program

M. Frank Rose and Michael E. Lisano, II

Space Power Institute
Auburn University, Alabama

Abstract

The TSATS (Thermal Storage Advanced Thruster System) rocket test stand is completely assembled and operational. The first trial experimental runs of a low-energy TSATS prototype rocket have been made using the test stand. The features of the rocket test stand and the calibration of the associated diagnostics are described and discussed below. Design and construction of the TSATS prototype is then discussed, and experimental objectives, procedures and results are detailed.

Introduction

The basic idea for TSATS came from an investigation of the ability of certain materials to store waste thermal energy associated with SDIO weapons concepts. Materials such as LiH can store roughly 3 MJ/kg in the heat of fusion (~950 K) and much more than that in the "sensible heat" if the temperature swing is allowed to be on the order of 1000 K. Rocket propulsion is simply the process of heating a gas or suitable propellant, to a gaseous phase, and allowing it to expand through a suitable nozzle. In the case of TSATS, the necessary thermal energy is stored in a thermal energy storage material (TES) and is renewable from a number of sources such as isotopes (RTG), solar concentrators or electrical energy during "off peak" hours. Utilizing TES, a simple monopropellant thruster can be built, locally rechargeable, for utility purposes around manned or man-tended space platforms. In essence, TSATS is similar to the nuclear rockets and much of our analysis has tended to follow that technology. In this work, we built a simple test stand to illustrate the concept using "safe gases (He, N) and a safe storage media. It is our intent to extend this work through a grant from the Alabama Space Grant University program.

Experimental

Features of the TSATS Rocket Test Stand

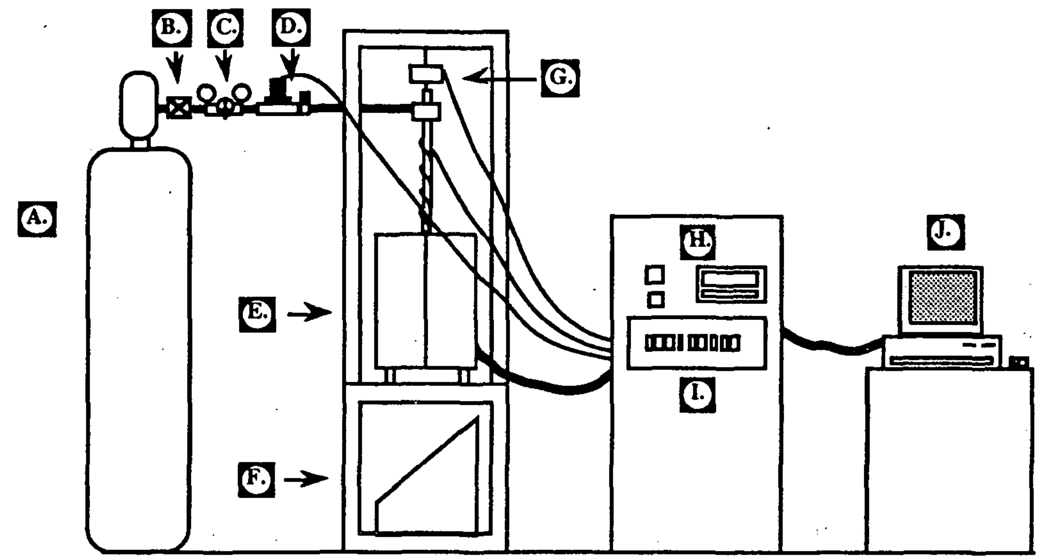
The TSATS rocket test stand (Fig. 1) is an integrated rocket propellant-feed system and thrust stand. A small TSATS rocket, which consists of a thermal storage block, heat exchanger, and nozzle, is suspended vertically in the center of the research furnace by a stainless steel tube that is part of the rocket's propellant-feed ductwork. Propellant (high-pressure helium gas in the first runs) passes through a pressure regulator (6000 psig inlet to 500 psig outlet) and a heated-tube-type electronic mass flow controller (500 psig to 450 psig), then to the TSATS, where it is heated, expanded in a nozzle, and exhausted through the bottom of the furnace. The TSATS is instrumented with:

- eight K-type thermocouples to measure temperatures of the rocket body and exhaust plume,
- a thin-beam load cell, from which the rocket is suspended, to measure rocket thrust, and
- a pressure transducer to measure the approximate stagnation pressure of the propellant entering the rocket.

