DESIGN OF A HIGH EFFICIENCY POWER PROCESSOR
FOR THE RUSSIAN STATIONARY PLASMA THRUSTER (SPT)

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ABSTRACT
The design and development of a Power Processor Unit (PPU) for the Russian SPT is described. The tasks included developing a specification that met both the needs of the SPT and also those of typical Western spacecraft.

In compliance with that specification SS/L designed and built a preliminary PPU breadboard, while Fakel Enterprises built a SPT simulator. The PPU design goals of high efficiency and flexibility to accommodate other types of SPTs were achieved. Testing with the simulator proved the basic design. Extensive testing with the SPT-100 followed. The PPU consists of five basic types of power supplies and is designed to interface with existing SS/L spacecraft hardware. During the last year tests with the SPT and the simulator, and some minor "tweaking" of the PPU specification and the hardware, have resulted in a mature design.

I. INTRODUCTION
To date all SPTs have operated in space using Russian power processors. Russian PPUs are heavier, less efficient, and designed for a shorter life time relative to Western norms. SS/L and its Russian colleague thus decided to design a Western version of a PPU for the SPT. This effort has resulted in a successful design, fabrication, and test of a brassboard PPU. The brassboard PPU has been operated with static and dynamic simulated loads and with SPT-100s at several different facilities.

II. REQUIREMENTS and GOALS
The most difficult part of the task was getting started and defining a specification for the PPU. All documentation for the Russian PPU was in Russian, and not available in the West. The Russian documentation was also tailored for Russian needs. It took several months of dialogue between the Russian experts and SS/L personnel and several revisions of the documentation. At the end of this effort a specification for the PPU was agreed on that met both the needs of the SPT and the needs of Western spacecraft.

A. REQUIREMENTS FROM THE SPT
The SPT placed several basic requirements on the PPU design. The SPT requires 5 types of regulated power supplies for operation.
1) Anode or discharge supply
2) Magnet supply
3) Cathode Heater supply
4) Ignitor supply
5) Fuel flow controller and solenoid valve drive
6) Monitoring of thruster operation
7) Fault detection  
8) Start-up sequencing  
9) Receive and act on commands from the spacecraft computer for start, stop, thrust control (anode current), cathode selection (with capillary selection).  
10) Receive from spacecraft computer the heater set, magnet set, and capillary set values of current.

B. SS/L DESIGN OBJECTIVES
The additional features and objectives that SS/L added to the SPT requirements are:

1. Minimum mass with a goal of 7 Kg.  
2. Maximum reliability with a calculated failure rate of 1000 FITS or better, design life of 22.5 years.  
3. No single point failure modes, i.e., total circuit redundancy.  
4. Operation from a 42 Volt regulated bus.  
5. Maximum power conversion efficiency to minimize power consumption and thermal dissipation. Efficiency of main power converter to be 95% minimum.  
6. Easy conversion for use with an SPT-70 or other thruster design.  
7. Interface with the standard SS/L command telemetry Digital Control Unit (DCU).  
8. Dynamic environmental levels typical of Western spacecraft and launch vehicles.  
10. Designed for electro-magnetic compatibility using MIL-STD 461 and MIL-STD 1541 as design guides. The Equipment shall meet the requirement of MIL-STD 461 RE02, CE01, CE03, RS02, and meet all performance requirements when subjected to the following steady state narrow band interference voltage superimposed upon the primary input power bus.  
   * 1 Hz to 500 Hz 1.5 Vp-p  
   * Above 500 Hz Decaying from 1.5 Vp-p at 6 dB / octave  
11. Radiation designed for geosynchronous equatorial trapped space radiation, solar flare proton and cosmic ray environment for a mission life of 15 years plus a 50% extra margin.  

The internal radiation environment for unshielded parts on the order of 100 krad (Si).

III. DEVELOPMENT
Intense interchange between the Russian designers of the SPT and SS/L personnel culminated in a detailed technical specification for the SPT-100 PPU. This detailed specification was key in the successful development, integration, and test of the PPU with the SPT-100. At the same time as the specification for the PPU was being worked out a team at SS/L investigated how best to accomplish the set goals.

1. Minimum mass was achieved by using up to date circuit techniques and electronic components. Use of radiation hardened FETs allowed switching at 80 KHz to reduce magnetics and capacitor size while providing high operating efficiencies.  
2. High reliability and total redundancy was accomplished by providing separate power supplies for each of the redundant SPT-100 cathodes, igniters, flow control units and heaters. The single SPT-100 anode is supplied by 9 parallel power sources. The PPU can tolerate failure of any two of the nine sources without impact.  
3. High conversion efficiency was accomplished using parallel power sources, each operating at relatively low current and thus low resistive losses. The FETs and the
associated fast gate driver circuitry provide minimum switching loss.

4. Operation from a regulated bus allowed the deletion of most prereregulation and a much simplified overall electrical design.

5. The design was made modular to provide maximum flexibility, ease of fabrication and ease of test. The entire PPU for the SPT-100 consists of ten trays. The SPT-70 PPU is the same as the SPT-100 PPU except for a few set resistors and two less anode discharge trays due to the lower current requirement.

