A 1.8 kW STATIC ARCJET SIMULATOR

E. Detoma, G. Parisi
FIAT CIEI
SEPA
Corso Giulio Cesare, 300 - 10154 TORINO To [Italy]

W. Deininger
BPD Difesa e Spazio
Corso Garibaldi, 22 - 00034 COLLEFERRO Rm [Italy]

ABSTRACT

Electrically simulating the arcjet thruster is very important in optimizing the operation of its Power Conditioning Unit (PCU) without resorting to a physical connection to the real thruster, which may be inconvenient or hard to implement while testing the PCU in the laboratory. It is also very important to be able to adequately test the electronics after integration onto a satellite to ensure proper PCU operation. Since activating the arcjet is not possible on the launch pad, a good electrical simulator is an ideal solution. The difficulty in implementing an arcjet electrical simulator lies in the fact that an electrical arc exhibits a non-linear voltage-to-current (V/I) relationship, and the arcjet is no exception to this behaviour. The non-linear load has been implemented in the past using analog circuitry and the results have been reported in the literature. Our approach involves the digital control of the V/I characteristics of the load, stored in Eproms. This allows a quick change from one curve to another, since several V/I curves can be stored, and switching from one to another can be achieved in a fraction of a millisecond. The last feature is useful to simulate the arc transition from High Mode to Low Mode, and to test the response of the PCU in detecting and controlling such a behaviour. Another advantage of digital storage is the good reproducibility of the desired characteristic versus what can be obtained with an analog implementation. In this paper, we will present the design and the main features of the device that has been constructed in SEPA, and that has been used to test and optimize a PCU for a 1.8 kW arcjet system, developed for BPD under a contract from the Italian Space Agency (ASI).

ACRONYMS AND ABBREVIATIONS

A/D    Analog to Digital [converter or conversion]
ASI    Italian Space Agency
CU     Control Unit
D/A    Digital to Analog [converter or conversion]
IEEE   Institute of Electrical and Electronics Engineers
MS-DOS MicroSoft Disk Operating System
EPROM Erasable Programmable Read Only Memory
MOSFET Metal-Oxide-Semiconductor Field-Effect Transistor
PCU    Power Conditioning Unit
PDU    Power Dissipation Unit
PWM    Pulse Width Modulation [or Modulator]
S/H    Sample and Hold [amplifier]
V/I    Voltage vs. Current [relationship or characteristic]

1 INTRODUCTION

Electric propulsion has recently attracted renewed attention in the space community due to the mass savings and/or payload increases it can provide to geostationary satellites\textsuperscript{1-10}. Although electric propulsion has been around for quite a long time, electric propulsion systems have been recognized as a mature technology for potential use only during the past several years. This is due to several factors. First, extensive test programs have not only improved the system performance, but have largely resolved the concerns related to the integration and compatibility with the spacecraft. A second factor is the competition which has developed in the geostationary telecommunications satellite (GTS) community. This competition pushes satellites to use higher performance subsystems to enhance the satellite capacity. In this sense, electric propulsion systems are attractive since they can offer launch mass reduction, increases on orbit life and/or payload mass increases that fully justify the development costs. Finally, power generation and storage systems, which are now available on board communications satellites, also provide the power/energy requirements of an electric propulsion system.

Electric propulsion systems based on arcjet thrusters are being developed world-wide. Laboratory and advanced development work is ongoing in Italy\textsuperscript{1,11-13}, Germany\textsuperscript{11,14,15}, Japan\textsuperscript{16,17} and the USA\textsuperscript{18,21} with system qualification complete in the USA\textsuperscript{20,21}. An arcjet propulsion system will be used operationally starting this year on commercial Telesat 4 GTSs for North-South station keeping (NSSK)\textsuperscript{21}. A flight arcjet subsystem for NSSK will utilize four arcjet subsystem assemblies. Two engines would be considered the primary NSSK system while the other two would be considered redundant spares. Each hydrazine arcjet satellite propulsion subsystem assembly will include an arcjet assembly, power conditioning unit and interconnecting power cable. Much development work has occurred on arcjet PCUs\textsuperscript{20,29-32}. The PCU will be required to start-up and operate the arcjet once a flow of hydrazine has been established. Therefore the PCU will be composed of a high voltage start-up unit and a power converter. In addition, it will also include input and output filters, a feedback control system and internal diagnostics. Functional testing of a PCU following integration on satellite is important to ensure that it will function properly. Currently these checks are conducted with a dummy load of resistors. This technique does not allow a full checkout of all of the subsystems and telemetry signals.