Other diagnostics which may be implemented as the experimental program proceeds are:

- the SPI Infrared Optical Thermography System,
- additional thermocouples and RTD's, and
- additional pressure measurement at the rocket nozzle exit.

The thermocouples, load cell, and transducer signals were processed and read simultaneously with a National Instruments™ I/O board and LabVIEW® software on a Macintosh IIci computer.



A. High-Pressure Helium Gas (Propellant)
B. Main Cut-Off Valve
C. High-Pressure Regulator (500 PSIG out)
D. High-Throughput Flow Controller
E. Research Furnace, Containing TSATS Rocket
F. Plume Deflector
G. Thin-Beam Load Cell (Thrust Measurement)
H. Furnace Temperature Controller
I. Thermocouple and Strain Gage Signal Conditioning
J. Macintosh IIci with I/O Board and LabVIEW(TM) software

Figure 1: TSATS Experimental Rocket Test Stand

Details of Rocket Test Stand Equipment and Configuration

Referring to Figure 1, the propellant source for the TSATS experimental rocket is a 6,000 psi bottle of helium gas. The propellant feed mechanism for the rocket is pressure driven (as opposed to pumps). Pressure feeding of the propellant was selected for its ease of implementation and minimal need for maintenance. A high-pressure bottle of helium was selected over low-pressure bottles because high flow rates (on the order of 500 SLPM) of helium were required to develop approximately 0.50 lbs of thrust with the rocket in its final design form. The main cut-on/cut-off valve for the rocket is located on top of the high-pressure helium bottle.

The pressure regulator for the TSATS experimental rocket is a single-stage, high-flow pressure regulator. The regulator inlet pressure was required to be a maximum of 6,000 psig, and the regulator outlet pressure was required to be a maximum of 500 psia. The inlet pressure gauge of the regulator had a range of 0-10,000 psig, and the outlet pressure gauge had a range of 0-4,000 psig (marked in 250 psi increments). The regulator, fitted for helium gas, was attached directly to the high-pressure helium gas bottle described in the section above.

The mass flow controller for the TSATS experimental rocket is a high-throughput (750 SLM nitrogen) electronic mass flow controller. The flow controller consists of two primary sections: (1) an inlet, with a thermal-tube-type mass flowmeter that measures the flow rate (based on the heat convection rate of a small shunt flow), and (2) an outlet, with a solenoid valve that is controlled by a signal emitted from the mass flowmeter.

The inlet portion of the flow controller is attached to the high-pressure regulator outlet by a Swagelok™ "quick-connect" fitting. This permits easy replacement of high-pressure bottles through rapid disconnecting and reconnecting of the flow controller and pressure regulator. The mass flowmeter is powered by a ±15 V power supply located in the control panel, and its setpoint (proportional to desired flow rate) voltage is selected at the control panel, as well. The measured flow rate signal (0-5 V) is conditioned at the control panel and read at the computer by means of an input-output (I/O) board which handles analog-to-digital signal processing. The outlet portion of the flow controller, containing the solenoid valve is attached to a horizontal four-foot-long flexible stainless steel hose. The solenoid valve is continuously controllable in aperture size, between fully opened and fully closed, and has an override feature that allows immediate full opening and closing.

A four-foot-long stainless steel flexible hose runs from the mass flow controller horizontally to a T-joint that is suspended from the thrust-measurement load cell. The T-joint has three apertures, one being horizontally oriented, the second being oriented upward, and the third being oriented downward. The horizontal aperture receives flow from the flexible hose. The upward-facing aperture terminates in an electric pressure gauge (0-1,000 psig). The signal from this pressure gauge (0-100 mV) is processed at the control panel and read from the computer. The downward-facing aperture is swaged to a rigid stainless steel tube (0.5 in inner diameter) which extends from the T-joint down into the split tube furnace. The TSATS rocket prototype is attached to a 0.25 inch NPT male fitting at the bottom of the vertical rigid steel tube, and is thus suspended from the T-joint and the thrust measurement load cell. (Vendor: flexible tubing, T-joint and all Swagelok™ fittings from Birmingham Valve and Fitting Co.)

Thrust measurement for the TSATS experimental rocket is done by suspending the rocket beneath a thin-beam load cell, and firing the rocket upwards, resulting in an apparent "weight loss" of the system equal to the thrust of the rocket. The load-cell is a strain-gauge device, with a rated range of 0 to 40 lbs. The load cell was mounted on a frame, directly over the opening in the top of the split-tube furnace; the weight of the TSATS rocket, the vertical rigid steel tube, and the T-joint are suspended by a "hook" beneath the load cell. The weight of the horizontal flexible steel tube was supported by the frame. (Vendor: Omega Engineering Supply Co.)