A block diagram of the PPU is shown in Figure 1. A diagram presenting the redundancy/reliability concept is shown in Figure 2.

First test with passive laboratory loads showed that the individual PPU modules operated as designed. In the second test phase the PPU was checked against the specification at various operating conditions by SS/L with support from the SPT manufacturer, Fakel Enterprise, Kaliningrad Region, Russia. After some modifications to the PPU, it was
mated with a dynamic simulator designed and built by Fakel. Figures 3 and 4 show the Fakel SPT-100 Dynamic simulator and the brassboard PPU in test with the simulator. After extensive testing and some more fine tuning of the PPU (and the specification), the PPU was taken to the test facilities in Ft. Collins, Colorado, where it was integrated and tested with an SPT-100 for the first time.

Several months of extensive testing followed to characterize and maximize beam stability and to decide the best configuration for the magnet supply (series or parallel application with the discharge current).

Most of the goals have been met with the brassboard.

The brassboard weight is 7.1 Kg. The design is in product engineering (packaging/ mechanical layout) at this time and the weight of the flight version is not final.

The calculated reliability exceeds the goal.

The design has total redundancy.

Efficiency for the first brassboard measures 96% for the anode supply. Subsequent brassboards have been about 94% because the FET drivers used on the first unit were not guaranteed to meet the required radiation levels and had to be replaced with a more rugged, but slightly less optimum characteristics.
IV. PPU DESCRIPTION
The PPU consists of five types of power supply modules to drive the SPT and associated capillary fuel control.
1. Anode Supply
   (9 for 7 redundancy)
2. Redundant Magnet Supplies
   (2 for 1)
3. Redundant Heater Supplies
   (2 for 1)
4. Redundant Ignitor Supplies
   (2 for 1)
5. Redundant Fuel Flow Controller and Solenoid Valve Drivers (2 for 1)

It was determined that maximum system operating capability and minimum technical risk could be obtained by utilizing SS/L command telemetry hardware. This was accomplished by designing the PPU to interface directly with the Spacecraft control electronics and associated equipment to provide the following functions:
1. Analog monitoring of thruster operation.
2. Command for start, stop, thrust control and redundant cathode selection.
3. Heater current setting, Magnet current setting, Anode current plasma discharge arc operation.
   The PPU powers, monitors and sequences the Stationary Plasma Thruster (SPT) and its associated flow controller (XFC) for start-up and operation. All thruster and flow control electrical connections are made to it's dedicated PPU.
   The PPU has two types of command inputs. Digital inputs are 28V pulses. Analog inputs are 0 to 5V.
   1) The spacecraft computer receives the PPU's analog telemetry. This includes these channels per thruster:
      * Heater current, 2 channels, one channel is operational
      * Floating voltage, 1 channel
      * Anode voltage, 1 channel
   2) The spacecraft computer selects which of the 2 thruster cathodes to energize by commanding the PPU for primary or secondary fuel paths in each thruster. This also selects which capillary fuel controller is used.
   3) The spacecraft computer commands the thrust level with an analog signal to the PPU. The thrust level is adjustable in flight.
   4) The spacecraft computer commands thruster firing initiation, and thruster shut-down with a 28 Volt pulse.
   5) The spacecraft computer selects the analog references for heater set current, magnet set current, and capillary tube current. These levels are ground controllable and can be adjusted for thruster lifetime variations.

A. ANODE SUPPLY (DISCHARGE SUPPLY)
The anode supply supports the plasma discharge arc during operation. This is a DC supply where the positive output connects to the thruster anode, the negative connects to both cathodes, and the return is isolated from spacecraft and primary bus returns. The anode supply has 4 operational states:
1) between firings the supply will be in a power-down mode drawing no power.
2) The steady state output voltage is 300 Volts +/- 3 Volts.
3) Delivered power to the discharge will be in the range of 1500 Watts.
4) The supply will current limit to 9 Amps under any load.

   The thruster is a complex load to the anode supply. Start-up transients and plasma instabilities
require a filter (also called a stabilizer) inserted between the anode supply and the thruster. Working with this filter is the anode power control circuit. The PPU anode regulator can respond within 50 microseconds to an anode load change.

**B HEATER SUPPLY**

Each of the two cathodes has a heater, only one of which is commanded on at a time by the spacecraft computer. The heater is used only for start-up; during normal thruster operation the heaters are off.

The heater supply is a DC current source adjustable over the range of 10 to 14 Amps, ground selected for thruster lifetime variations. When engine ignition occurs the heater supply is turned off by the PPU logic. The heater supplies are isolated from spacecraft and primary bus returns.

**C MAGNET SUPPLY**

The magnet supply is an adjustable, floating, low noise, DC current source that operates continuously with the thruster.

The magnet supply output is adjustable from 0 to 3.5 Amps and can be spacecraft controlled to adjust for thruster lifetime variations. The magnet supply is isolated from spacecraft and primary bus returns.