This paper describes the definition, implementation and testing of a electrical arcjet simulator which was developed as part of an ASI-funded systems study activity being conducted by BPD Difesa e Spazio (BPD) in support of low power arcjet system implementation in Europe. The arcjet simulator activity has been carried out by FIAT CIEI - Divisione SEPA (SEPA) in support of BPD. The overall sys-
systems study covers the definition of a Reference Mission\textsuperscript{26}; detailed arcjet propulsion subsystem specifications and requirements definition\textsuperscript{27} based on the Reference Mission constraints; and layout of the overall propulsion subsystem including design of its primary components\textsuperscript{28} along with identification of critical areas and delineation of a development plan to achieve subsystem ground qualification by the mid-nineties. The simulator development activity was part of a breadboard PCU development task within the overall program. These activities were conducted to provide an appropriate background for definition of a flight-type PCU. The simulator summarized in this paper is aimed at simulating a, nominally, 1.6 kW hydrazine arcjet. It can be used for PCU development testing, as in the current program, and in the future as ground support equipment to fully test integrated PCUs on satellites.

2 ELECTRIC CHARACTERISTICS OF THE ARC

The electric arc is a self-sustained discharge having a relatively low voltage drop and capable of supporting large currents\textsuperscript{25}. In general the V/I characteristics exhibits a peculiar negative slope characteristic of the arc, i.e.

- the voltage across the arc increases as the current flowing through the arc decreases and vice versa;
- for a constant voltage, the current increases when the flow of propellant (and the pressure) is reduced or for a constant current, the voltage increases as the flow (pressure) increases.

The arc can be initiated either by the separation of contacts or by a transition from a higher voltage discharge: this second mechanism is used to establish the arc in arcjet thrusters.

Without going into any detail on the physics of the discharge and associated ionization processes near the electrodes, we will consider a simplified model for the arc in a stable condition (after the ignition process has already taken place and the arc discharge has been stabilized). While for a hissing arc the V/I relationship is essentially linear, for a silent arc the relationship is given by the Ayrton equation, which is in the form of a hyperbola:

\textbf{The Ayrton Equation:}

\[ V = a + b \frac{c + d \cdot x}{I} \] \hspace{1cm} \textit{(at constant pressure)} \hspace{1cm} (1)

where:

- \( V \) is the voltage across the arc
- \( I \) is the arc current
- \( x \) is the gap length
- \( a, b, c, d \) are constants depending on the electrodes and on the gas combination

Some departure from this equation has been shown to occur for rare earth electrodes and short gaps, but for our purposes we will assume the eq. (1) as a model representative of the electric behaviour of the arc, confident also in the experimental data taken on laboratory models at BPD and elsewhere.

As noted above, the effect of increasing the pressure as a consequence of the increase in the flow of the gas translates into a corresponding increase in the voltage, according to the relation:

\[ V = M \cdot \ln p + N \] \hspace{1cm} (2)

for constant arc current and gap, where: \( M \) and \( N \) are constants, and \( p \) is the gas pressure.

2.1 Simplified Electric Model of the Arc

For the purpose of deriving a simplified model to describe the V/I characteristics of the arc for the purpose of simulation, we can rewrite the eq. (1) in the simpler form:

\textbf{Simplified form of the Ayrton Equation:}

\[ V = \frac{a}{I} + b \] \hspace{1cm} \textit{(at constant pressure)} \hspace{1cm} (3)

where:

- \( V \) is the voltage across the arc
- \( I \) is the arc current
- \( a, b \) are constants depending on the gas pressure for a constant electrodes geometry

where we have collected all the constants (for a constant electrodes geometry the gap is considered constant) while retaining the hyperbolic shape of the function.