A split-tube research furnace is used to supply heat to the TSATS experimental rocket. A furnace capable of reaching 1500°C was selected. The elements are made of the material Super-Kenthel® and the insulation of the furnace is alumina. The heated zone of the furnace is a cylinder four inches in diameter and, eleven inches in length. The axis of this cylinder is oriented vertically.

A bore hole, one inch in diameter, is located on both the top and the bottom of the furnace. These holes are centered on the axis of the heated zone cylinder. The top bore hole allows the rigid steel propellent tube to pass into the furnace from above. The bottom bore hole serves as a rocket exhaust exit.

A K-type thermocouple centered on the side of the furnace interior measures furnace temperature. The signal from this thermocouple is used by the furnace controller, a separate piece of electronic hardware, to ramp the furnace to a selected temperature in a programmed sequence of "ramps" and "soaks". (Vendor: Applied Test Systems furnace and controller)

The controller for the split-tube research furnace, the manual controls for the mass flow controller, and the signal conditioning modules for the experimental diagnostic signals are located on an instrumentation rack located adjacent to the furnace stand (see Fig. 1). The furnace control panel consists of a main power switch and a programmable electronic controller. The mass flow controller control panel also has a main power switch for the mass flow controller, as well as a ten-turn potentiometer to control flow rate and a valve override switch, to rapidly open or close the valve completely. Eleven diagnostic signals are conditioned through linearizing and amplifying circuit modules on a common backplane on the rack. These eleven channels are: eight K-type thermocouple signals (measuring rocket and ambient temperatures), one load cell strain gauge signal (measuring thrust), one pressure gauge signal (measuring gas stagnation pressure entering the TSATS), and one flow controller signal (proportional to the mass flow rate of helium). (Vendors: National Instruments and Analog Devices backplane conditioning modules)

An Apple Macintosh IIci personal computer is used to display and record signals from eleven diagnostics--eight thermocouples, one load cell, one pressure gauge, and one flow meter. The software application LabVIEW® is used to generate a "virtual instrument," i.e., a real-time display of measured values using simulated meters. The linearized and amplified diagnostic signals from the control panel are digitized by A/D converters on a National Instruments I/O board installed in the Macintosh. The digital signals are read sequentially at 10 millisecond intervals, are multiplied by scaling factors set in LabVIEW, and are displayed simultaneously on the computer screen during the experiment's duration. The "screen" is saved at one-second intervals, through a feature of LabVIEW, and hence the entire experimental run can be recorded and replayed. (Vendors: Apple, National Instruments)

Design and Construction of the First TSATS Prototype Rocket

The low-energy TSATS prototype is intended primarily to characterize the instrumentation and control systems of the TSATS Rocket Test Stand, and secondarily to test the theoretical predictions of the performance of a simple TSATS. This prototype has been designed to be easily manufactured and modified. It uses a nonflammable propellant (helium), and operates at temperatures that are low compared to ultimately desired temperatures of TSATS operation (1,000 K vs 2,500 K). These features enhanced safety during the early stages of TSATS hardware experimentation.

The prototype (Fig. 2) is a 3 1/2" diameter 304 stainless steel cylinder, four inches in length, with a single 0.25" diameter hole passing through the entire axial length of the rocket. The propellant feed tube empties into one end of the quarter-inch hole, being attached by a threaded section. A small rocket nozzle (0.040" throat diameter, 10° half-angle conic diverging portion) is attached by threads to the bottom of the TSATS rocket. The quarter-inch diameter four-inch long hole is the heat exchanger portion of the TSATS rocket, through which a flow of helium gas propellant will convect heat from the hot steel cylinder.

