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DEVELOP AND FABRICATE A RADIATION DOSE MEASUREMENT SYSTEM FOR SATELLITES

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13. ABSTRACT *(Maximum 200 words)*

A second generation Dosimeter has been designed to fulfill the need for accurate radiation dose measurements. Two identical Dosimeters, a flight unit and a backup unit, have been fabricated, tested and calibrated. The backup Dosimeter was integrated into the payload of the Advanced Photovoltaic and Electronic Experiments (APEX) satellite, as part of the Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) experiment. APEX was launched shortly after 1430 UT on 8/3/94, with the initial orbit having apogee/perigee in the equatorial plane. The Dosimeter was turned on in Rev. 20, at about 0410 UT on 8/5/94. The initial turn on showed no anomalies, with the Dosimeter operating properly. The Dosimeter was then monitored for several days and proper operation has been verified.

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1. INTRODUCTION

Accurate characterization of the space radiation environment is one of the important inputs into the design of space systems that utilize complex electronic components. Radiation dose information can be used to optimize the design of a space system in terms of its expected lifetime, the types of electronic parts that can be used, and the shielding required for its critical components.

Electronic devices, photovoltaic power systems, and spacecraft power systems are susceptible to damage due to the received radiation dose from incident energetic protons and electrons. In addition, many types of electronic parts, particularly microprocessors and associated memory units, are subject to single-event-upsets (SEU's) caused by the passage of single high-energy heavy ions through the device or high energy proton induced "nuclear star" events. The instantaneous radiation dose rate and the associated total accumulated dose provide important information for the estimation of satellite lifetime and for real-time decisions regarding satellite integrity. This information can be used to provide advance warning of when critical components are approaching failure due to radiation damage, and it can also provide confidence in the reliable operation of a component by showing that the radiation damage is not yet significant. In the case of solar flares, a dose measurement could show that radiation exposure has (perhaps suddenly) become very important and that the consequences must be addressed.

The increasing use of complex solid-state electronic devices in the space radiation environment makes it important to have reliable data on the radiation doses these devices will receive behind various thicknesses of shielding. As part of the effort to obtain this data, a Dosimeter was designed, fabricated, calibrated, and integrated into the payload of a Defense Meteorological Satellite Program (DMSP) satellite by Panametrics, Inc., for the Geophysics Laboratory. A second, essentially identical, Dosimeter was designed, fabricated, calibrated, and integrated into the payload of the Combined Release and Radiation Effects Satellite (CRRES) by Panametrics, Inc., for the Geophysics Laboratory. The DMSP and CRRES Dosimeters, which measure the accumulated radiation dose in four silicon solid-state detectors behind four different thicknesses of aluminum shielding (one solid-state detector behind each shield), are described in Refs. 1 and 2, respectively.

The general objective of the current contract is the design and fabrication of an improved, second-generation Dosimeter intended to fulfill the need for accurate radiation dose measurements. This system is to have the following characteristics:

1) Separately measure the total accumulated dose due to electrons and protons,
2) Detect and measure energy deposition of large-energy deposition events (possible SEU's),
3) Accurately measure the dose during normal activity periods and during large solar flare events (such as August 1972 or March 1989),
4) Be easily adaptable mechanically and electronically to different spacecraft and different radiation environments (for example, orbits inside or outside the radiation belts),
5) Have modest telemetry requirements.

The specific objectives of this contract are as follows:

1) Conceptual design of a Dosimeter instrument which meets the five requirements listed above,
2) Detailed design of the Dosimeter instrument,
3) Fabrication, testing and delivery of the Protoflight[1] Dosimeter unit,
4) Fabrication, testing and delivery of the Backup[1] flight Dosimeter unit.
5) Integration of the Protoflight[1] or Backup[1] Dosimeter into the payload of the Advanced Photovoltaic and Electronic Experiments (APEX) satellite, as part of the Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) experiment.
6) Integration and launch support of the APEX spacecraft.

[1]The "Protoflight" and "Backup" designations are specified in the contract. The "Protoflight" Dosimeter and "Backup" Dosimeter are both fully qualified flight instruments.

2. DESIGN

2.1 Detection System

An isometric drawing of the Dosimeter is shown in Figure 1, and the instrument's block diagram is shown in Figure 2.

The integral particle flux and radiation dose is measured by solid-state detectors located behind degraders and backed by a large amount of shielding, which reduces the response to rear entry particles. As shown in Figures 1 and 2, the instrument has four degraders (3 hemispherical and 1 planar, all of which are referred to as "domes") with solid-state detectors located underneath them. Dome 1 was specially configured as a planar Al shield 4.3 mils thick to allow accurate dosimetry measurements of the particles (5-10 Mev protons) most likely to cause solar cell degradation. This was necessary to meet PASP Plus requirements. The two thinnest domes have two detectors under each dome, one with a large sensitive volume and one with a small volume. The purpose of this arrangement is to ensure a large dynamic range of the instrument; the small detector will work reliably even with very high flux levels that may saturate the larger detector. A summary of the detector characteristics is given in Table 1. A cross sectional view of D1, the planar and thinnest dome, is shown in Figure 3. A cross sectional view of D3, which is typical of the three hemispherical domes except that there are two solid-state detectors under D2, is shown in Figure 4.

Protons and electrons that penetrate the degraders will deposit, on the average, different amounts of energy in the solid-state detectors, so their contributions to the total dose can be separated. The solid-state detectors are approximately 400 μm thick and most penetrating electrons deposit less than 1 MeV of energy in them, while most penetrating protons deposit between 1 and 10 MeV. A summary of the dome moderators utilized, with the resultant threshold energies, is given in Table 2. Energy deposition curves for the four domes are shown in Figures 5-8. The electron flux measurements with the thicker domes may not be reliable due to the production of bremsstrahlung by low-energy, non-penetrating electrons. The total electron radiation dose will, however, still be correctly determined. The flexibility of this design approach is that the same physical envelope of the dome-detector assembly can be used for very different degrader thicknesses and detector configurations. Thus, a simple mechanical change can be used to tailor the proton and electron thresholds to the specific mission requirements.

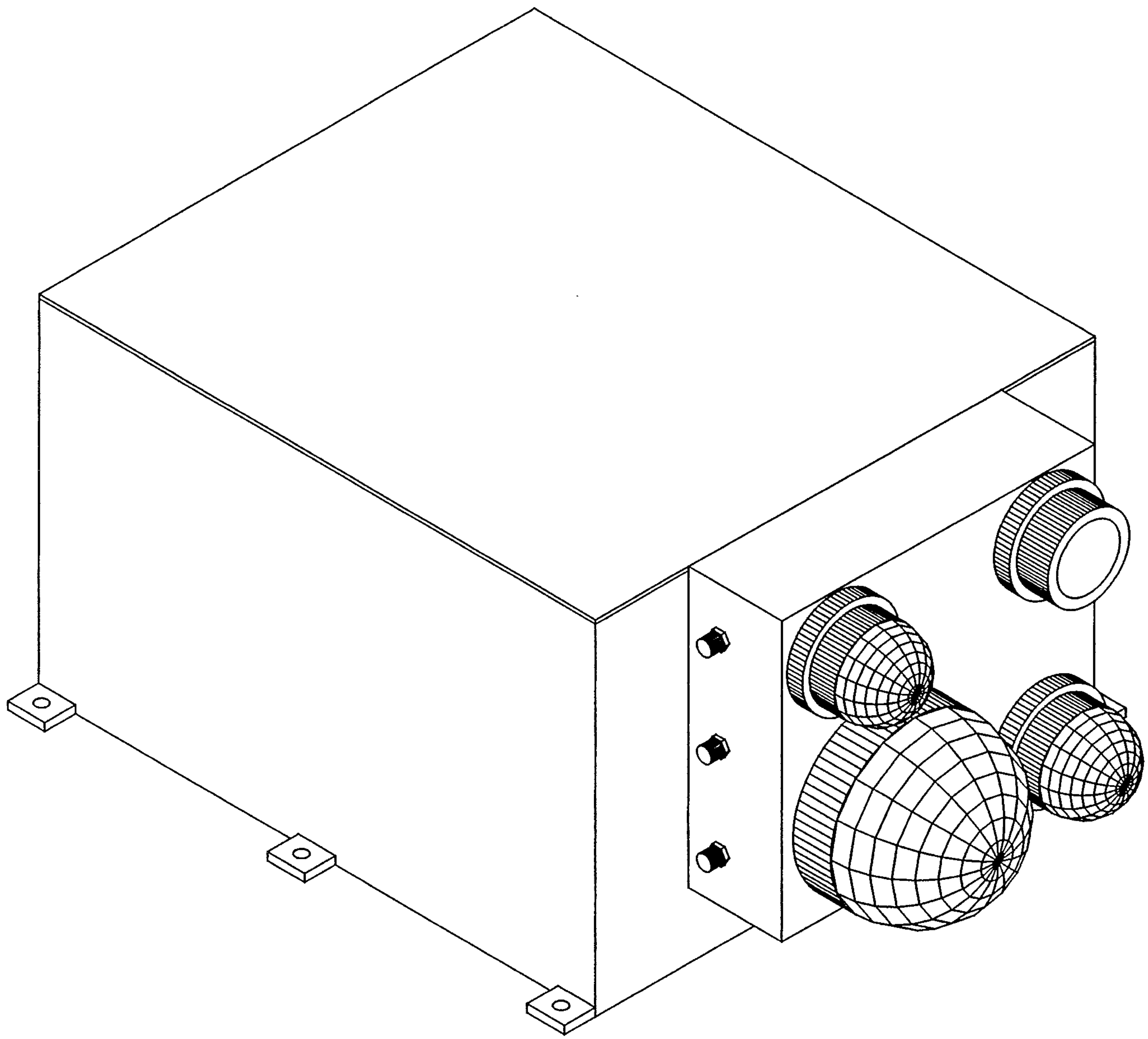


Figure 1. Isometric View of Dosimeter

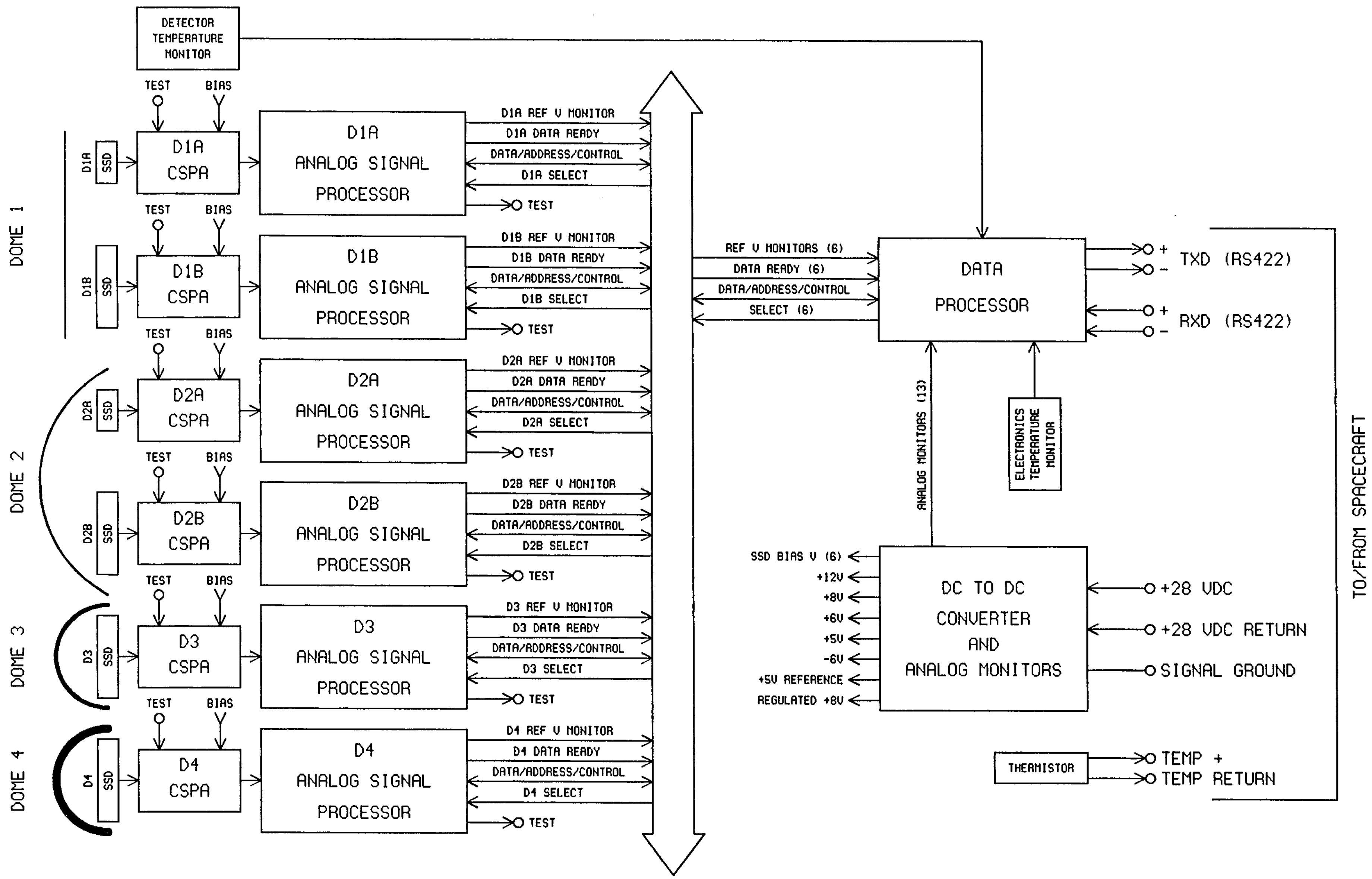


Figure 2. Electronics Block Diagram

Table 1.
Summary of Detector Characteristics

Dome	Detector			Dose at Overflow (Rads Si)		Flux at Overflow (particles/cm²-s)		
	Data Channel Designation	Area (cm^2)	Geometric Factor (cm^2-sr)	LOLET	HILET	TOTAL	LOLET	HILET
D1	D1A	0.008	0.03	10^6	10^7	10^9	10^8	10^8
D1	D1B	0.051	0.16	10^5	10^6	10^8	10^7	10^7
D2	D2A	0.008	0.08	10^6	10^7	10^9	10^8	10^8
D2	D2B	0.051	0.35	10^5	10^6	10^8	10^7	10^7
D3	D3	0.051	0.35	10^5	10^6	10^8	10^7	10^7
D4	D4	1.000	4.4	10^4	10^5	10^7	10^6	10^6

Table 2.
Dome Moderators and Energy Ranges

Dome	Detectors	Aluminum Shields		Electron threshold	Proton energy range	VHILET threshold
		(g/cm^2)	Shape	(MeV) (LOLET)	(MeV) (HILET)	(MeV)
D1	D1A, D1B	0.0294	flat	0.15	5 - 80	40, 40
D2	D2A, D2B	0.55	hemisphere	1.0	20 - 115	40, 40
D3	D3	1.55	hemisphere	2.5	32 - 120	40
D4	D4	3.05	hemisphere	5.0	52 - 125	75