3 OPERATING CONDITIONS FOR AN ARCJET THRUSTER

From a purely electrical point of view, four situations can be envisaged to occur during the operation an arcjet thruster:

1. **Steady-State Operation**, in which the arcjet behaves electrically as a load characterized by a negative resistance with a characteristic hyperbolic shape given by eq. (3). The coefficients \( a \) and \( b \) for the eq. (3) are available as a result of the extrapolation of experimental data taken at different power levels and propellant flows.

2. **Start-up** condition, where the arc can be modelled as an insulator with very high resistance, in which a periodic discharge takes place between two electrodes by dielectric breakdown, until enough ionization is created to sustain a continuous discharge in a high temperature (plasma) medium.

Again, from the electrical point of view, the condition can be easily simulated by a current-limited discharge in a tube filled with gas under controlled conditions. Commercial gas tubes, used as surge arrestors, can be effectively used to simulate this situation, providing at the same time an effective protection for the electronic load simulating the steady-state condition.

Generally, the arc ignition is immediately followed by a surge in the current through the arc with respect to the nominal values in the steady-state condition.

3. **Anomalous Behaviour in the arc**, to simulate situations as the transition from high-mode to low-mode, to which the PCU must react by shutting off the arc (going into a high resistance mode for the simulator) followed by the restart procedure. The low-mode for the arc differs from the high-mode only by different values for the coefficients \( a \) and \( b \) in eq. (3), and the transition can be simulated by switching to a different V/I curve pre-programmed in the simulator.

3. **Anomaly or deliberate Switching-Off of the supply provided by the PCU**. Loss of electric supply to the arc can be deliberately provoked as a consequence of the transition from high to low-mode, or can occur because of failures. In this case, the simulator will simulate the opening of the arc by switching off the electronic load.
4 THEORY OF OPERATION OF THE SIMULATOR

The implementation of the simulator is shown in the block diagram shown in fig. 1 and described in the following.

The steady state conditions are simulated by a controllable dissipating load, composed of passive elements (resistors) and active devices (MOSFETs), to control the voltage across the same load according to the current flowing through the load itself.

A device, for simplicity indicated as a TransZorb in the schematic, simulates the start-up conditions, by providing a fast discharge while protecting at the same time the dissipating load by the high voltages pulses applied across the load by the PCU at start-up.

For the steady-state conditions, a sense resistor provides a voltage output proportional to the current flowing through the load (alternatively, the signal can be provided by an isolated Hall-effect current sensor); this signal is bandwidth reduced by a low pass filter and the resulting voltage is then converted to a digital number by a 8-bit high-speed analog-to-digital (A/D) converter.

Since the switching frequency of the current PCUs is in the range of 16 to 33 kHz, the controllable bandwidth cannot be higher than that, since the PWM regulator behaves like a sampling system with an equivalent clock equal to the switching frequency. Therefore, the low-pass filter drives the frequency response of the simulator, and its corner frequency has been set to 50 kHz, considerably higher than what the current PCU can effectively control, thereby providing some range for future PCU designs, operating at higher switching frequencies.

The 8-bit A/D converter samples the signal with a frequency (100 kHz) higher than the corner frequency of the low-pass filter; in this way, the sampled signal at the input of the A/D converter exhibits a constant-value voltage during the conversion time, and no sample-and-hold (S/H) device is required to precede the converter to insure a stable conversion (in a sense, the low-pass filter behaves as a S/H device in the frequency domain). The data output from the A/D converter is used to address a bank of Electrically Programmable Read Only Memories (EPROMs), storing the desired V/I characteristic. The current flowing through the load at any instant in time defines a particular memory location holding the corresponding value of the voltage across the load.