**D IGNITOR SUPPLY**

Each of the two cathodes has an ignitor. The plasma is ignited in the cathode with xenon flow. The ignition voltage is a pulse train of two sources wired together in series: start, and follow through. The pulse train is commanded on for thruster ignition and is shut off after engine start, usually within 2 seconds. The DC coupled ignitor supply is isolated from spacecraft and primary bus returns.

1) The start pulse is a positive voltage source and will supply 100 mA minimum at that voltage. Operation into a short is allowed.

2) The follow through pulse is a simultaneous positive voltage source. The current delivered is nominally 5 amps for 150 to 5000 uS. The pulse supply operates into a short, delivering 8 amps minimum for this time.

3) This double pulse shape will be repeated at 10 Hz until engine start-up. When the engine ignition is observed by the PPU the ignitor supply is turned off.

**F. FUEL FLOW CONTROLLER (Capillary Tube Drive/Termo-throttle)**

Fuel (xenon) is bang-bang regulated with a thermally constricting capillary tube. The discharge (anode supply) current is compared against the spacecraft computer commanded set-point to step control the capillary tube temperature. This set-point is the thrust control. There is a start-up mode to pre-heat this tube and establish an initial flow. Two capillary tubes are supplied per thruster, primary and secondary. The spacecraft computer selects the operating tube simultaneously with cathode select. These outputs are common to spacecraft chassis.

The spacecraft computer will command the fuel flow controller to select one of two capillary tubes to drive with the "cathode select" input. A separate supply in the flow controller electronics also drives the xenon valves that direct the fuel to the selected capillary tube. Fuel valves are turned on 10 sec before the ignition command.

During the time that the thruster cathode heater is energized, the capillary current is set to an initial current level.

Upon engine ignition, the tube control reverts to it's normal bang-bang operation. The thrust level is
controlled by the spacecraft computer
commanded discharge current set point
which is used as the reference for
the fuel flow controller electronics.

F. COMMANDS TO THE PPU
There are +28 volt, 125 millisecond
pulse inputs for the following:
1) Start primary cathode command
2) Stop primary cathode command
3) Start secondary cathode
   command
4) Stop secondary cathode command
The two spacecraft computer inputs
are active, the PPU obeys the latest
command from either.
Continuous analog inputs are:
1) Heater current set
2) Magnet current set
3) Thrust level set (anode
current)
4) Capillary warm-up current set

G. TELEMETRY FROM THE PPU
All outputs go to both spacecraft
computers separately and
simultaneously and are buffered
against shorts. The PPU analog
telemetry outputs are:
1) Heater current, primary
2) Heater current, secondary
3) Floating voltage
4) Anode voltage
5) Anode current
6) Magnet current, primary
7) Magnet current, secondary
8) Capillary current, primary
9) Capillary current, secondary
Digital signals to the spacecraft
computer are:
1) Primary ON (continuous signal)
2) Secondary ON (continuous
signal)
3) Primary OFF (follows input
pulse)
4) Secondary OFF (follows input
pulse)
5) Ignitor voltage OK
6) Ignitor current OK

The PPU will meet all performance
requirements over the input voltage
range of +39.5 to +42.5 volts DC.

Maximum power drain is 2000 watts
during start-up and diminishing to
1500 watts maximum during normal
operation with the thruster at 4.5
Amps anode current. The start up
sequence and the associated power
delivered to the thruster is shown in
Figure 5.

V. TEST RESULTS
The PPU is currently operating SPT-
100s in tests at three different
facilities. All the existing PPUs
have been tested with a Dynamic SPT
Simulator designed and built by
Fakel. This simulator has proved to
be such an exact representation of
the actual SPT that when the first
PPU was taken to the test facility of
Dr. Harold Kaufman (Front Range
Research) to be mated with an SPT,
the PPU and the SPT turned on with
the first ignition attempt.
Primary concerns were possible
ignition problems and thrust
oscillation levels. At this time
there has been no ignition failure
traced to the PPU/SPT. Ignition has
occurred on the first ignition pulse,
typically within the first 50 msec
after the ignition command was
applied. Discharge current regulation
is shown for two different cases in
Figure 6.
Not all of the testing has been
smooth, there have been some problems
setting up the PPU with the SPT at
some of the test facilities. These
problems can be traced to basic
differences between spacecraft and
earth facility set up. The PPU was
designed for spacecraft use, in which
flight harness length and line losses
are kept to a minimum. There is no
such problem for earth facilities and
some of the harnesses from PPU to SPT
have been so long and had so much
loss that the PPU has run out of
design margin. Where the facility
harness has been fixed (for at least
the high current connections to the
SPT) operation has been proper.

Figure 5 Start up Power sequence

VI. CONCLUSION
The design and development of a PPU for the SPT-100 was described. The SPT requirements, and SS/L design objectives were covered. Design decisions that led to the brassboard PPU, and description of the different types of supplies and the command and telemetry to and from the PPU have been described. The tests with the Dynamic Simulator built by the SPT manufacturer and subsequent testing with the SPT have, plus some fine tuning of the design have resulted in a mature electrical design that is presently being packaged for flight.
Figure 6
Discharge current regulation for 4.5 and 3.5 Amps