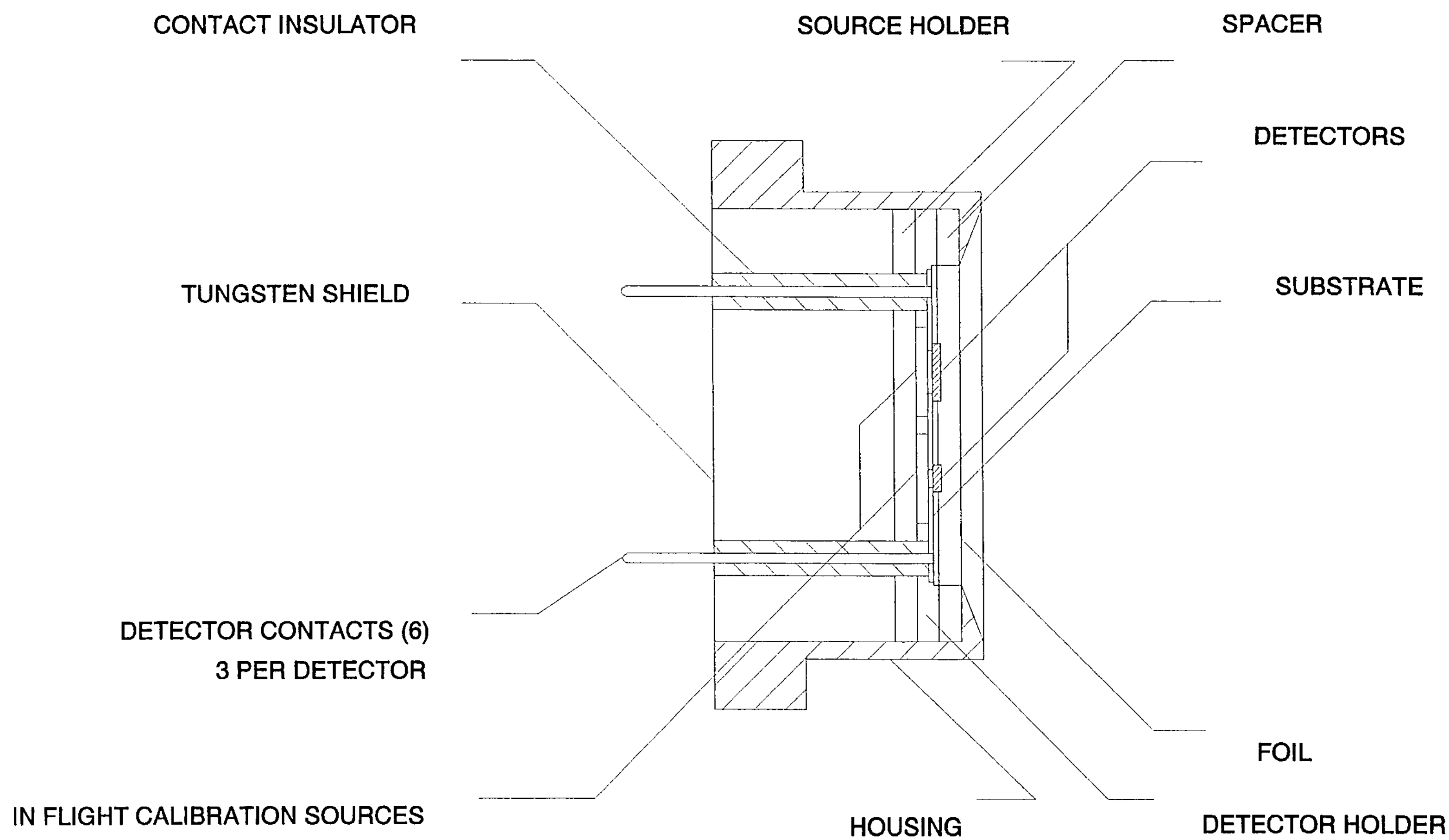


Figure 3. Dome 1 Cross Section

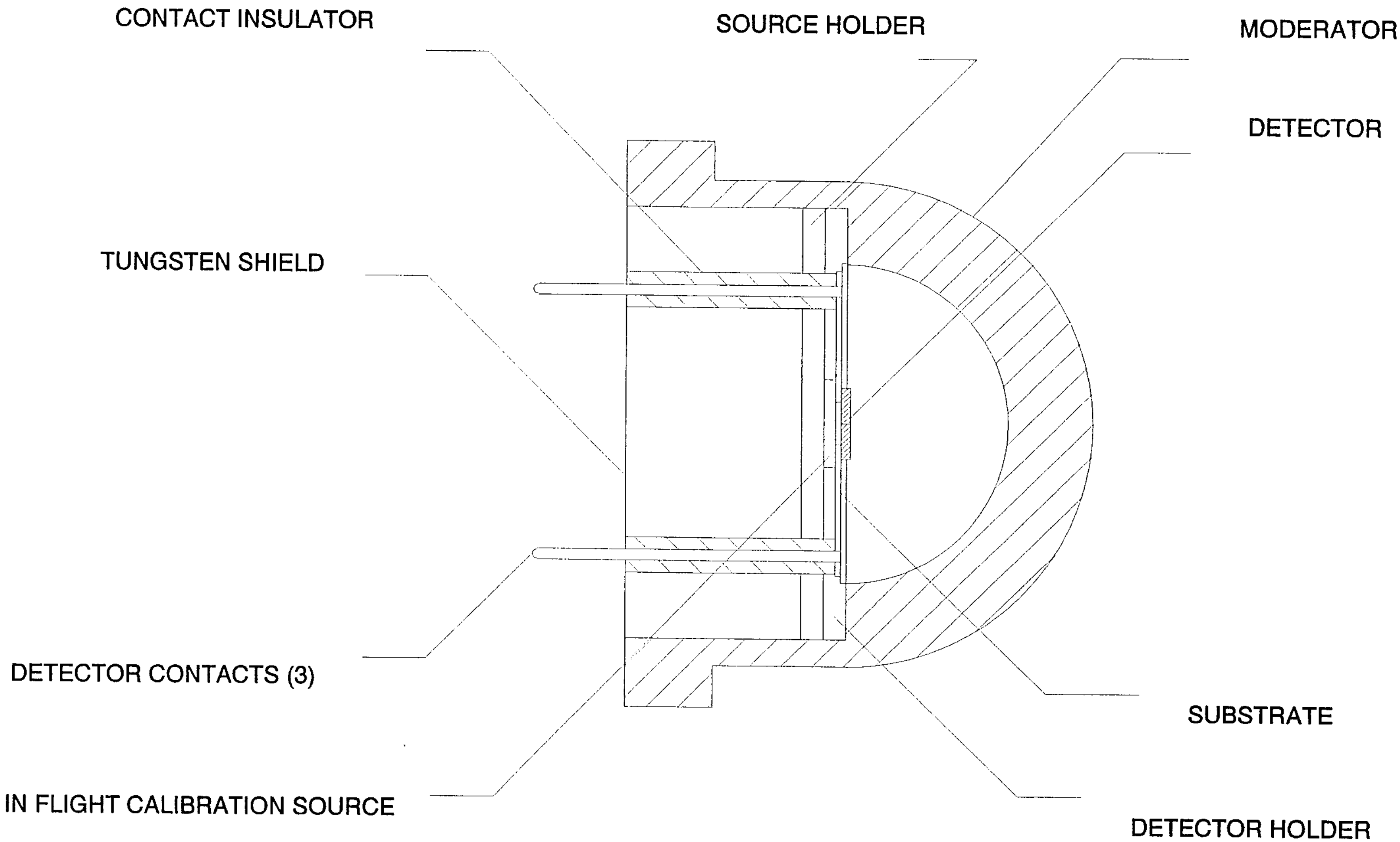


Figure 4. Dome 3 Cross Section

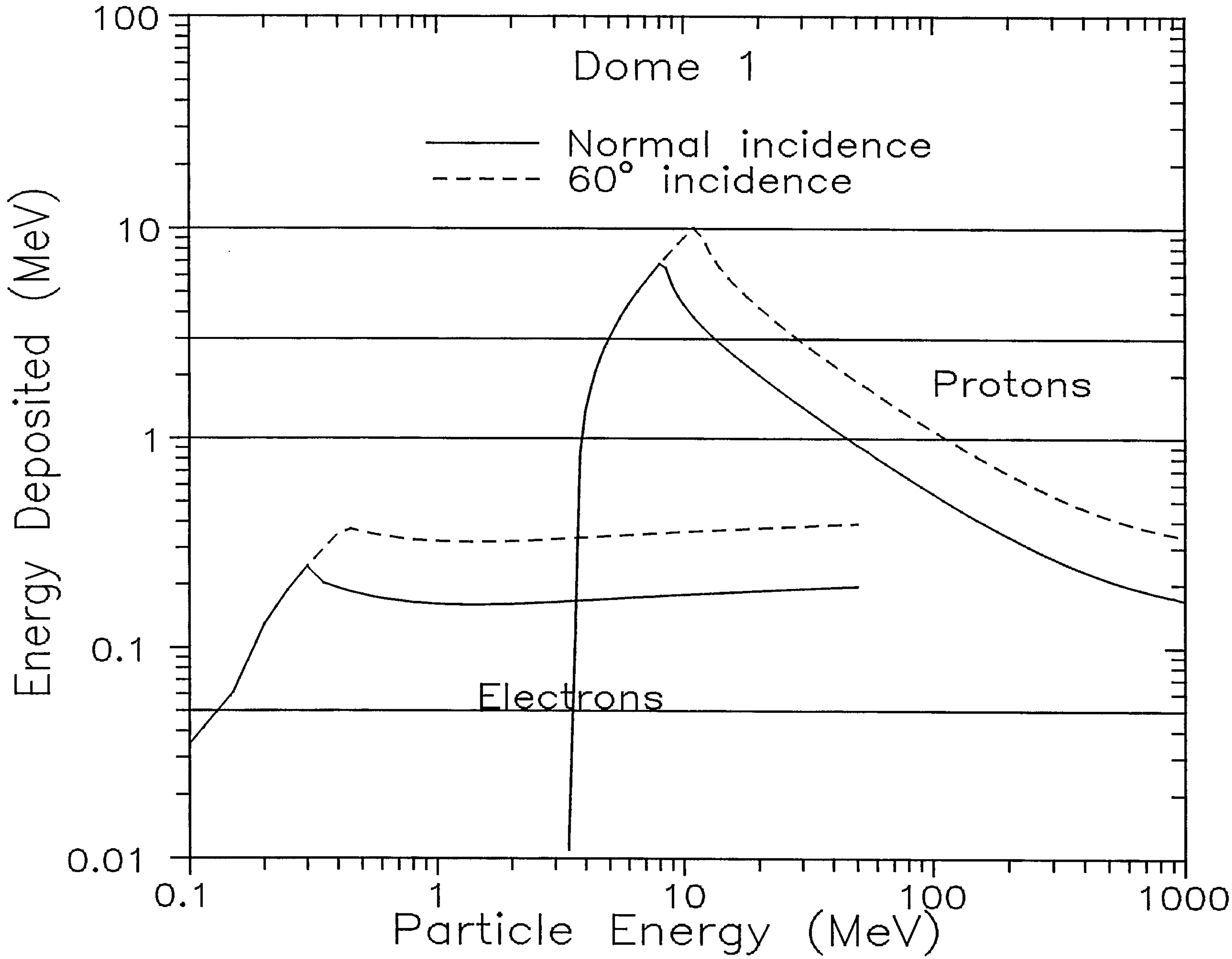


Figure 5. Dome 1 Energy Deposition Curves

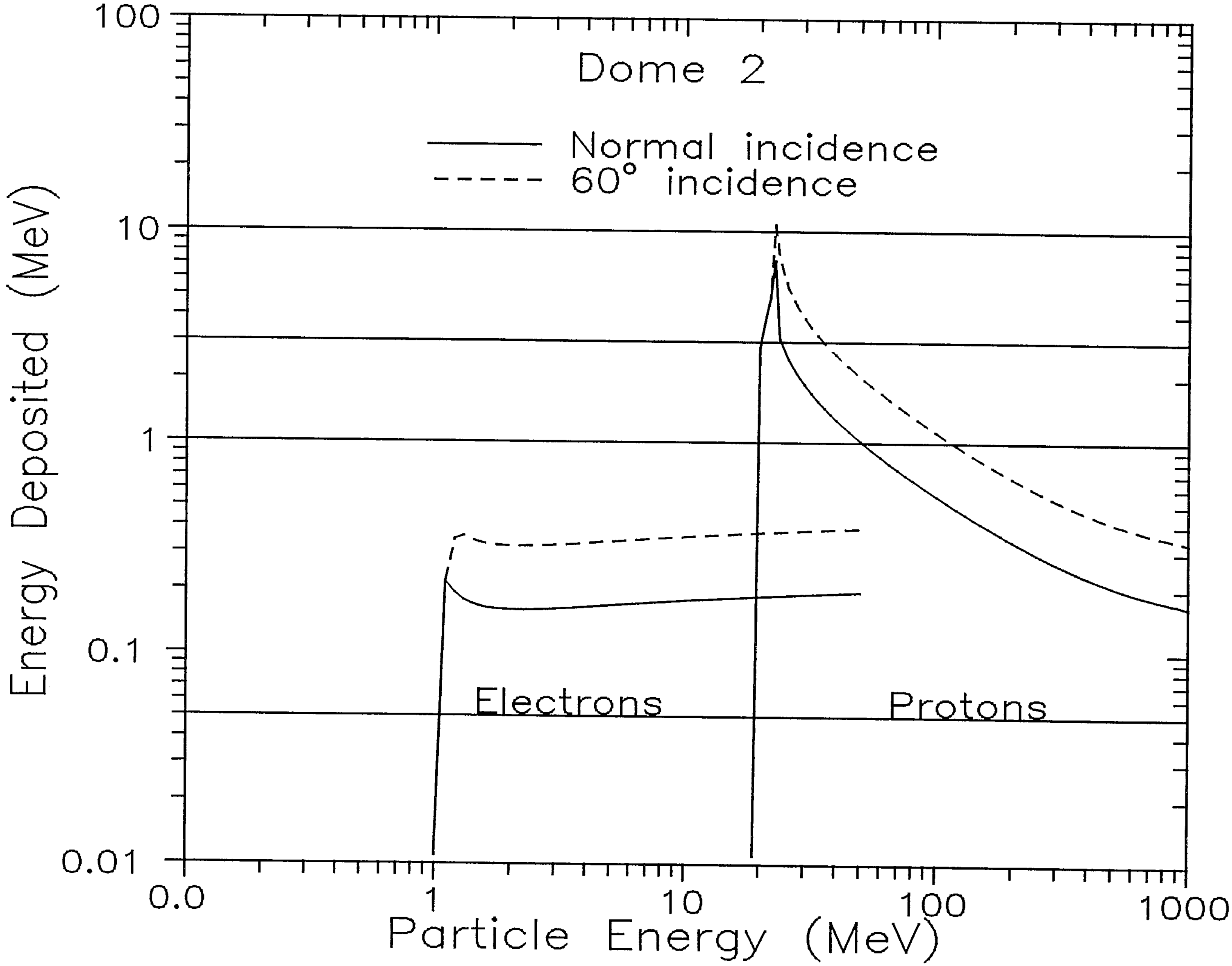


Figure 6. Dome 2 Energy Deposition Curves

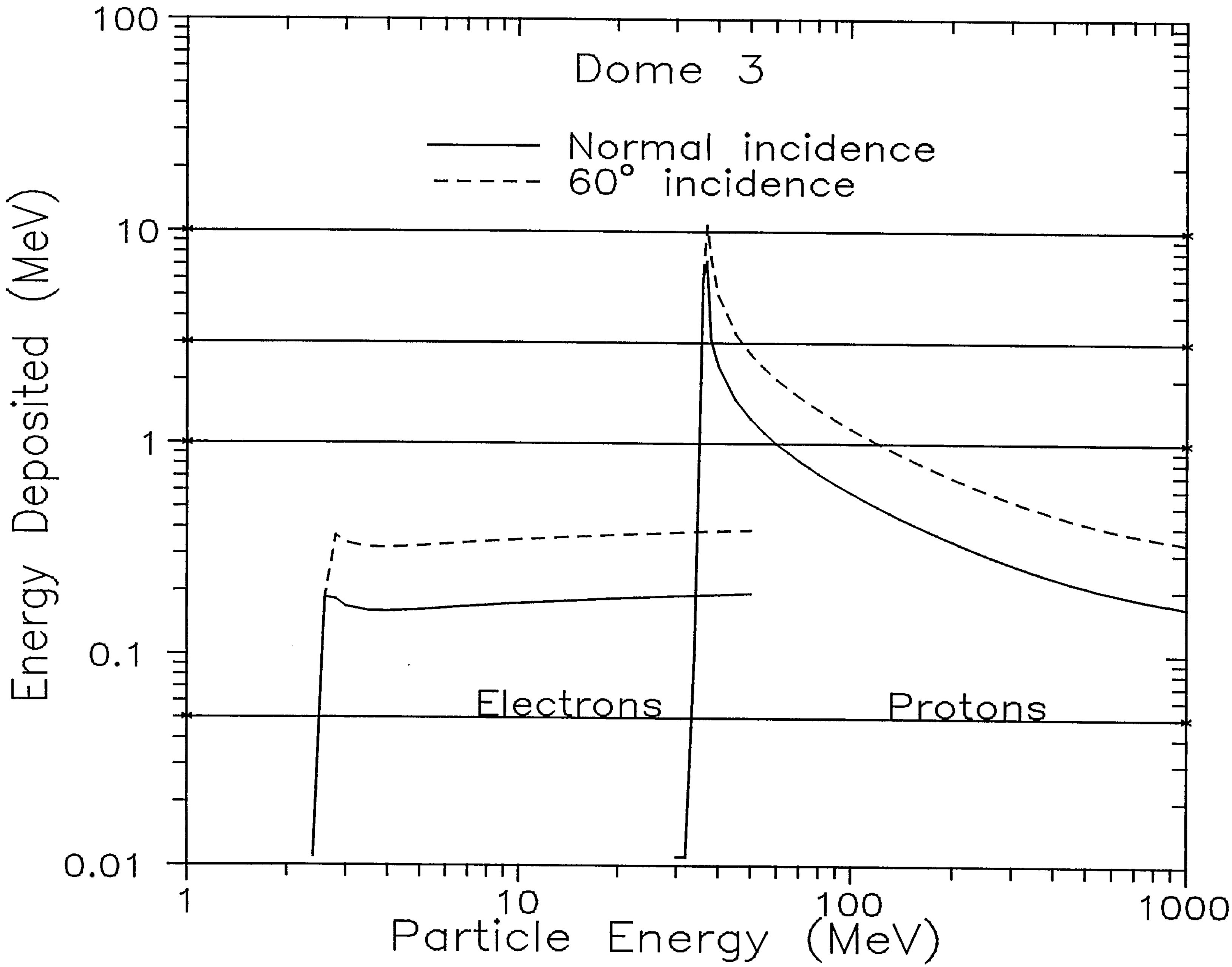


Figure 7. Dome 3 Energy Deposition Curves

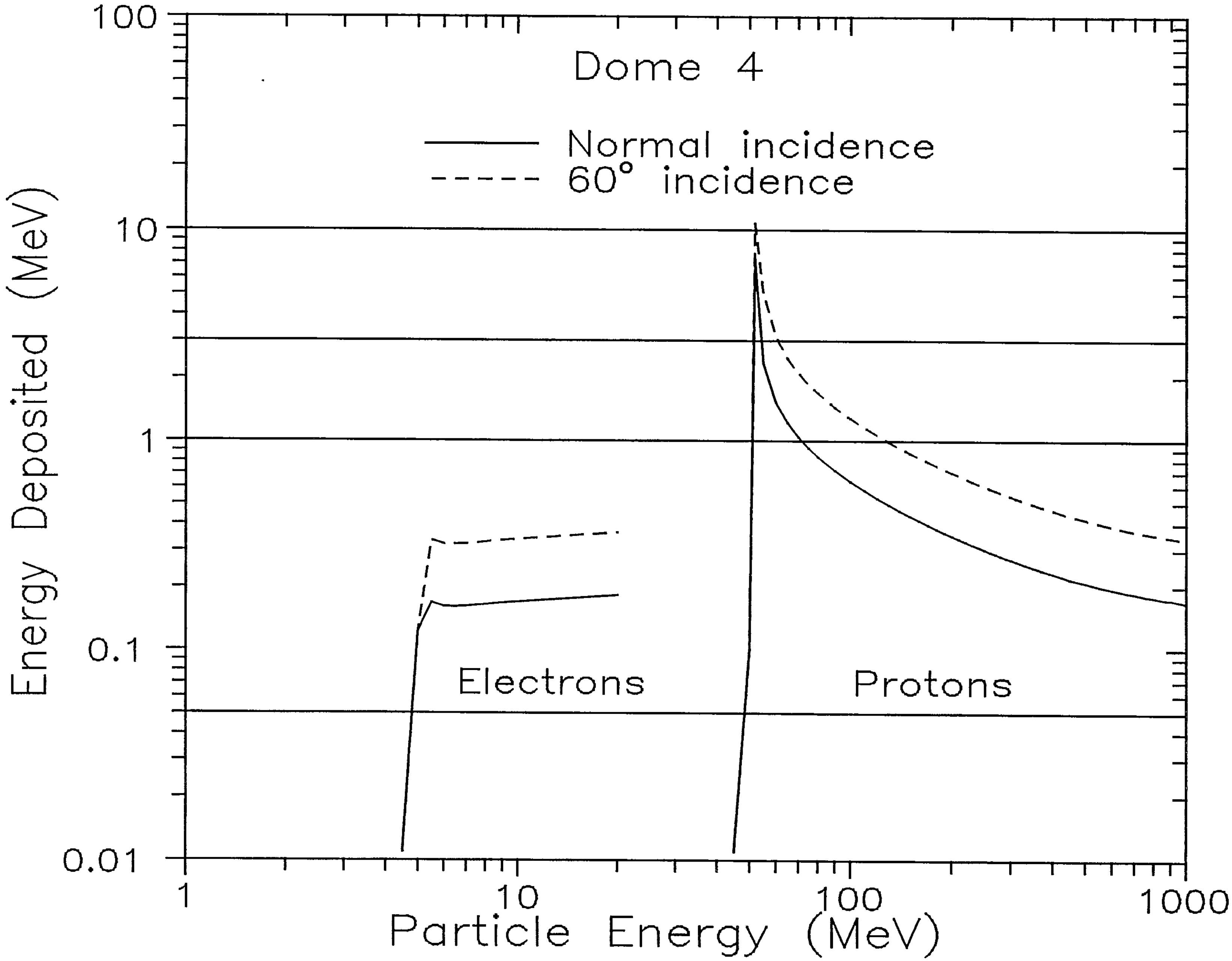


Figure 8. Dome 4 Energy Deposition Curves

2.2 Electronics

2.2.1 Charge Sensitive Pre-Amplifier and Analog Signal Processor

A block diagram of the Charge Sensitive Pre-Amplifier (CSPA) and Analog Signal Processor (ASP) circuitry is shown in Figure 9. A signal-processing timing diagram is shown in Figure 10. The SSD generates a charge signal proportional to the energy deposited in its sensitive volume by an incident particle. The CSPA collects the charge pulse and converts it to an amplified unipolar voltage pulse, which is further amplified and converted to a bipolar pulse by the shaping amplifiers. Particles that deposit more than 50 keV in the SSD trigger the 50 keV level discriminator, which increments a 24-bit event counter (TOTAL COUNT) and enables the zero-cross discriminator. The zero-cross discriminator fires on the subsequent bipolar signal zero crossing, strobing the flash 8-bit analog to digital converter (ADC) such that the delayed bipolar signal is sampled at its peak amplitude. The ADC data (DOSE) is