More than one V/I curve can be stored in the EPROMs, and can be selected manually or via an external electrical signal (this is handy to trigger an external instrument, such as a scope, if a measurement of the reaction time of the PCU is needed when a transition from high to low-mode takes place). The resistance of the load is uniquely set by the 16-bits output by the EPROMs; 4 of the 16 bits are used to switch on or off some of the resistors that constitute the dissipative load, in order to minimize the power dissipation in the active devices, while the remaining 12 bits are used to drive a digital-to-analog (D/A) converter, providing a precise voltage proportional to the voltage to be forced across the load: this is obtained by controlling the resistance of the load itself. A voltage-controlled precise shunt regulator drives the active devices in order to maintain the voltage programmed for a given current flowing in the load, thereby realizing the desired V/I response. A high frequency (> 100 kHz) ramp waveform can be superimposed to the control voltage in order to simulate relaxation oscillations that have been experimentally detected to occur in the actual operation of the arc. Other external signals can be injected too.

FIGURE 1: Block Diagram of the Arcjet Electrical Simulator
The Start-up conditions are simulated by inhibiting the active devices, thereby switching off the dissipating load; in this way the only load presented to the PCU are the TransZorb devices and the input attenuator, presenting a relatively high impedance to the PCU. When high-voltage pulses are applied across the load, these are reduced in amplitude by the input attenuator and integrated by analog means, with a traditional integrator built around a classic operational amplifier. When a preset analog voltage is reached at the output of the Starter Pulse Charge Integrator, the arc is switched on by enabling the active devices in the dissipative load. The reduction in resistance across the load signals the PCU that the arc has been successfully ignited and no more high voltage pulses are required.

A possible start-up surge in the current through the load can be simulated at start-up by forcing in saturation the active devices, thereby lowering the impedance of the load. The voltage across the arc in these conditions is lower than the nominal as given by the appropriate V/I characteristic for the current flowing into the load. After a predefined time interval, the V/I characteristic of the arc takes control, driving the load into its steady-state operation.

If the voltage across the arc drops to zero or below a minimum preset value, an output signal is generated to switch off the active devices in the dissipative load, thereby simulating the opening of the arc. This signal is also used to reset the Starter Pulse Charge Integrator, to allow for a Start-up sequence to take place again.

**5 IMPLEMENTATION OF THE ARCJET SIMULATOR**

The simulator is implemented in two interconnected separate units: the Power Dissipation Unit (PDU) and a Control Unit (CU). The block diagram of the interconnections between the two units is shown in fig. 2.

The PDU handles all the power dissipation of the simulator, and can be conveniently located away from the Control Unit; the PDU supplies the CU with the following signals (see fig. 2):

- **current sense**, a voltage level proportional to the current flowing through the load; this signal is used to control the primary loop of the simulator, to force a voltage across the load according to the current flowing and the characteristic selected;

- **output voltage**, scaled down through a resistive divider; this signal drives the start-up pulses integrator (to simulate the arc ignition) and the arc undervoltage detection circuitry (to simulate the arc shut-down by opening the load).

The two signals, through suitable buffering, are used also to drive the voltage and current meters mounted on the front panel of the CU and to provide convenient monitor outputs for the experimenter.

In turn, the CU drives the PDU with a number of signals (see fig. 2):

- an **output voltage signal** to drive the precision shunt regulator to force a voltage across the load depending upon the current and the V/I characteristic being selected;

- 15 logic (digital) signals, optically isolated, to drive the MOSFETs resistor switches;

- a **disable signal** to shut off the load (high resistance mode);

- a signal to **remotely turn-on** the PDU (mains power supply).

The PDU encloses the Power Dissipating Load, the Input Voltage Dividers, the Precision Shunt Regulator and the Current Sense Circuitry.
5.1 Dissipating Load Design

About 2 kW of electrical power need to be dissipated in a controlled way in the form of heat. Load control is achieved through the use of power transistors, driven by appropriate control circuits. The power transistors chosen are of the MOSFET type, since they can be easily controlled with a minimum of drive power. However, in order to reduce the number of the active devices and the stress that they have to bear, it is advisable to dissipate most of the power on passive resistors, leaving to the active components the range to perform the control function by dissipating the residual power. Therefore, the controllable load has been composed of a series arrangement of a resistor and a power MOSFET (fig. 3). The tricky part of the design is the choice of the proper value of the resistor in order to obtain an efficient dissipation while conserving enough range for the active device to perform a proper regulation.