Six thermocouple ports were drilled into the TSATS prototype (see Fig. 2) to permit measurement of temperatures within the block at six

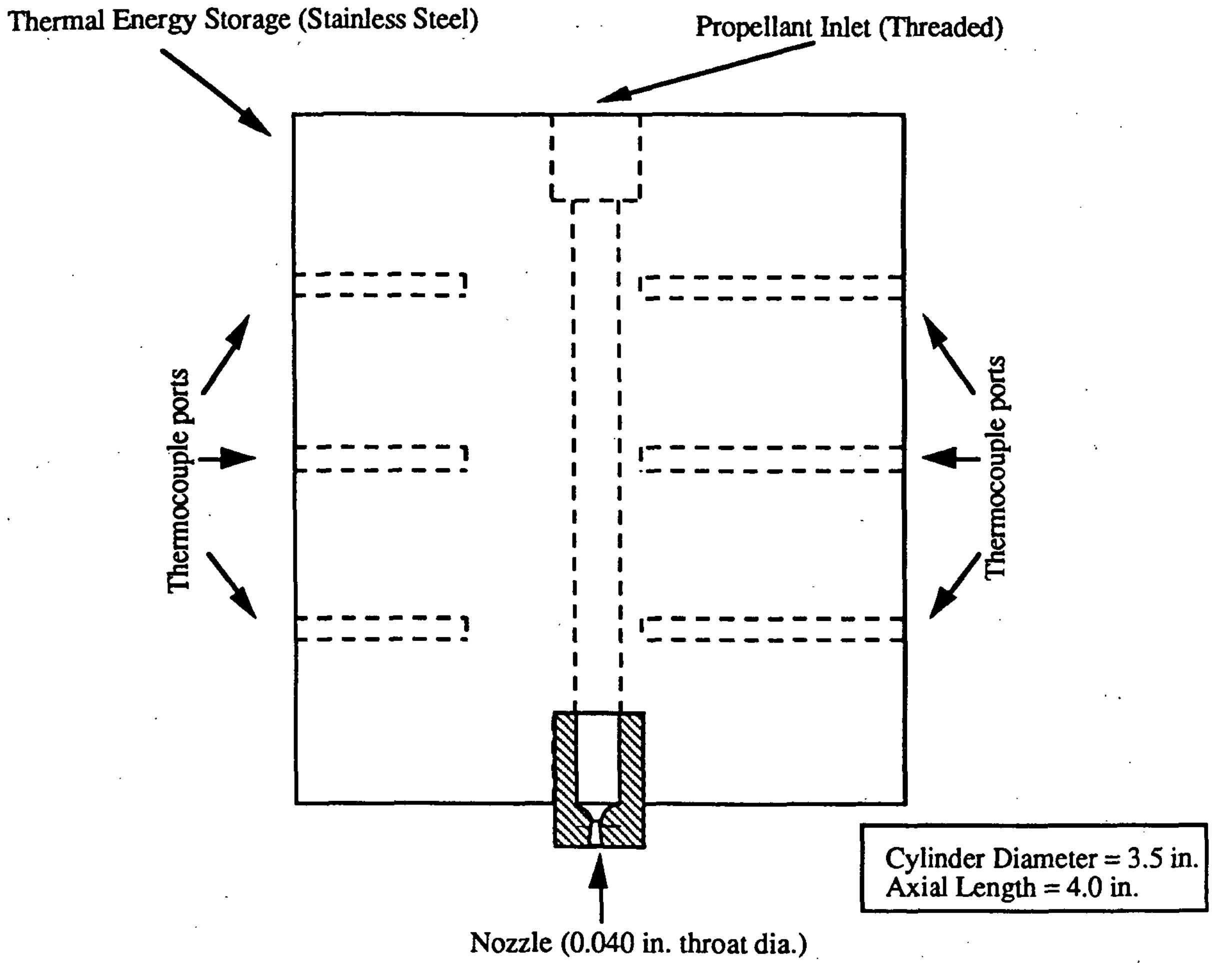


Figure 2: TSATS Experimental Rocket, Low-Energy Prototype

stations. Two sets of three 1/4" holes (upper, center, and lower) were drilled. One set of ports allows thermocouple access to a depth of 1.50", perpendicular to the outer cylinder wall. This set of thermocouples measures the temperature of the steel cylinder 1/8" from the heat exchanger hole wall. The other set of ports allows thermocouple access to a depth of 3/4", perpendicular to the outer cylinder wall. This set of thermocouples measures the temperature of the steel cylinder 7/8" from the heat exchanger hole wall, approximately centered between the hole wall and the steel cylinder outer wall. The upper, center, and lower stations for both sets of ports were located 1", 2", and 3", respectively, from the top of the steel cylinder.