latched, and a data processor interrupt signal is generated. The data processor subsequently reads the ADC data and resets the data latch and timing circuitry – enabling the ASP to process the next event. Note that the ADC normally "freeruns" at 20 kHz in order to reduce power consumption. Particles which deposit more than 40 MeV (75 Mev for D4) in the SSD trigger the 40 MeV level discriminator, which increments an 8-bit counter (VHILET COUNT). The data processor reads and resets the 24-bit TOTAL COUNT and 8-bit VHILET COUNT counters every 6 seconds. There are six (6) identical CSPA/ASP's, one for each Solid-State Detector (SSD). The six (6) CSPA's are contained on a single printed circuit board, while there are six (6) identical ASP printed circuit boards. A temperature monitor on the CSPA printed circuit board is subcommutated in the telemetered data.

2.2.2 Data Processor

A block diagram of the data processing circuitry is shown in Figure 11. The data processor is built around United Technology's 1750A microprocessor. The 1750A is available radiation-hardened, and is single-event-upset immune. It is a CMOS, 16-bit, Harvard Architecture (separate program and data memory), Reduced Instruction Set Computer (RISC), which can run at speeds of up to 12 MHz. It contains a Universal Asynchronous Receiver/Transmitter (UART) and two 16-bit timers.

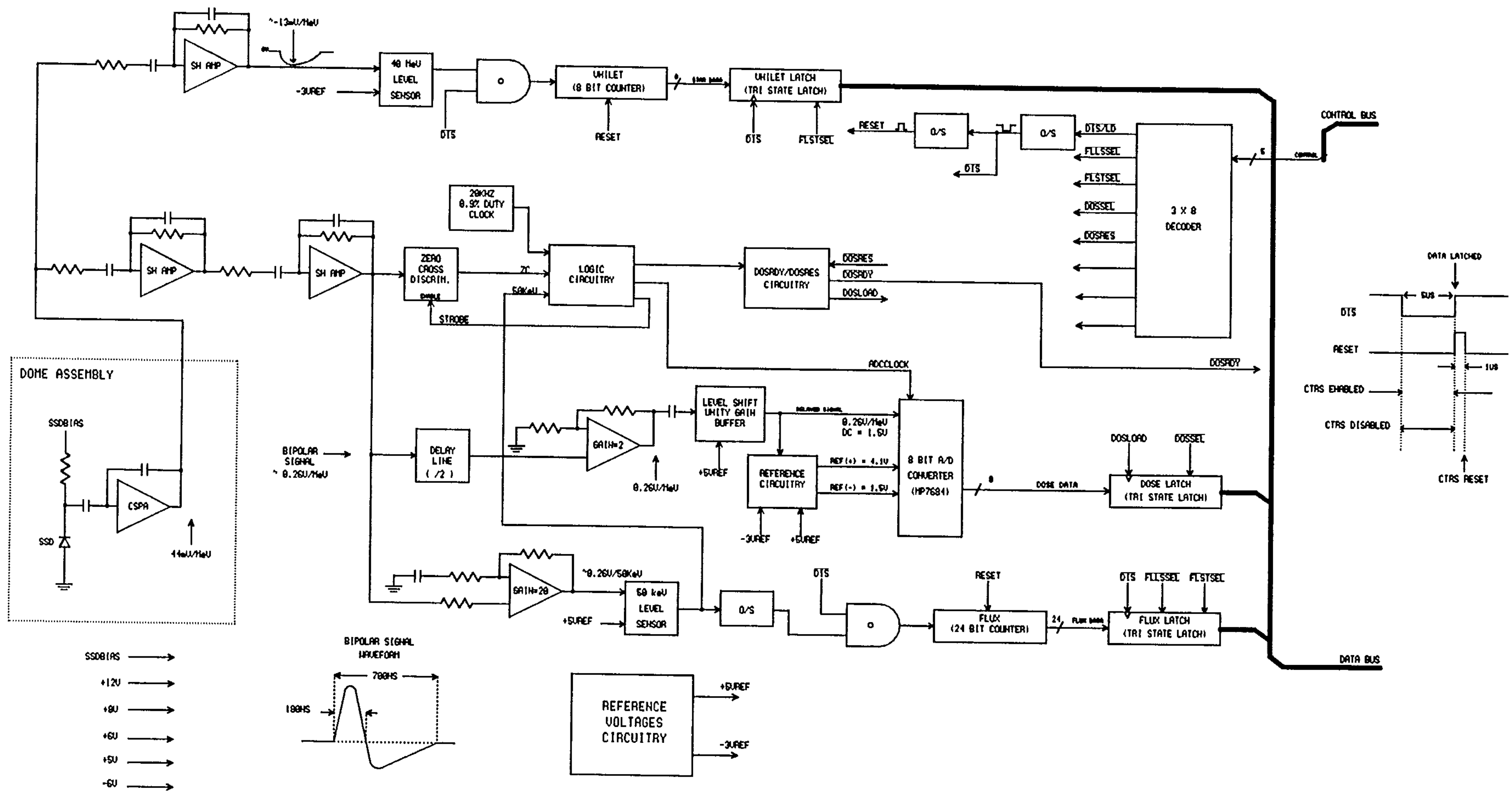


Figure 9. Charge Sensitive Preamplifier and Analog Signal Processor Block Diagram