The design goal is to minimize the dissipation on the MOSFET; this implies a minimum voltage drop across the active device, which cannot be reduced to zero, however, since the device must still be able to operate in the active region. Around 10 to 20 V across the MOSFET will generate a total dissipation between 180 and 360 Watt for a nominal load current at 18 A. Therefore, we have restricted the active device to dissipate between 150 and 400 W as a design goal, and the fixed resistor in series with it has been replaced by a fixed bank of resistors which can be shunted by a number of equivalent resistors switched by power MOSFETs under control of the CU. This has the effect to vary the (passive) resistive part of the load according to the working point selected; in this way, we can achieve a wider range of operation than what normally can be provided by a single resistor alone, given the dissipation constraints imposed on the active devices.

5.2 Thermal Design

Five forced-air cooling heatsinks are used to thermally dissipate the heat generated by the electrical power in the resistors and in the active devices. Individual fans are attached to each heatsink, blowing the air from the front to the rear panel of the power unit.

Thermal safety is provided by thermostats attached to each individual heatsink: a raise in temperature will be indicated by an alarm lamp on the front panel of the unit and to perform the control function by dissipating the residual power. Therefore, the controllable load has been composed of a series arrangement of a resistor and a power MOSFET (fig. 3). The tricky part of the design is the choice of the proper value of the resistor in order to obtain an efficient dissipation while conserving enough range for the active device to perform a proper regulation.

The design goal is to minimize the dissipation on the MOSFET; this implies a minimum voltage drop across the active device, which cannot be reduced to zero, however, since the device must still be able to operate in the active region. Around 10 to 20 V across the MOSFET will generate a total dissipation between 180 and 360 Watt for a nominal load current at 18 A. Therefore, we have restricted the active device to dissipate between 150 and 400 W as a design goal, and the fixed resistor in series with it has been replaced by a fixed bank of resistors which can be shunted by a number of equivalent resistors switched by power MOSFETs under control of the CU. This has the effect to vary the (passive) resistive part of the load according to the working point selected; in this way, we can achieve a wider range of operation than what normally can be provided by a single resistor alone, given the dissipation constraints imposed on the active devices.

5.3 Precision, Voltage-Controlled, Output Shunt Regulator

The design of the electronic circuitry of the CU is conventional; the control circuitry is of mixed design, analog and digital, where the analog part is just only used to condition the signals provided to or generated by the A/D and D/A converters. The VI characteristics are stored in EPROM, to allow the maximum design and implementation flexibility in the definition of the characteristics themselves.

The selection of the desired characteristic can be operated manually or driven by an electrical signal, which is particularly important when performing transient response measurements; a trigger signal is always provide to synch external measurements to the transition.

Once a voltage is generated corresponding to the output voltage across the load for a given current (and a given characteristic), this is fed from the CU to the PDU to force the required voltage across the load by varying its impedance. The latter function is performed by a classic circuit known as 'voltage shunt regulator', shown in its simplified form in fig. 4. This is the equivalent of a
"voltage-controlled Zener diode", in which the operational amplifier controls the conduction of the power MOSFET with the aim to force the same voltage value for the inverting and non-inverting input of the error amplifier.