Experimental Objectives

The overall objective of the TSATS experimental program is to test (by constructing and firing prototypes) the performance of transient thermal rockets, i.e., rockets which convert stored heat energy to propellant kinetic energy (i.e., thrust energy). The key mechanisms to be examined in TSATS prototyping and firing are: (1) thermal energy storage in a solid or liquid material, (2) heat exchanger performance, and (3) nozzle performance.

The initial tests of the first TSATS prototype rocket were run in such a manner as to test the instrumentation and propellant feed scheme of the TSATS rocket test stand. The objectives of these first firings are: (1) simple rocket prototype performance, and (2) rocket test stand instrumental capability.

Calibration and Scale Factors of TSATS Rocket Test Stand Instrumentation

The TSATS prototype rocket was attached to the thrust stand, and all six K-type thermocouples were inserted and secured by nut/chaser rod assemblies. The thermocouple wires were then wound around the propellant feed tube, and through the framework over the oven. This was done to establish the "zero" loading condition of the thin beam load cell.

Weights in equal pairs were placed on top of the rocket cylinder, so that four readings were obtained: zero loading, zero loading plus two pounds (downward), zero loading plus four pounds (downward), and zero loading plus six pounds (downward). The scale factor thus derived for the load cell was 10.776 lbs/volt. The correlation of the line drawn through the data points was 0.99999. The axis intercept was -8.6754 lbs at 0 volts.

The thermocouple scale factor implemented was based on the linearizing circuit modules used to process the thermocouple signals. The scale factor was 100°C/volt, with an axis intercept of 0°C at zero volts.

The pressure gauge scale factor was 10 psig/millivolt with an axis intercept of 0 psig at 0 volts. A slight zero offset was noted for the pressure gauge signal.

The mass flow controller flowmeter reading scale factor was 200 SLM/volt, with an axis intercept of 0 SLM at 0 volts. A zero offset was noted for the flowmeter signal.

Experimental Procedure for Initial Tests of Rocket and Test Stand

After calibration of the thrust measurement load cell was complete, the lower eight inches of the propellant feed tube and the TSATS rocket prototype, with thermocouples installed and firmly pinned, were enclosed in the split tube research furnace. The furnace was then programmed to ramp up to a desired maximum temperature, and to "soak" at that temperature for a period of time.

For both "heated" firings of the TSATS rocket prototype (i.e., rocket firings made after rocket was heated in furnace to high temperatures), the following procedure was followed:

- Main cut-off valve on high-pressure helium gas bottle was opened. The bottle pressure was read from pressure regulator inlet gauge and recorded.

- The mass flow controller was confirmed to be in the "override-closed valve" mode. The mass flow controller flow rate control knob was set at "zero flow" point.
- "Zero-point" measurements of thrust (load cell), propellant mass flow, and TSATS inlet stagnation pressure (pressure gauge) were recorded from computer screen.
- The furnace controller and power were turned off. The furnace was opened to prevent nozzle exhaust flow obstruction by the bottom wall of furnace tube. The TSATS rocket prototype is now at maximum temperature profile, and exposed to the atmosphere external to the furnace. An optical thermography camera (IR video diagnostic) was used to record the firing session.
- The control mode for the mass flow controller was switched from "override-closed valve" to "automatic control" mode.
- The LabVIEW data recording feature is activated and TSATS "fired" by initiating gas flow.
- The computer simultaneously displays temperatures from six TSATS thermocouples, pressure gauge signal, mass flow controller signal, and thrust-measurement load cell signal, as well as two thermocouple signals indicating lab ambient temperature.

Results of First Firings of TSATS Prototype Rocket

The first test firing made of the TSATS prototype rocket was a "cold" firing; that is, the rocket was not heated in the research furnace, but remained at room temperature (approximately 25°C) during firing. The duration of this firing was approximately five minutes. Parameters measured during the first TSATS cold firing are listed in Table 1.

TABLE 1

Test Data: TSATS Firing No. 1 (Cold Thruster)

Initial Pressure: Regulator Inlet	2600 psig
Initial Pressure: Regulator Outlet	500 psig
Mass Flow Controller Signal	1.83 V (366 SLM Helium)
Pressure Gauge Signal	11.96 mV (119.6 psig at TSATS Inlet)
Thrust Measurement Signal	0.4 lbs (± 0.05 lbs)

Regulator inlet pressure at the end of the rocket firing was not recorded. Thrust measurement signal (taken from load cell) was noted to oscillate with very high frequency between 0.35 and 0.45 lbs. The cause of this oscillation was not exactly determined, but was ascribed to random noise, since there were no audible fluctuations in the "flow noise" or visible vibrations of the rocket or thrust stand. The signals from all instrumentation were filtered with software in all firings thereafter. The filtering routine averaged ten samplings of each instrument signal (eight thermocouples, load cell for thrust measurement, pressure gauge, and flow controller) every 1/10 second, yielding smoother data readings.