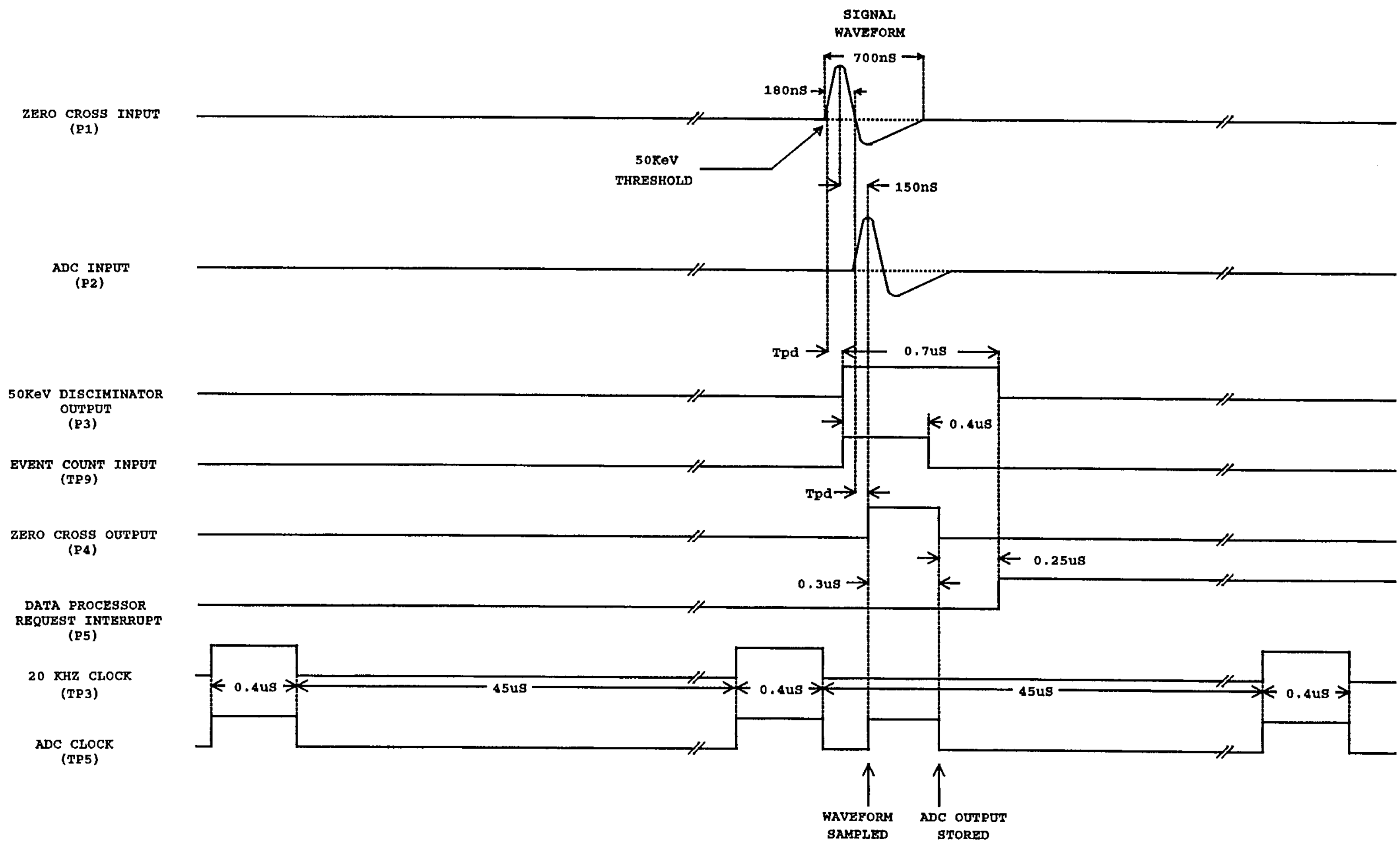


Figure 10. Analog Signal Processing Timing Diagram

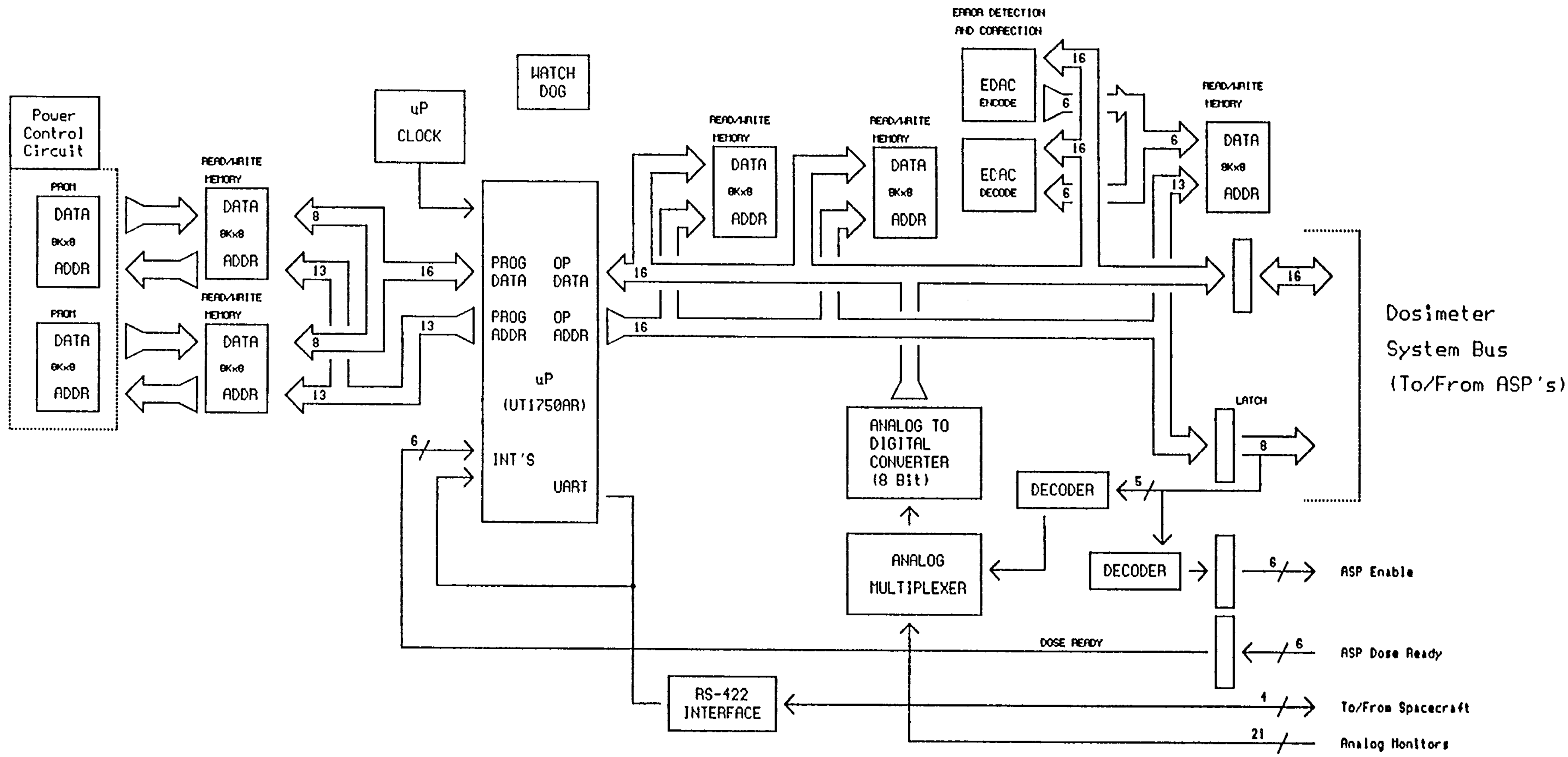


Figure 11. Data Processor Block Diagram

A 24 MHz crystal-controlled oscillator is divided by 2 to provide a 12 MHz clock (uP CLOCK) to the microprocessor. There are 8K (8192 16-bit words) of program rad-hard bipolar programmable read only memory (PROGRAM PROM) and 8K (8192 16-bit words) of program low-power CMOS read/write memory (PROGRAM RAM). Program execution may be from either PROGRAM PROM or PROGRAM RAM, as selected by ground command. In normal operation PROGRAM PROM is loaded into PROGRAM RAM, and PROGRAM PROM is powered off to reduce power consumption (program execution is out of PROGRAM RAM). Program changes may be uplinked by ground command. There are also 8K (8192 16-bit words) of data read/write memory (DATA RAM). PROGRAM RAM and DATA RAM are single-event-upset immune. Error Detection and Correction (EDAC) corrects all single bit DATA RAM errors. Uncorrectable multi-bit DATA RAM errors are reported in the telemetered data. The EDAC is enabled/disabled by ground command.

ASP data collection and control are provided via the system data/address bus. The UART provides the spacecraft command/data communications link, via an EIA RS-422 balanced electrical interface. Twenty-one (21) critical analog monitors are digitized and incorporated in the telemetered data. A watchdog circuit provides positive indication of proper program execution.

2.2.3 DC-to-DC Converter

A block diagram of the DC-to-DC Converter is shown in Figure 12. The input bus filter attenuates bus transients and ripple. The high efficiency (~89%) switching regulator generates five (5) output voltages (+12 +8, +6, +5 and -6 volts). Feedback from the +5V output provides line and load regulation for that output, and line regulation for the remaining outputs. Post regulators generate two (2) well regulated output voltages (+8VREF and +5VREF). A Cockroft-Walton voltage multiplier generates an unregulated +300V which is applied to six (6) high-voltage regulators, which provide regulated bias voltages for the solid-state detectors. Analog monitors for all output voltages (13 total) are subcommutated in the telemetered data. Secondary return (signal ground) is isolated from primary return (+28V return). Input current is limited to 150% of the worst case nominal input current. Two (2) temperature monitors are provided, one unconditioned (passive), the other conditioned (active). The passive temperature monitor is read directly by the spacecraft, allowing the Dosimeter's temperature to be determined whether the Dosimeter power is on or off. The active temperature monitor is subcommutated in the telemetered data.

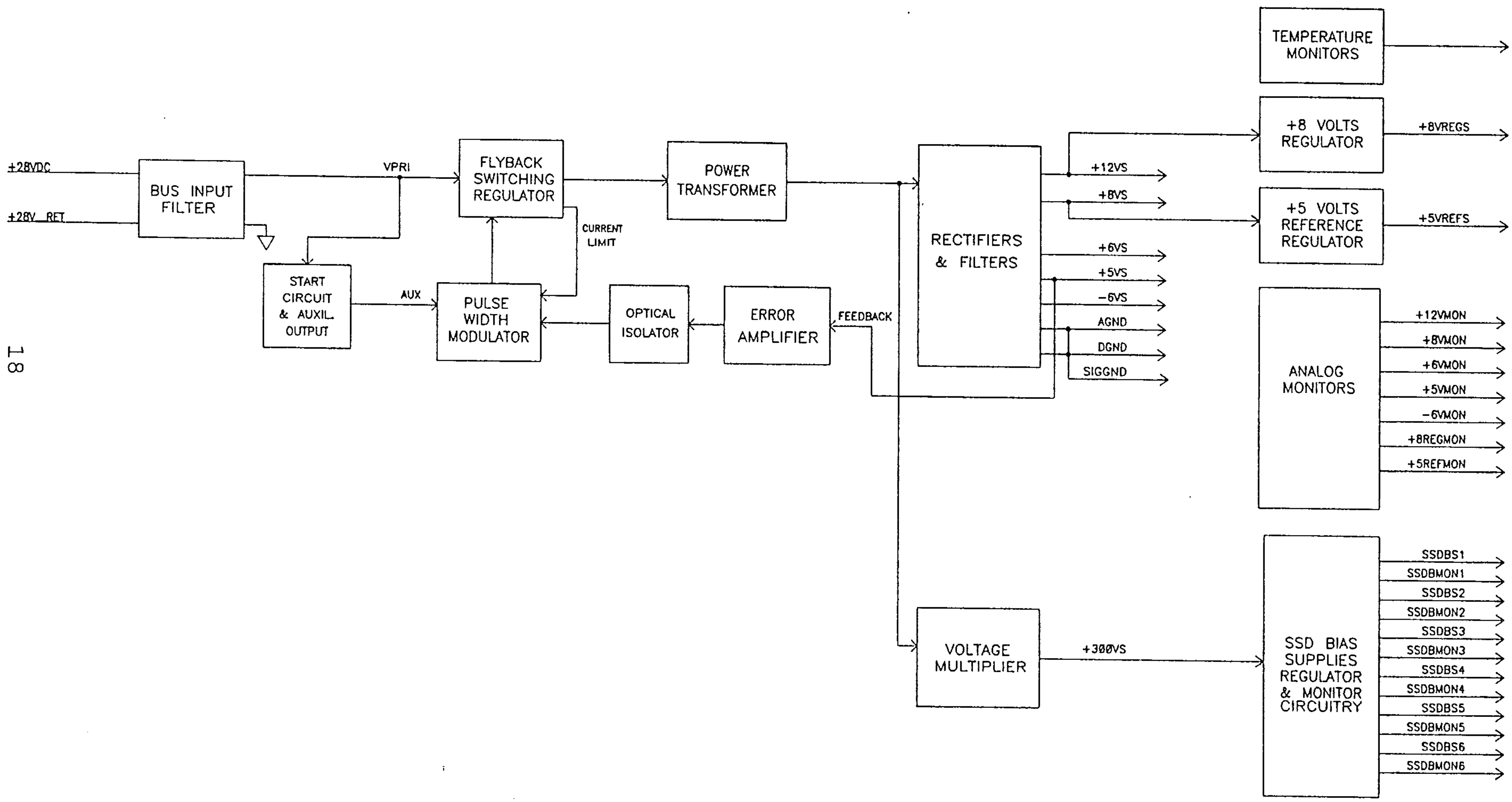


Figure 12. DC-to-DC Converter Block Diagram

2.3 Software

The software flowcharts are shown in Figures 13 through 15. The power-up sequence and the program executive (the main microprocessor loop) are shown in Figure 13. Following the power-up sequence, telemetry output and various housekeeping tasks are handled in the main loop, which runs in the background. Each of the six ASP's, as well as the serial command/data interface, are handled via fast polling loops and interrupt latches.

The ASP polling and processing flow charts are shown in Figure 14. If a detector is struck by an incident particle that deposits more than 50 keV in the detector, an interrupt flag is latched. The resulting dose is read by the microprocessor and various counters are incremented appropriately. Eight (8) data entities, as shown in Table 3, are generated for each detector.

The serial-input processing flow chart is shown in Figure 15. An interrupt flag is latched whenever a command is received from the spacecraft. Of the several commands that have been defined, as shown in Table 4, only the first two (the telemetry packet request commands) are detailed in Figure 15. Under normal conditions, telemetry packet request commands are to be received from the spacecraft at a fixed rate of once per second. Housekeeping telemetry packets, as defined in Table 5, are used primarily to verify proper instrument operation at turn-on. Once proper Dosimeter operation is established, normal data packets, as defined in Tables 6 and 7, are used to transfer all primary science data (PSD) and some housekeeping data to the spacecraft. Note that the PSD is time multiplexed. The PSD for one detector is transferred to the spacecraft in each normal data packet. Thus, six (6) data packets (6 seconds) are required to read all of the PSD, and each detector's PSD is accumulated for six (6) seconds. The normal telemetry packet data accumulation and transfer timing is shown in Figure 16.