6 OFF-LINE V/I CHARACTERISTICS GENERATION

The desired V/I characteristics are generated off-line by software running on a IBM-compatible personal computer, under the MS-DOS operating system. Given the particular hyperbolic form of the arc V/I characteristic, operation far outside the nominal range of operation of the thruster is prohibited by various reasons:

a. at currents much higher than the nominal (16.2 A @ 100 V was the design assumption), the voltage drops dramatically, asymptotically reaching zero when the current goes to infinity; this presents a practical impossibility, which has been circumvented by forcing a constant voltage across the load when the current is much higher than a predefined limit, for instance, 20 A.

b. at currents much lower than the nominal, the voltage increases, asymptotically reaching infinity when the current drops to zero; again, the PCU is current-controlled and output voltage-limited, therefore, for currents through the load lower than a predefined value, its operation switches to a "power dissipation controlled characteristics", limiting however the maximum voltage to 200 V across the load.

The switchover to a power dissipation controlled characteristic is intended also to limit the power dissipation across the active devices of the arcjet within their Safe Operating Area. Since a maximum value for the series (passive) resistance is quickly reached at the minimum of the current range, an additional decrease in the current has the effect to increase the voltage and the dissipation across the active devices and, very quickly, this may reach dangerous levels for working conditions which are outside the normal operation of the arcjet thruster.

Therefore, after the lower current end of the range is reached (around 13.5 A for the thruster simulated in the current design), a departure from the hyperbolic characteristic is forced, and the impedance of the load follows a negative, third-order polynomial characteristic, with the purpose to quickly drop the product V.I and limit the dissipation on the MOSFETs to safe values.

Therefore, given the nominal operation of the arcjet thruster restricted between two values of current, \( I_{\text{low}} \) and \( I_{\text{high}} \), each experimental characteristic is composed of three areas of operation:

- a constant voltage \( V_c \) area, for values of the current higher than the nominal operating range of the arcjet; this will practically revert to an ohmic resistance as soon as the minimum resistance of the passive (resistive) load produces a voltage drop higher than \( V_c \);

- a negative resistance, hyperbolic in shape, simulating the operation of the arcjet thruster within the nominal operation range (from \( I_{\text{high}} \) to \( I_{\text{low}} \)),

- a power-limited dissipation area, represented by a third-order polynomial impedance, for currents flowing through the load smaller than \( I_{\text{low}} \).

The software generates the data to program the EPROMs starting from the values given above, i.e.,

- the high \( I_{\text{high}} \) and low \( I_{\text{low}} \) current values limiting the area of nominal operation of the arcjet thruster,

- the value of the constant voltage \( V_c \),

- the two coefficients, \( a \) and \( b \), of the hyperbola represented by the eq. (3);

- the four coefficients of the third-order polynomial for the "power dissipation limited area",

and produces an output file on disk in the Intel-8 format, that is afterwards used to burn the EPROMs on a general purpose EPROM programmer.
7 PRELIMINARY RESULTS FROM FUNCTIONAL TESTS OF THE SIMULATOR

Preliminary tests have been conducted by connecting the breadboard of a PCU, being developed under the same ASI grant, to the simulator. Some of the results are reported thereafter. The PCU breadboard that was developed can operate either in constant-current or constant-power mode: however, the results presented were obtained with the PCU working in constant-current mode, since in this mode the response is faster and the interpretation of the results is simpler.

Fig. 5 shows the behaviour of the simulator when the PCU changes the output current; actually, the current step shown in the lower trace is 2 A, with the current through the load changing from 17 to 15 A at a rate of about 8 Hz. The corresponding voltage change is from 92.7 to 100 Vdc. The time scale (horizontal axis) is set to 10 ms/div, and the response shows the classic behaviour of a negative resistance: the output voltage across the load increases as the current flowing through the load is decreased.

The measurement was taken using a Tektronix mod. 2440 digital oscilloscope, equipped with a Tektronix A6303 current probe, and the results were plotted directly to a pen plotter connected to the oscilloscope via the IEEE-488 standard interface.

The current trace is considerably less noisy than the voltage measurement: this is due to the fact that we have used an isolated Hall-effect probe for the current monitoring: the voltage is derived with an oscilloscope probe directly connected across the load terminals. Even when extreme care was exercised to shorten, as much as possible, the ground strap of the probe, high voltage spikes have troubled all our voltage measurements, especially when the signal is flowing in a long coax cable. We found that good termination practice of cables, as used in RF work, is mandatory if surges and spikes (several with a few tens of ns in duration) must be kept under control. This is one area in which we will work to improve the existing design.