The specific impulse of the rocket on this run was calculated to be between 159 sec and 204 sec; the uncertainty is due to the wide swing in thrust reading.

The first "hot" firing of TSATS (i.e., firing of the rocket after heating it to a maximum temperature) was preceded by a cold firing of the rocket, to give a reference or control specific impulse data point. See Table 2.

TABLE 2

Test Data: TSATS Firing No. 2

(Part 1: Cold Firing)

Initial Pressure: Regulator Inlet	4900 psig
Initial Pressure: Regulator Outlet	250 psig
Mass Flow Controller Signal	492 SLM Helium
Pressure Gauge Signal	121.42 psig
Thrust Measurement Signal	0.67 lbs

The total time for the cold firing was five minutes, forty-four seconds. Specific impulse is calculated to have been 226 sec.

The furnace was then "wrapped around" the TSATS rocket. The furnace controller was set to ramp up to 500°C over a 4-hour period. After furnace ramp-up was completed, the six thermocouples on board the TSATS rocket each read 458°C. A thermocouple displaying room temperature read 23.21°C. At this point, the furnace was opened on its hinge, permitting (1) free passage for the TSATS plume, and (2) thermography camera view of the TSATS rocket. The first "hot-firing" of

TSATS was begun at this time. See Table 3 for resulting measured "steady-state" parameters.

TABLE 3

Test Data: TSATS Firing No. 2

(Part 2: Hot Firing)

Initial Pressure: Regulator Inlet	4200 psig
Initial Pressure: Regulator Outlet	250 psig
Mass Flow Controller Signal	456 SLM Helium
Pressure Gauge Signal	262.4 psig
Thrust Measurement Signal	0.71 lbs

The total time for the hot firing was ten minutes. Specific impulse is calculated to be 260 sec.

Conclusions

From the preliminary results described above, it is concluded that: the TSATS Rocket Test Stand at SPI is capable of measuring important parameters of operating TSATS prototypes. The data acquisition scheme lends itself well to easy recording of measured data. The sensitivities and characteristics time responses of the instrumentation are adequate to describe the firing profile of a TSATS rocket, from maximum to minimum temperature. In addition, the Test Stand is easy to maintain, due to its simple design. Many key replacement parts are inexpensive, "off-the-shelf" instrumentation, which can be obtained from any engineering supply vendor.

The first TSATS prototype rocket performed moderately well. Comparison of test data, particularly the test data from the second test firing, compares favorably with TSATS design data (see Figs. 3(a) through 3(c)). From Fig. 3(a), design thrust levels were approximately 0.44 lbs, or 1.97 N. Thrust measured was 0.5 lbs, ±0.1 lbs. From Figure 3(b), design helium flow rates were approximately 0.00100 kg/sec. Finally, predicted specific impulse or Isp, which is exhaust velocity shown in Fig. 3(c) divided by 9.806 m/sec^2, is approximately 203 sec. The measured specific impulse after t = 20 seconds was approximately 180 seconds, about 10% off design conditions. The low-power heat exchanger design, rapid wall cooling in the heat exchanger duct, and a suspected leak at the junction of the nozzle and TSATS body may have contributed to the low specific impulse value which the rocket developed after t = 20 seconds.

Further work under separate Institute funds is continuing and will be reported in the literature.