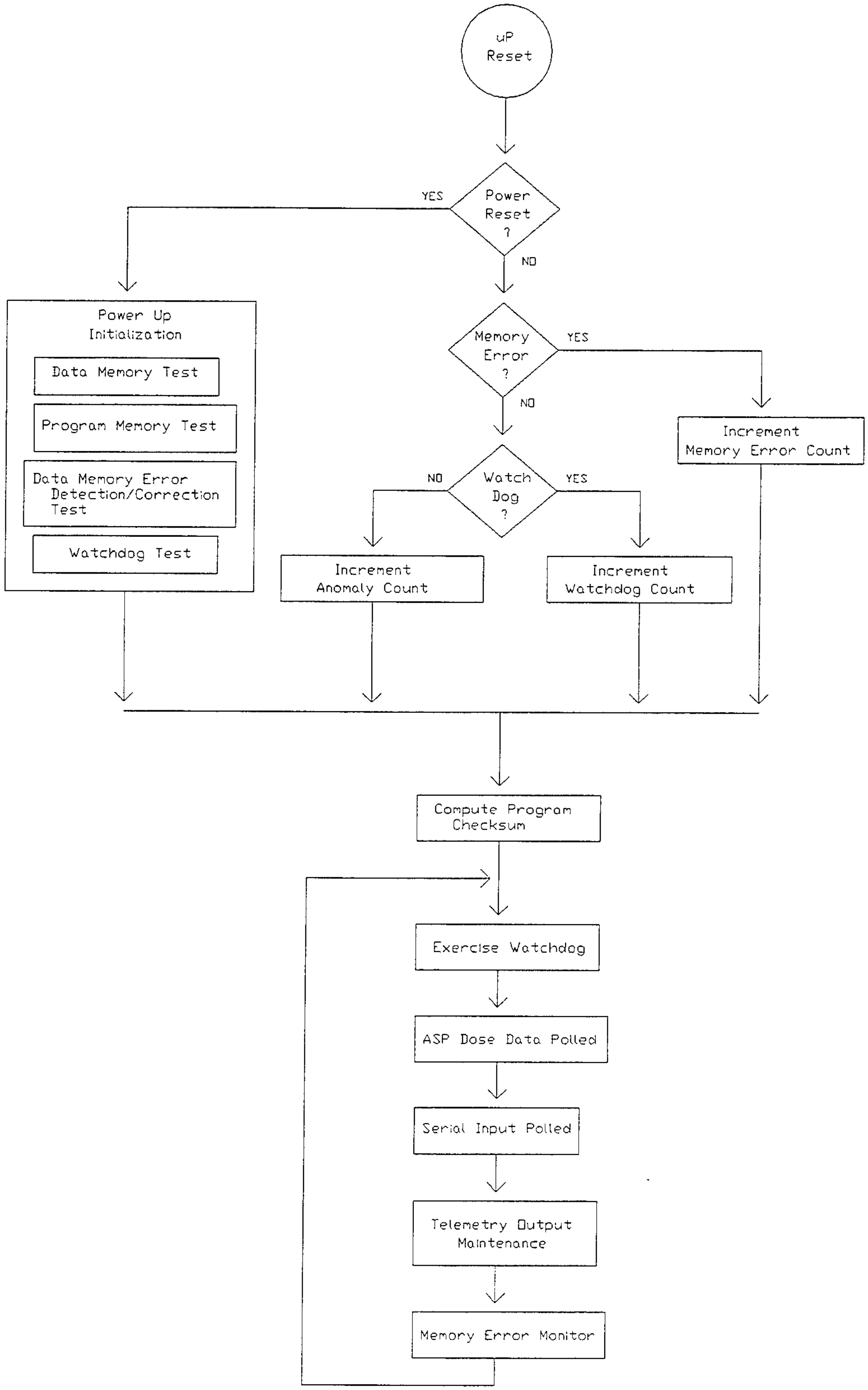


Figure 13. Power Up and Program Executive Software Flow Chart

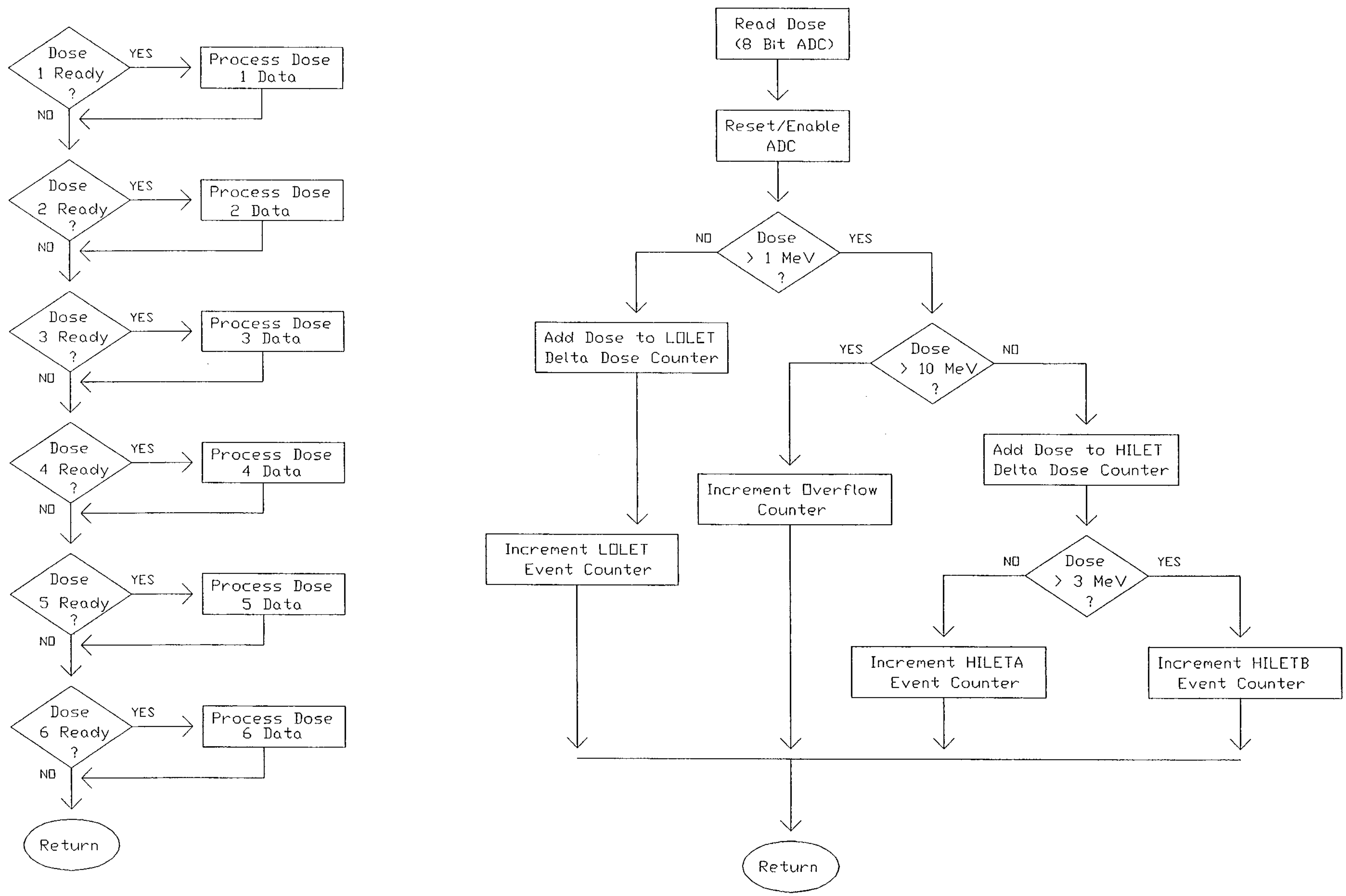


Figure 14. ASP Polling and Processing Software Flow Charts

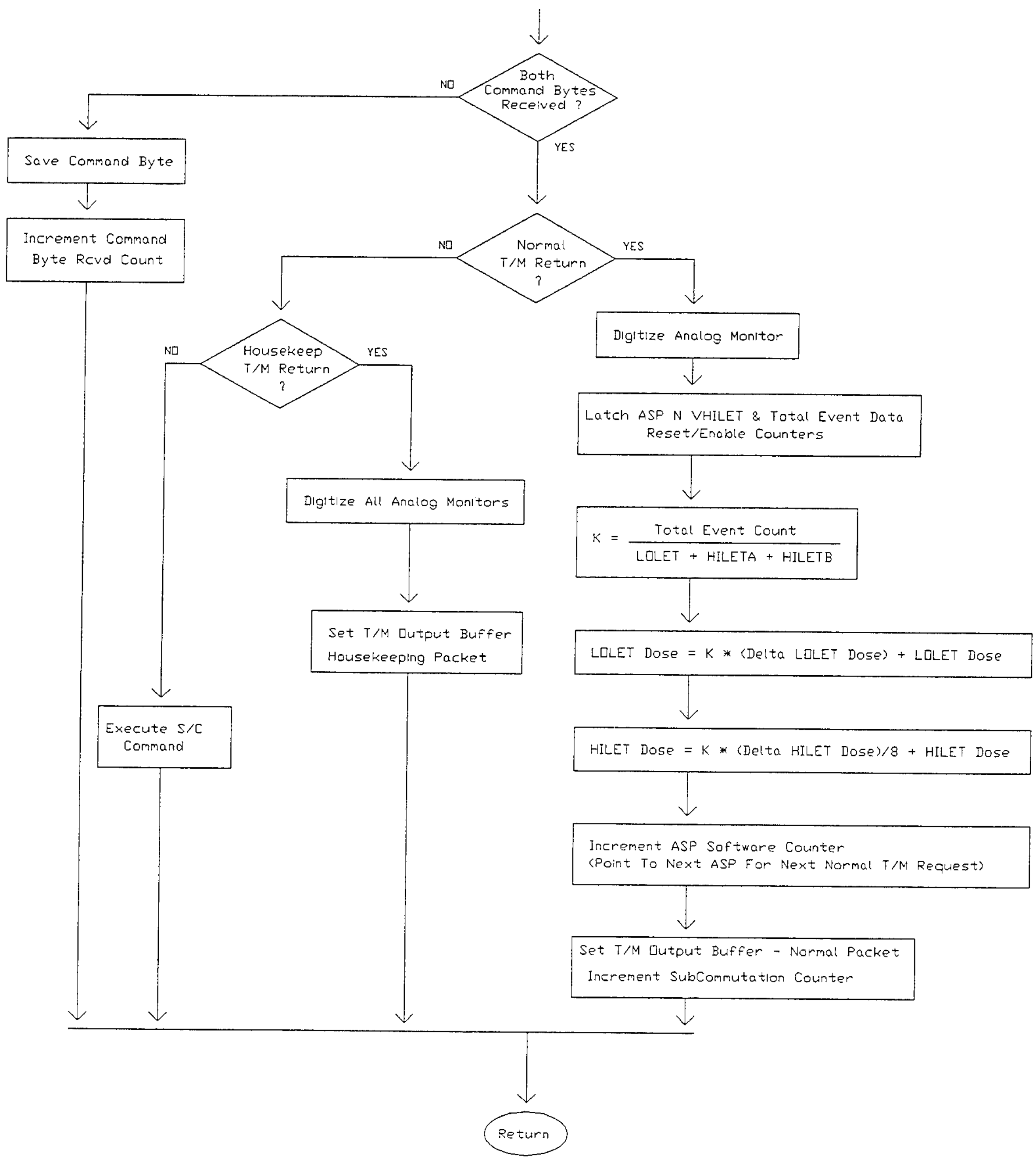


Figure 15. Serial Command/Data Software Flow Chart

Table 3.
Primary Science Data Entities

Entity	Mnemonic
Processed 50 keV to 1 MeV Event Count	LOLET COUNT
Processed 1 MeV to 3 Mev Event Count	HILETA COUNT
Processed 3 Mev to 10 MeV Event Count	HILETB COUNT
Processed Digital to Analog Converter Overflow Event Count (≥ 10 MeV)	OVERFLOW COUNT
Very High Energy Deposition Event Count (≥ 40 MeV for D1A, D1B, D2A, D2B and D3) (≥ 75 MeV for D4)	VHILET COUNT
Total Event Count (≥50 keV)	TOTAL COUNT
50 keV to 1 MeV Dose	LOLET DOSE
1 MeV to 10 MeV Dose	HILET DOSE

Table 4.
Dosimeter Commands

Second Byte MSB LSB 8 7 6 5 4 3 2 1	First Byte MSB LSB 8 7 6 5 4 3 2 1	Action/Response/Comments
0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	Return normal telemetry packet Note - This command must be sent at 1 second ± 0.01 second intervals for normal Dosimeter operation
0 0 1 0 0 0 0 0	0 0 0 0 0 0 0 0	Return housekeeping telemetry packet
0 1 0 0 0 0 0 0	0 0 0 0 0 0 0 0	Reset dose counters
0 1 0 0 0 0 1 1	0 0 0 0 0 0 0 0	Enable data memory EDAC
0 1 0 0 0 1 0 0	0 0 0 0 0 0 0 0	Disable data memory EDAC
0 1 0 0 0 1 0 1	0 0 0 0 0 0 0 0	Reset fault flags
0 1 0 0 0 1 1 0	0 0 0 0 0 0 0 0	Test watchdog
0 1 1 A A A A A	A A A A A A A A	Power down PROM and run out of RAM (AA...A = 13 bit starting address)
1 0 0 A A A A A	A A A A A A A A	Power up PROM and run out of PROM (AA...A = 13 bit starting address)
1 0 1 C C C C C 1 1 0 A A A A A 1 1 1 0 0 0 0 0 . . . . 1 1 1 0 0 0 0 0	C C C C C C C C A A A A A A A A D D D D D D D D . . . . D D D D D D D D	Upload block of data to Dosimeter RAM (CC...C = 13 bit data byte count) (AA...A = 13 bit starting address) (DD...D = 8 bit data byte) Program data must be sent in byte pairs with the least significant byte sent first, followed by the most significant byte

Bit 8 is the Most Significant Bit (MSB)
Bit 1 is the Least Significant Bit (LSB)
LSB (Bit 1) is the first bit shifted out

Table 5.
Housekeeping Telemetry Packet Data Assignment

Byte No.	Bits	Contents
1	0-7	Frame ID, MSB (Bit 7) = 1 identifies housekeeping packet
2	0-7	D1A Detector Bias Voltage Monitor
3	0-7	D1B Detector Bias Voltage Monitor
4	0-7	D2A Detector Bias Voltage Monitor
5	0-7	D2B Detector Bias Voltage Monitor
6	0-7	D3 Detector Bias Voltage Monitor
7	0-7	D4 Detector Bias Voltage Monitor
8	0-7	D1A Reference Voltage Monitor
9	0-7	D1B Reference Voltage Monitor
10	0-7	D2A Reference Voltage Monitor
11	0-7	D2B Reference Voltage Monitor
12	0-7	D3 Reference Voltage Monitor
13	0-7	D4 Reference Voltage Monitor
14	0-7	+12V Monitor
15	0-7	+8V Monitor
16	0-7	+6V Monitor
17	0-7	+5V Monitor
18	0-7	+5V Reference Monitor
19	0-7	-6V Monitor
20	0-7	Regulated +8V Monitor
21	0-7	Detector Temperature Monitor
22	0-7	Electronics Temperature Monitor
23	0-3	Watchdog Count
23	4-7	Program Memory Fault Count
24	0-3	Data Memory Single Bit Fault Count
24	4-7	Data Memory Multiple Bit Fault Count