Another measurement (fig. 6), taken with an expanded time scale, shows finer details of the transitions. The time base (horizontal scale) is now 1 ms/div, and the current step shown in the lower trace is still 2 A, with the current through the load changing from 17 to 15 A at a rate of about 8 Hz. The plot shows that the output current transition occurs in less than 200 μs. The simulator response is of the same order of magnitude: no apparent change in the response time was observed by switching the loop bandwidth from 5 to 50 kHz.

**Figure 5:** Simulator Response to a Current Step (10 ms/div)
FIGURE 6: Simulator Response to a Current Step (1 ms/div)

CH1gnd

CH2gnd

Channel 1

Channel 2

INVERTER UNIT (IU) RESPONSE TO A CURRENT CHANGE ON THE ARCJET SIMULATOR (NEGATIVE RESISTANCE LOAD)
INCREASE IN THE LOOP BANDWIDTH OF THE SIMULATOR CONTROL UNIT (50 KHz)

Measurement Conditions, Channel 1 - Output Current (from 15 to 17 A)
Current Probe: Tektronix Mod. A6303
Vertical Sensitivity: 5 A/div
Channel 2 - IU Output Voltage, from 110 V to 92.7 Vdc
Oscilloscope probe (1:10) connected to the load terminals
Vertical sensitivity: 20 V/div
Time base - 1 ms/div
Load - Curve 80
Current Modulation, from 15 to 17 A @ about 80 Hz

8 CONCLUSIONS

The design and construction of the static arcjet simulator was carried on as a mean to test the breadboard of the PCU for a 1.8 kW arcjet system, being developed by SEPA and Ansaldo Ricerche for BPD, under a grant from the Italian National Space Agency (ASI).

Preliminary tests have been conducted by connecting the breadboard of a PCU, being developed under the same ASI grant, to the simulator. While these results, being preliminary, cannot be taken as fully representative of the behaviour of the simulator, nevertheless they show the versatility of the instrument in carrying out basic tests with the PCU without resorting to a physical connection to a real thruster.

In this way, PCU design verification, characterization and tests have been carried on the electronic laboratory, with the simulator conveniently sitting on the bench where the PCU was tested, instead of working with a real thruster, requiring a vacuum chamber, gas supply pipes and complicated to operate while, at the same time, changing the operating characteristics of its PCU.

The simulator, instead, allows the user to precisely set the operating conditions independently of other parameters, such as propellant pressure or arc instabilities, and to simulate even conditions difficult to reproduce at will in the real world, such as high to low mode transitions or critical situations, that may arise once in a while for a real arcjet, but nevertheless should be taken into account in the design and testing of the PCU.

The simulator proved to be a versatile tool to work with in the laboratory, and we foresee than burn-in, endurance testing and acceptance tests of the PCUs can be carried on using simulators, since they provide a load as close as possible to the electrical characteristics of the real arcjet thrusters. The capability to simulate transient conditions is essential, since they constitute the critical areas of operation of the PCU (switch-on, current/power set commands, shut-off, response to anomalies, etc.). Furthermore, a simulator can be used as a piece of primary ground support equipment during PCU integration into a satellite and launch preparation.
ACKNOWLEDGMENTS

The authors would like to thank Mr. L. Caselli, Mr. N. Pagano, Mrs. E. DeCataldo, Mr. F. Tubiana, Mr. E. Vrano and Mr. L. Zen of SEPA who build the simulator and Ing. M. Carpita and Ing. G. Botto of Ansaldo Ricerche for their assistance during the tests of the simulator with the breadboard of the FCU.

The research described in this paper was conducted by BPD Difesa e Spazio/FIAT CIEI and sponsored by the Italian Space Agency (ASI) through contract No. 165-AF-1991. FIAT CIEI served as subcontractor to BPD. The contract technical monitor at ASI is M. F. Rossi.

REFERENCES