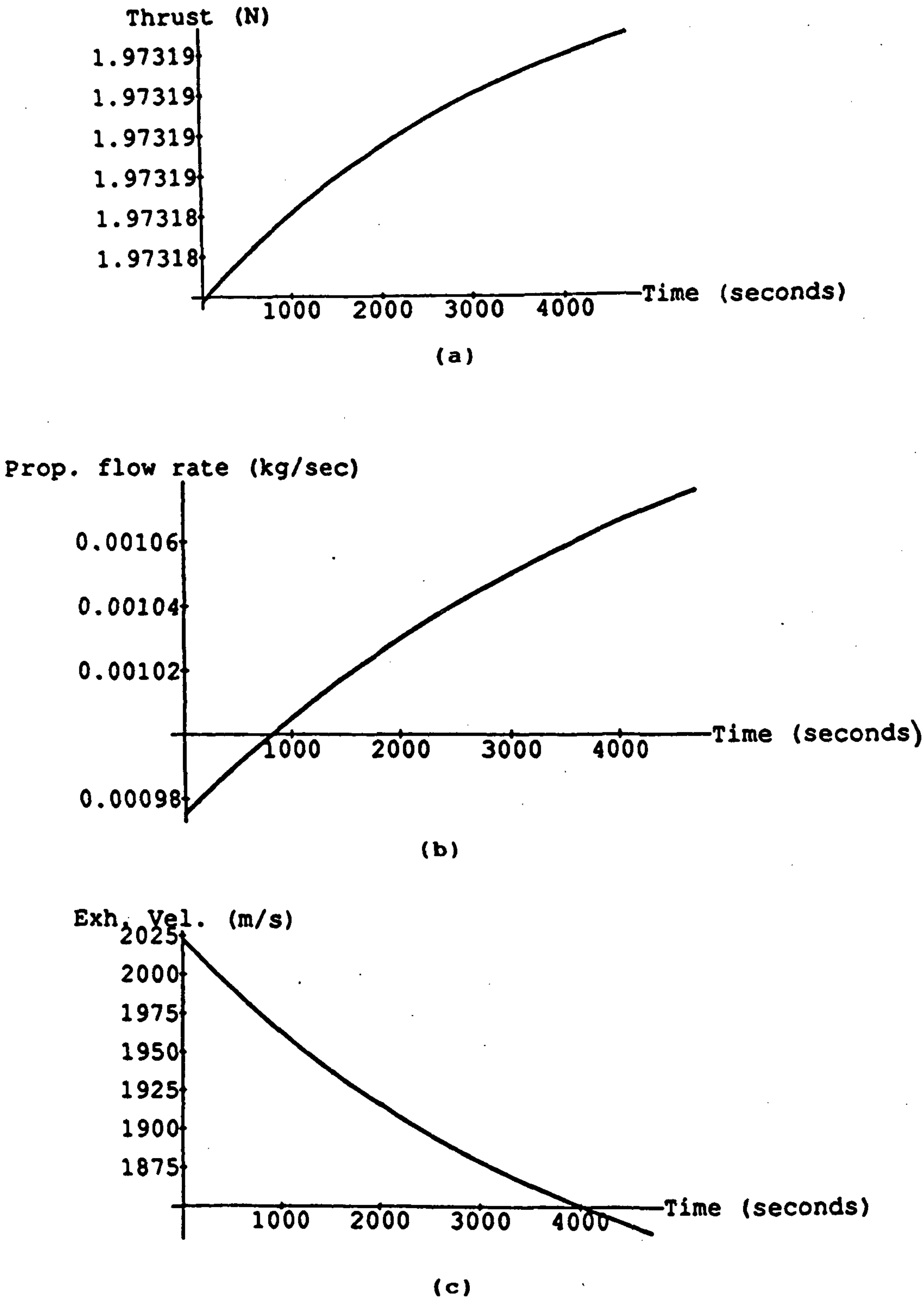


Figure 3. Modelled Performance of First TSATS Prototype Rocket, Using TAM-2 Modelling Code.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-187095		

4. Title and Subtitle	5. Report Date
Thermal Storage Advanced Thruster System (TSATS) Experimental Program	April 1991
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
M. Frank Rose and Michael E. Lisano, II	None
	10. Work Unit No. 506-42-31
9. Performing Organization Name and Address Auburn University Space Power Institute Auburn, Alabama 36830	11. Contract or Grant No. NAG3-1155
	13. Type of Report and Period Covered Contractor Report Final
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, John M. Sankovic, Space Propulsion Technology Division, NASA Lewis Research Center, (216) 433-2409.

16. Abstract

The TSATS (Thermal Storage Advanced Thruster System) rocket test stand is completely assembled and operational. The first trial experimental runs of a low-energy TSATS prototype rocket have been made using the test stand. The features of the rocket test stand and the calibration of the associated diagnostics are described and discussed below. Design and construction of the TSATS prototype is then discussed, and experimental objectives, procedures and results are detailed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Thermal storage Propulsion	Unclassified - Unlimited Subject Category 20

19. Security Classif. (of the report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	18	A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

Official Business
Penalty for Private Use $300

FOURTH CLASS MAIL

ADDRESS CORRECTION REQUESTED

U.S.MAIL

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

NASA