LSB (Bit 0) is the first bit shifted out
Byte 1 is the first byte shifted out

Table 5 (continued). Housekeeping Telemetry Packet Data Assignment

Byte No.	Bits	Contents
25	0	Data EDAC Memory Enable Flag (Active Lo) (0 = EDAC Memory Enabled, 1 = EDAC Memory Disabled)
25	1	Data EDAC Enable Flag (0 = EDAC Disabled, 1 = EDAC Enabled)
25	2	Program Memory ID (0=PROM, 1=RAM)
25	3	Spare
25	4	PROM Power On Flag
25	5-7	Spare
26	0-7	Last Command Most Significant Byte (Data Byte)
27	0-7	Last Command Least Significant Byte (Command Byte)
28	0	Program RAM Fault Flag
28	1	Serial Input Fault
28	2	Data Memory Single Bit Fault Flag
28	3	Data Memory Multiple Bit Fault Flag
28	4	Program Anomaly Fault
28	5	Data Memory EDAC Fault Flag
28	6	Watchdog Test Fault Flag
28	7	Watchdog Bite Flag
29	0-7	First Program Memory Error Least Significant Address Bits
30	0-4	First Program Memory Error Most Significant Address Bits
30	5-7	Number of Program Memory Errors Detected
31	0-7	First Data Memory Error Least Significant Address Bits
32	0-4	First Data Memory Error Most Significant Address Bits
32	5-7	Number of Data Memory Errors Detected
33	0-7	Telemetry Packet Checksum, Most Significant Byte
34	0-7	Telemetry Packet Checksum, Least Significant Byte

LSB (Bit 0) is the first bit shifted out
Byte 1 is the first byte shifted out

Table 6. Normal Telemetry Packet Data Assignment

Byte No.	Contents	Description
1	FRAME ID	MSB (Bit 7) = 0 identifies NORMAL telemetry packet Primary Science Data (PSD) Channel Identifier (= 0, 6, 12, 18 for D1A PSD data readout) (= 1, 7, 13, 19 for D1B PSD data readout) (= 2, 8, 14, 20 for D2A PSD data readout) (= 3, 9, 15, 21 for D2B PSD data readout) (= 4, 10, 16, 22 for D3 PSD data readout) (= 5, 11, 17, 23 for D4 PSD data readout) Also, Housekeeping Subcommutator Frame Identifier (see Table 7)
2	VHILET COUNT	PSD Very High Energy Deposition Event Count
3-5*	TOTAL COUNT	PSD Total Event Count (≥ 50 keV)
6-8*	LOLET COUNT	PSD Processed 50 keV to 1 MeV Event Count
9-11*	HILETA COUNT	PSD Processed 1 MeV to 3 Mev Event Count
12-14*	HILETB COUNT	PSD Processed 3 MeV to 10 MeV Event Count
15-19*	LOLET DOSE	PSD 50 keV to 1 MeV Dose
20-24*	HILET DOSE	PSD 1 MeV to 10 MeV Dose
25-26*	OVERFLOW COUNT	PSD A to D Converter Overflow Count (≥ 10 MeV)
27	COMMAND MSB	Last Command MSB (Data Byte)
28	COMMAND LSB	Last Command LSB (Command Byte)
29	FAULT FLAGS	Bit 0 = Program RAM Fault Flag Bit 1 = Serial Input Fault Flag Bit 2 = Data Memory Single Bit Fault Flag Bit 3 = Data Memory Multiple Bit Fault Flag Bit 4 = Program Anomaly Flag Bit 5 = Data Memory EDAC Fault Flag Bit 6 = Watchdog Test Fault Flag Bit 7 = Watchdog Bite Flag
30	PRG CKSUM MSB	Program Checksum, Most Significant Byte
31	PRG CKSUM LSB	Program Checksum, Least Significant Byte
32	HOUSEKEEPING	Subcommutated Housekeeping Data (see Table 7)
33	TM CKSUM MSB	Telemetry Packet Checksum, Most Significant Byte
34	TM CKSUM LSB	Telemetry Packet Checksum, Least Significant Byte

LSB (Bit 0) is the first bit shifted out
Byte 1 is the first byte shifted out
* First byte shifted out (low numbered byte) is the least significant byte

Table 7.
Normal Telemetry Packet Subcommutated Data Assignment

Frame ID (Byte 1 of Normal Telemetry Packet)	Bits	Housekeeping Data (Byte 32 of Normal Telemetry Packet)
0	0-7	D1A Detector Bias Voltage Monitor
1	0-7	D1B Detector Bias Voltage Monitor
2	0-7	D2A Detector Bias Voltage Monitor
3	0-7	D2B Detector Bias Voltage Monitor
4	0-7	D3 Detector Bias Voltage Monitor
5	0-7	D4 Detector Bias Voltage Monitor
6	0-7	D1A Reference Voltage Monitor
7	0-7	D1B Reference Voltage Monitor
8	0-7	D2A Reference Voltage Monitor
9	0-7	D2B Reference Voltage Monitor
10	0-7	D3 Reference Voltage Monitor
11	0-7	D4 Reference Voltage Monitor
12	0-7	+12V Monitor
13	0-7	+8V Monitor
14	0-7	+6V Monitor
15	0-7	+5V Monitor
16	0-7	+5V Reference Monitor
17	0-7	-6V Monitor
18	0-7	Regulated +8V Monitor
19	0-7	Detector Temperature Monitor
20	0-7	Electronics Temperature Monitor
21	0-3	Watchdog Count
21	4-7	Program Memory Fault Count
22	0-3	Data Memory Single Bit Fault Count
22	4-7	Data Memory Multiple Bit Fault Count
23	0	Data EDAC Memory Enable Flag (Active Lo)
23	1	Data EDAC Enable Flag
23	2	Program Memory ID, 0=PROM, 1=RAM
23	3	Spare
23	4	PROM Power On Flag
23	5	Spare
23	6	Spare
23	7	Spare
LSB (Bit 0) is the first bit shifted out		

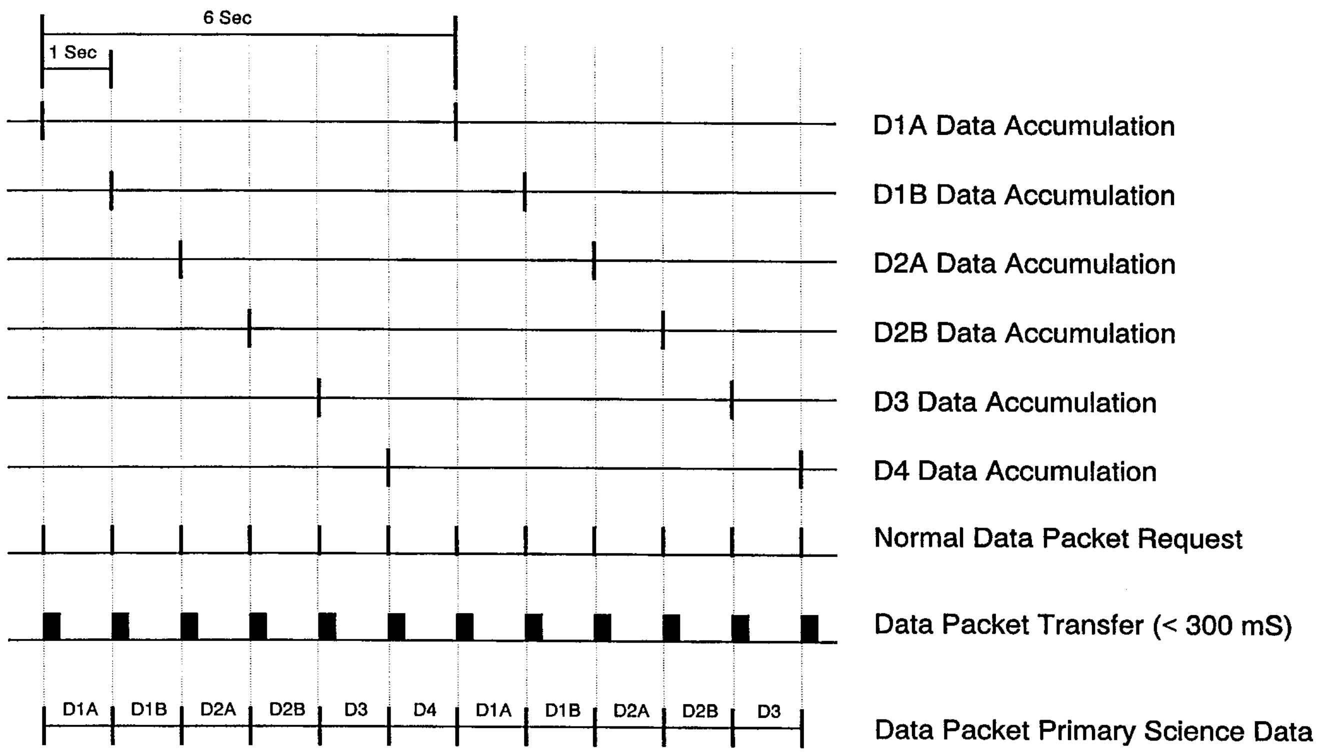


Figure 16. Normal Telemetry Packet Data Accumulation and Transfer Timing

2.4 Mechanical

An isometric drawing of the Dosimeter, with the top cover removed, is shown in Figure 17. The Dosimeter's Interface Control Drawing (ICD) is shown in Figure 18.

The six (6) CSPA's are on a single printed circuit board (PCB) which is located directly behind the SSD's. The six (6) ASP's (one PCB each), Data Processor (1 PCB) and DC-to-DC Converter (2 PCB's) plug into a motherboard, which provides the interboard connections. The ASP's are isolated from the Data Processor and DC-to-DC Converter by electrostatic shields which plug into the motherboard.

3. TEST AND CALIBRATION

Dosimeter testing and calibration was divided into four distinct phases, as follows:

a) Breadboard testing during the design process.
b) Initial integration and functional testing of the flight instruments.
c) Accelerator calibration of one of the flight instruments.
d) Qualification or acceptance testing of the flight instruments.

3.1 Breadboard Tests

Extensive CSPA/ASP breadboard tests at room ambient temperature and over the temperature range of -55°C to +100°C were completed. The CSPA/ASP operates properly over this extended temperature range, and its stability over the anticipated Dosimeter operating temperature range (-25°C to +35°C) is well within that required for accurate dose measurements. Since 12 ASP boards are required (total for 2 Dosimeters), a single "engineering model" PCB was fabricated and tested thoroughly. Some minor modifications were incorporated into the PCB layout following completion of the "engineering model" PCB tests.

Rather than fabricating and testing a "conventional" breadboard of the data processing circuitry, an initial PCB layout was completed, and a "breadboard" PCB was fabricated. Testing of the "breadboard" PCB was completed, and the PCB layout was modified as required.

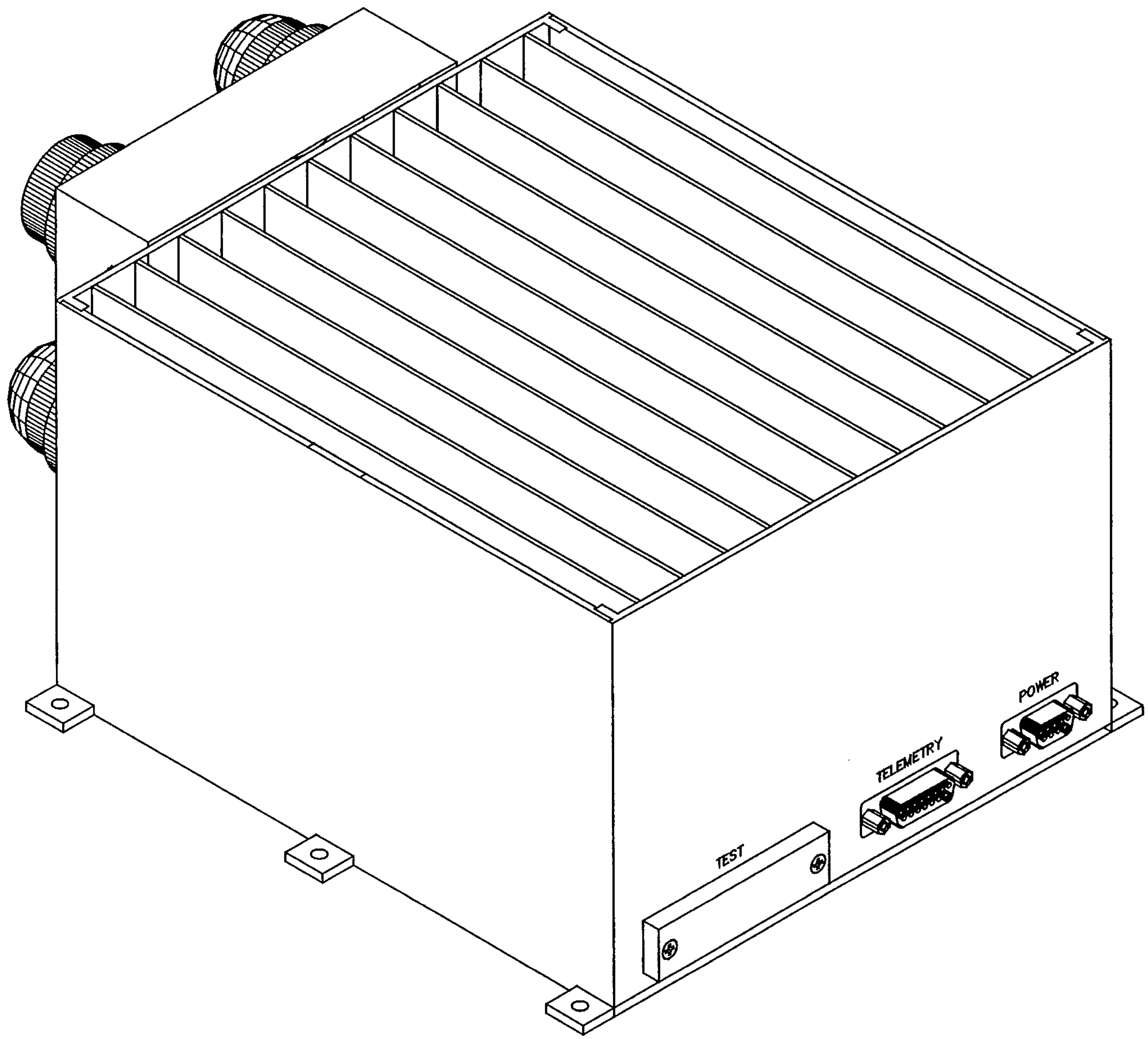


Figure 17. Isometric View of Dosimeter with Top Cover Removed

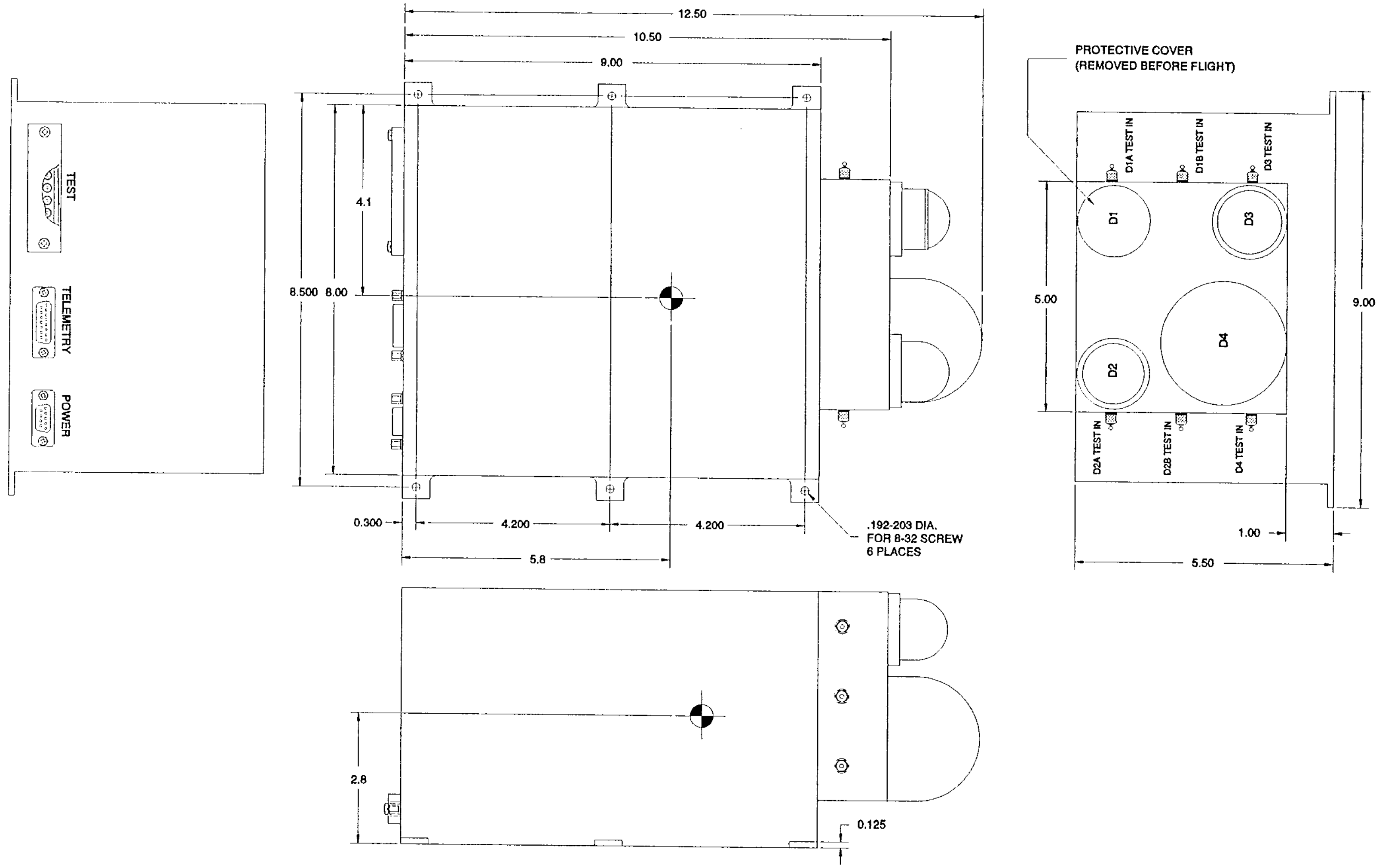


Figure 18. Dosimeter Interface Control Drawing

Extensive breadboard tests of the DC-to-DC Converter at room ambient temperature, and over the temperature range of -55°C to +125°C, were completed. The DC-to-DC Converter operates properly over this extended temperature range.

3.2 Integration and Functional Testing

Integration and functional testing begins with testing of the SSD's and PCB's. Many set-at-test parts which determine such parameters as gain, reference voltage levels, threshold firing levels, and logic timing, are initially adjusted at the PCB level. All circuit functions of each PCB are also fully exercised, including worst case interface conditions.

Final calibration, utilizing radioactive sources and electronic pulsers, is carried out following assembly and functional testing of the Dosimeter. Final amplifier gains and threshold firing levels are set at this time. Accelerator calibration of the Dosimeter is discussed in the following section.

This test phase concludes with an ambient pressure thermal test over the qualification temperature range, with Limited Performance Tests (LPT's) being carried out at several temperatures.

3.3 Accelerator Calibration

The DMSP and CRESS Dosimeters (References 1 and 2) were extensively calibrated with electrons and protons. These calibrations are applicable to this dosimeter's D2A, D2B, D3 and D4 channels. The Protoflight Dosimeter was calibrated at the MIT Van de Graaff accelerator with electrons from about 0.2 MeV to 3.1 MeV. The D1A, D1B, D2A, D2B and D3 channels were calibrated. Since protons do not scatter significantly the proton flux responses are close to the theoretical responses; therefore, accelerator calibration with protons is not required.

The LOLET flux channel angular responses for electrons are broad, being nearly uniform over the forward 2π sr. The calibrated electron responses of the LOLET channels can be fit by the following functions:

$$A_n(E,\theta) = A_n(E,0°)\ [(2 + 3\cos\theta)/5]$$

$$A_n(E,0°) = \begin{cases} 0 & \text{if } E/T_n < 1 \\ 1.5\ A_n^{\circ}\ (1 - T_n/E) & \text{if } 1 \le E/T_n \le 3 \\ A_n^{\circ} & \text{if } E/T_n \ge 3 \end{cases}$$

$$GF_n(E) = \begin{cases} 0 & \text{if } E/T_n < 1 \\ 7.38\ A_n^{\circ}\ (1 - T_n/E) & \text{if } 1 \le E/T_n \le 3 \\ 4.92\ A_n^{\circ} & \text{if } E/T_n \ge 3 \end{cases}$$

where A_n° is the calibrated SSD area at 0° and high energy, and T_n is the threshold energy determined by the range thickness of the shield.

The Backup Dosimeter Dose calibration factors are shown in Table 8. These factors are based on the SSD area, the measured SSD thickness, and the calibrated digitization level energies. Calibration factors convert the output dose counts into rads(Si) (= 100 erg/g(Si)). Also given are calibration constants to convert the output dose counts into Gy(Si) (= 1 J/kg(Si)). Total accumulated dose is given by:

$$D(SSD) = (\text{TM dose count}(SSD))\ X\ K(SSD)$$

where:

$$K(SSD) = \frac{(6.876\ X\ 10^{-8}\ rad/(TM\ dose\ count))\ X\ (Prescale)\ X\ (keV/digitizer\ count))}{A(SSD,\ cm^2)\ X\ thickness(SSD,\ microns)}$$

with (Prescale) = 1 for the LOLET dose counts and = 8 for the HILET dose counts.

As shown in Figures 3 and 4, a weak, degraded alpha particle source (Am-241) is located behind each solid state detector. These in-flight calibration sources are expected to be observable only near perigee. LOLET flux count rates due to the in-flight calibration sources may be masked by residual low energy ambient particles; however, HILETA and HILETB flux count rates will verify total solid state detector depletion and correct Analog Signal Processor gain. LOLET and HILET dose count rates will be used to verify overall Dosimeter operation. Note that in-flight calibration source count rates must be subtracted from the in-orbit data to provide the true ambient fluxes and doses. This is not expected to be significant except for the HILET data near perigee. In-flight calibration source count rates for the Backup Dosimeter are shown in Table 9.

Table 8.
Backup Dosimeter Dose Channel Calibration Factors

SSD	Area (cm^2)	Thickness (microns)	LOLET Dose Calibration			HILET Dose Calibration		
			keV / Digitizer count	rad / TM dose count	Gray / TM dose count	keV / Digitizer count	rad / TM dose count	Gray / TM dose count
D1A	0.00815	416	37.3	7.57×10^{-7}	7.57×10^{-9}	38.3	6.21×10^{-6}	6.21×10^{-8}
D1B	0.0514	393	38.4	1.306×10^{-7}	1.306×10^{-9}	39.2	1.067×10^{-6}	1.067×10^{-8}
D2A	0.00815	417	38.7	7.83×10^{-7}	7.83×10^{-9}	39.8	6.44×10^{-6}	6.44×10^{-8}
D2B	0.0514	382	39.1	1.369×10^{-7}	1.369×10^{-9}	40.1	1.123×10^{-6}	1.123×10^{-8}
D3	0.0514	400	37.6	1.257×10^{-7}	1.257×10^{-9}	39.1	1.045×10^{-6}	1.045×10^{-8}
D4	1.000	396	39.2	6.81×10^{-9}	6.81×10^{-11}	40.6	5.64×10^{-8}	5.64×10^{-10}

Table 9.
Backup Dosimeter In-Flight Calibration Source Count Rates

SSD	LOLET Count Rates (cps)		HILET Count Rates (cps)				
	Flux	Dose	HILETA Flux	HILETB Flux	HILETA / HILETB	Actual Dose	Telemetered Dose*
D1A	0.091	8.6	0.137	0.250	0.548	78.6	9.83
D1B	0.170	12.0	0.487	0.639	0.762	74.7	9.33
D2A	0.054	8.6	0.082	0.150	0.543	78.3	9.78
D2B	0.159	11.1	0.802	0.633	1.266	70.1	8.76
D3	0.087	9.8	0.352	0.591	0.596	77.2	9.65
D4	0.259	7.8	0.759	0.954	0.796	74.4	9.30

* HILET Telemetered Dose = 1/8 HILET Actual Dose

3.3 Qualification and Acceptance Tests

The Protoflight Dosimeter underwent qualification testing, which consisted of the following:

a) Baseline Comprehensive Performance Test
b) Electromagnetic Compatibility (EMC) Tests
c) Post EMC Comprehensive Performance Test
d) 3-Axis Random Vibration
e) Post Random Vibration Comprehensive Performance Test
f) Thermal Vacuum Test
g) Final Comprehensive Performance Test

The Electromagnetic Compatibility Tests, Random Vibration Test Levels, and Thermal Vacuum Test Profile are defined in Table 10, Table 11, and Figure 19, respectively. All tests were completed successfully.

The Backup Dosimeter underwent acceptance testing. The acceptance test sequence was identical to the qualification test sequence except that Electromagnetic Compatibility Tests (item b) and the Post EMC Comprehensive Performance Test (item c) were not done. All tests were completed successfully.

4. ON ORBIT PERFORMANCE

The Protoflight Dosimeter was delivered to Orbital Sciences Corporation on 6/7/92 for integration into the payload of the Advanced Photovoltaic Electronic Experiment (APEX) satellite, as part of the Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) experiment. Subsequently, various minor hardware and software problems were discovered and corrected while testing the Backup Dosimeter. Following discussions with the contract monitor, it was agreed that the Backup Dosimeter should be flown on APEX, rather than the Protoflight Dosimeter. Accordingly, the Backup Dosimeter was delivered to Orbital Sciences Corporation (OSC) on 9/28/93 for integration into the payload of the APEX satellite. The Protoflight Dosimeter was returned to Panametrics at that time, and the various minor hardware and software modifications which had been incorporated in the Backup Dosimeter were subsequently incorporated in the Protoflight Dosimeter.

Table 10. Electromagnetic Compatibility Tests	
Test	Test Method
Radiated Emissions, Magnetic Field, 0.03 to 50 kHz	RE01
Radiated Emissions, Electric Field, 0.014 to 10,000 MHz	RE02
Radiated Susceptibility, Magnetic Field, 0.03 to 50 kHz	RS01
Radiated Susceptibility, Magnetic and Electric Fields, Spikes and Power Frequencies	RS02
Radiated Susceptibility, Electric Field, 0.014 to 10,000 MHZ	RS03
Conducted Emissions, Power and Interconnecting Leads, 0.03 to 15 kHZ	CE01
Conducted Emissions, Power and Interconnecting Leads, 0.015 to 50 MHZ	CE02
Conducted Emissions, Power Leads, Spikes, Time Domain	CE07
Conducted Susceptibility, Power Leads, 0.03 to 50 kHz	CS01
Conducted Susceptibility, Power Leads, 0.05 to 400 MHz	CS02
Conducted Susceptibility, Spikes, Power Leads	CS06

Table 11. Random Vibration Test Levels	
Frequency Range	Level
20 to 50 Hz	+6 dB/Octave
50 to 1000 Hz	0.025 g^2/Hz
1000 to 2000 Hz	-6 dB/Octave
Composite Level = 6.10 g RMS Duration = One Minute Per Axis	

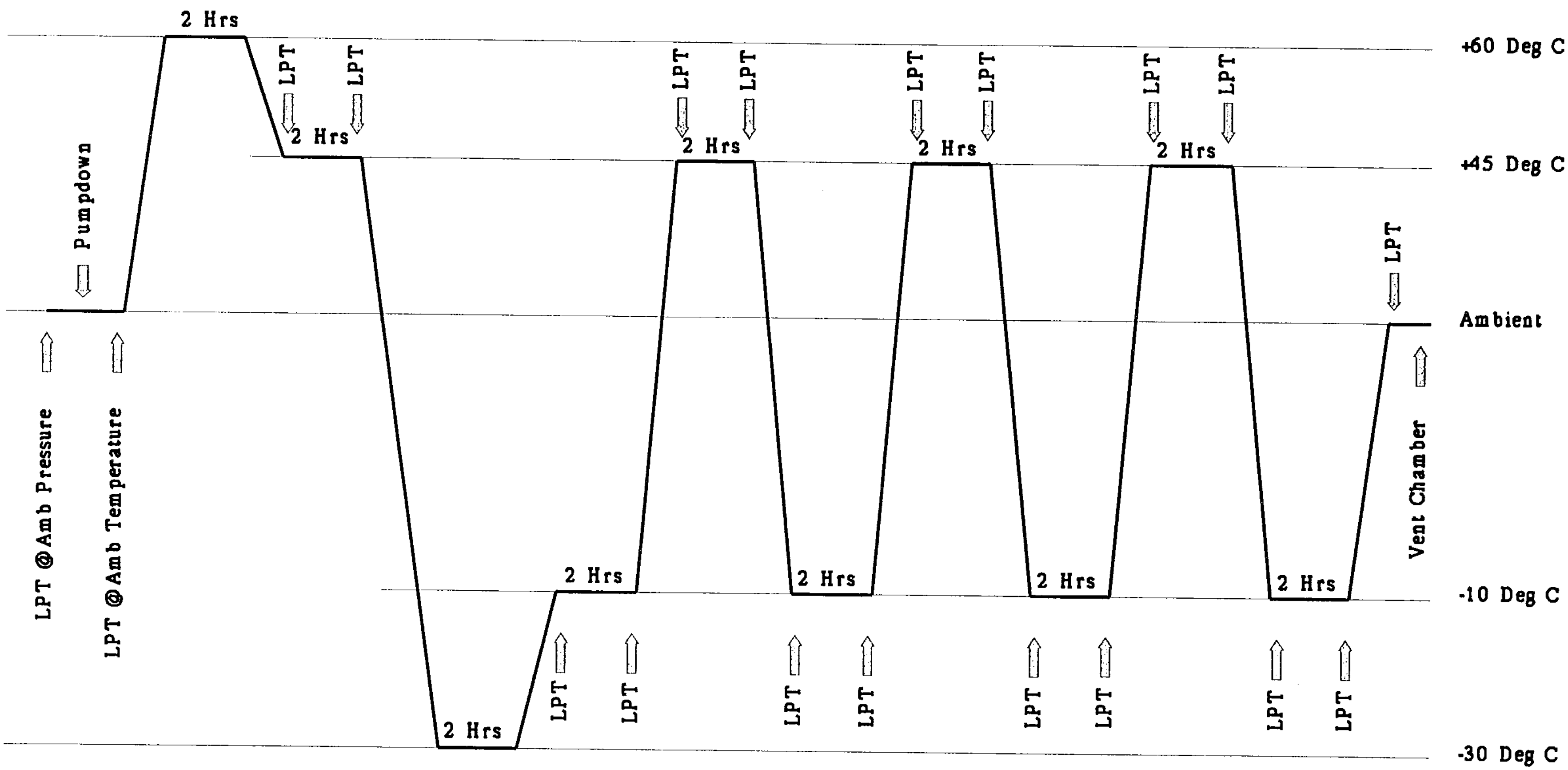
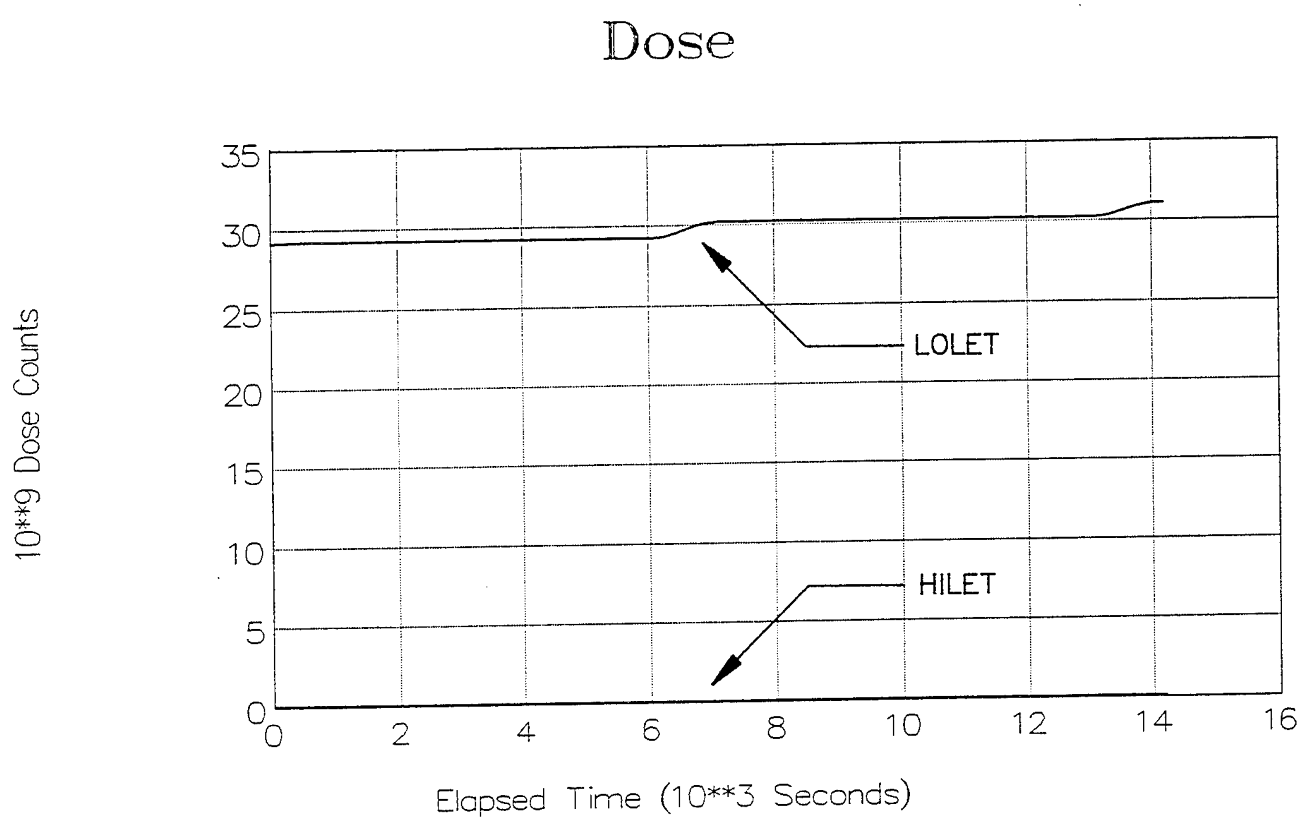


Figure 19. Thermal Vacuum Test Profile

APEX was launched shortly after 1430 UT on 8/3/94, with the initial orbits having apogee/perigee in the equatorial plane. After a few orbits the spacecraft experienced some anomalies in the attitude control system, so the Dosimeter's turn on was delayed. The anomalous behavior eventually ceased, and the Dosimeter was turned on in Rev. 20, at about 0410 UT on 8/5/94. The initial turn on showed no anomalies, with the Dosimeter operating properly. The Dosimeter was then monitored for several days to verify proper operation.

Typical Dosimeter data are illustrated by the flux and dose plots in Figures 20 through 23, which cover data from two complete orbits beginning at 2321:25 UT on 8/7/94. Figure 20 shows the D1A flux and dose data. The flux plot (bottom graph) shows the TOTAL (upper curve) and LOLET (lower curve) counts, with the HILETA, HILETB, OVERFLOW, and VHILET flux counts being comparatively small - essentially on the x-axis for the entire plot. The dose plot (top graph) shows the LOLET Dose (upper curve) and HILET Dose (lower curve - essentially on the x-axis for the entire plot). The D1A data show a response that is primarily from low energy electrons (>0.15 MeV) in the inner belt. The D1A measured dose is nearly all in the LOLET Dose. D1B shows essentially the same type of response, but the approximately 5 times higher TOTAL flux counts result in a greater dead-time effect.

The D2B flux and dose data are plotted in Figure 21. The flux plot (bottom graph) shows the TOTAL (uppermost curve), LOLET (second curve down), HILETA (third curve down), and HILETB (bottom curve) counts, with the OVERFLOW and VHILET flux counts being comparatively small - essentially on the x-axis for the entire plot. The dose plot (top graph) shows the LOLET Dose (upper curve) and HILET Dose (lower curve), with the HILET Dose being about half of the LOLET Dose. The largest flux peak in each orbit arises from the protons of the inner belt, as shown by the pattern of the LOLET, HILETA and HILETB flux counts. The smaller peaks on each side of the large inner belt proton peak arise from outer belt electrons (>1 MeV), since the these peaks have the TOTAL and LOLET fluxes nearly equal, with the HILETA and HILETB fluxes being relatively small. The dose curves are in agreement with the flux data, with the inner belt protons increasing both the LOLET and HILET Doses, while the outer belt electrons increase primarily the LOLET Dose. The D2A flux and dose data are similar to the D2B data, except for having about 1/5 the counts.



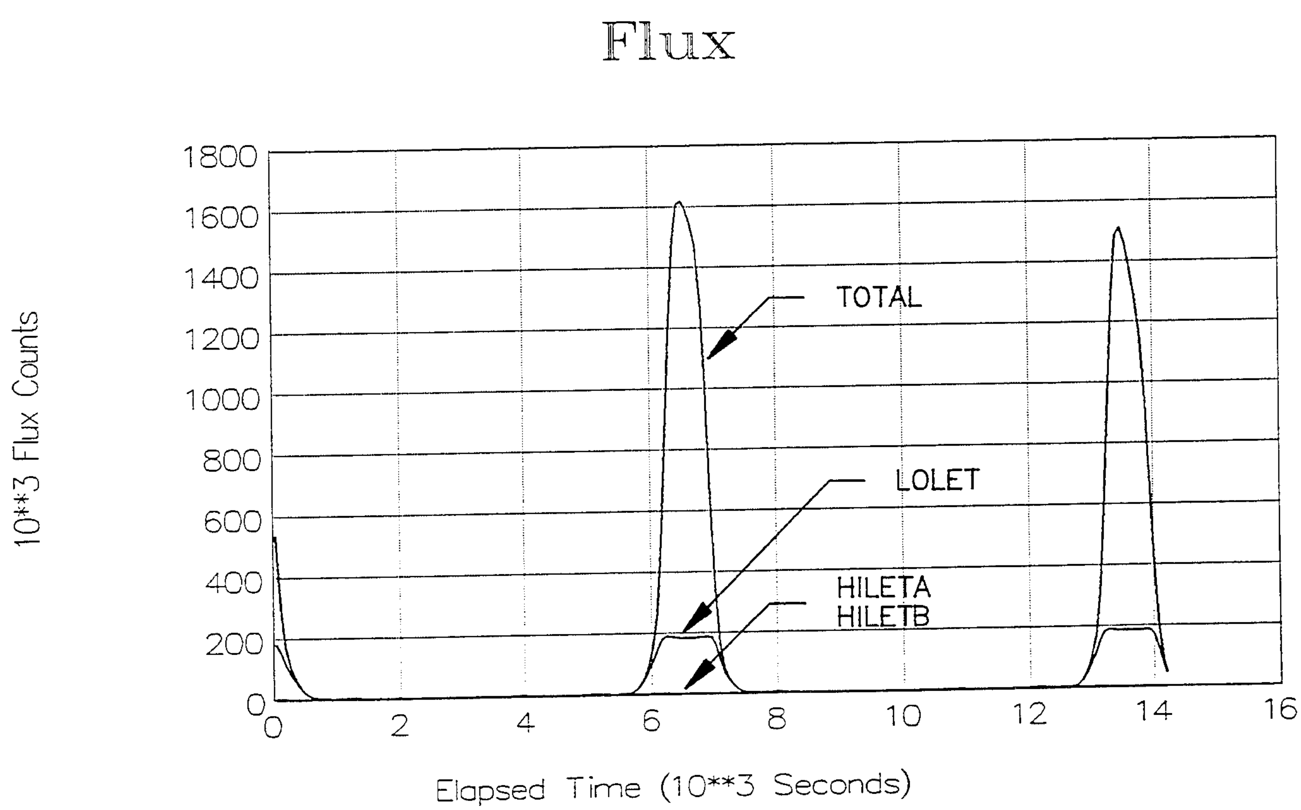


Figure 20. Dose and Flux Plots for the D1A Channel for 8/7/94, Starting at 2321:25.

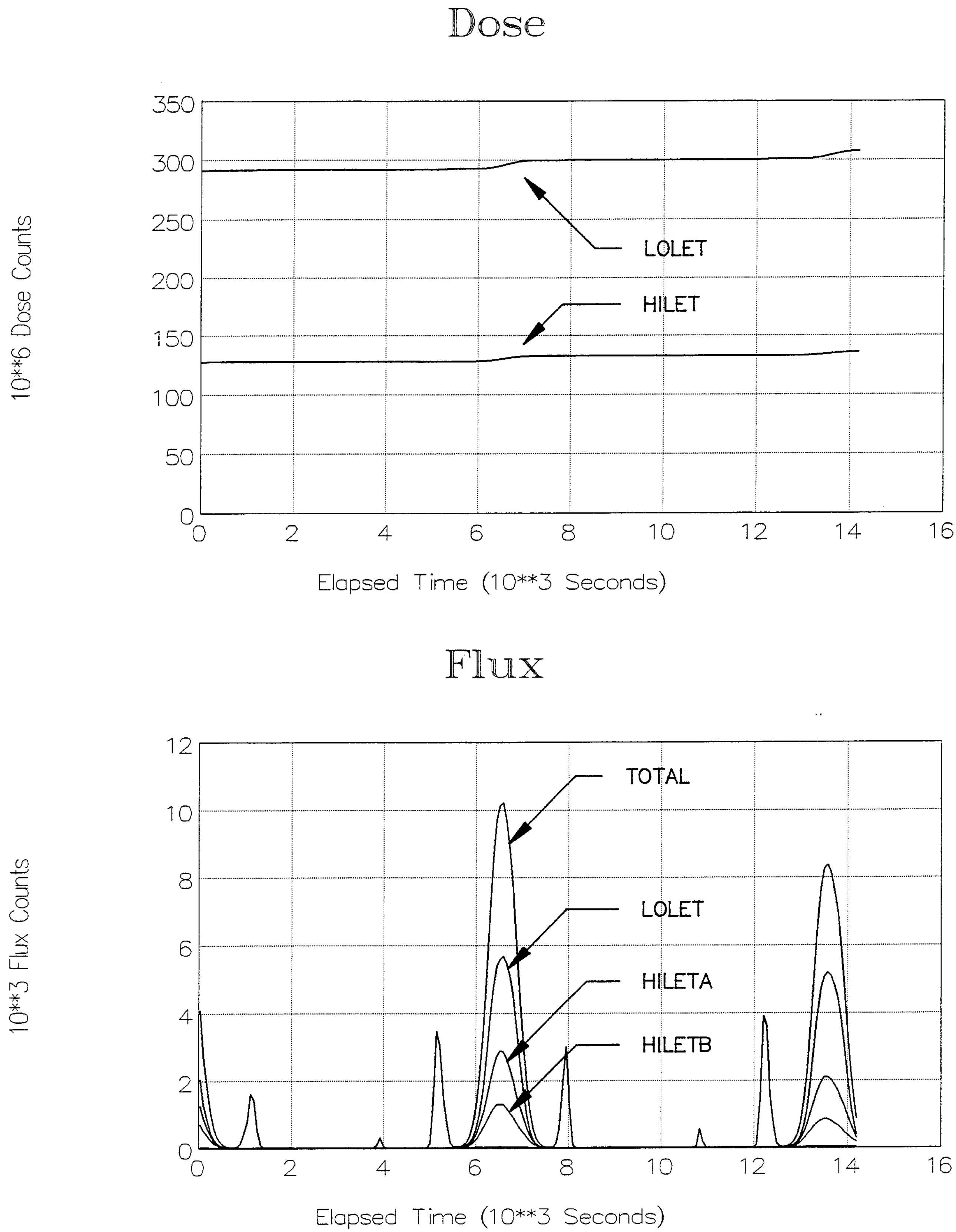


Figure 21. Dose and Flux Plots for the D2B Channel for 8/7/94, Starting at 2321:25.

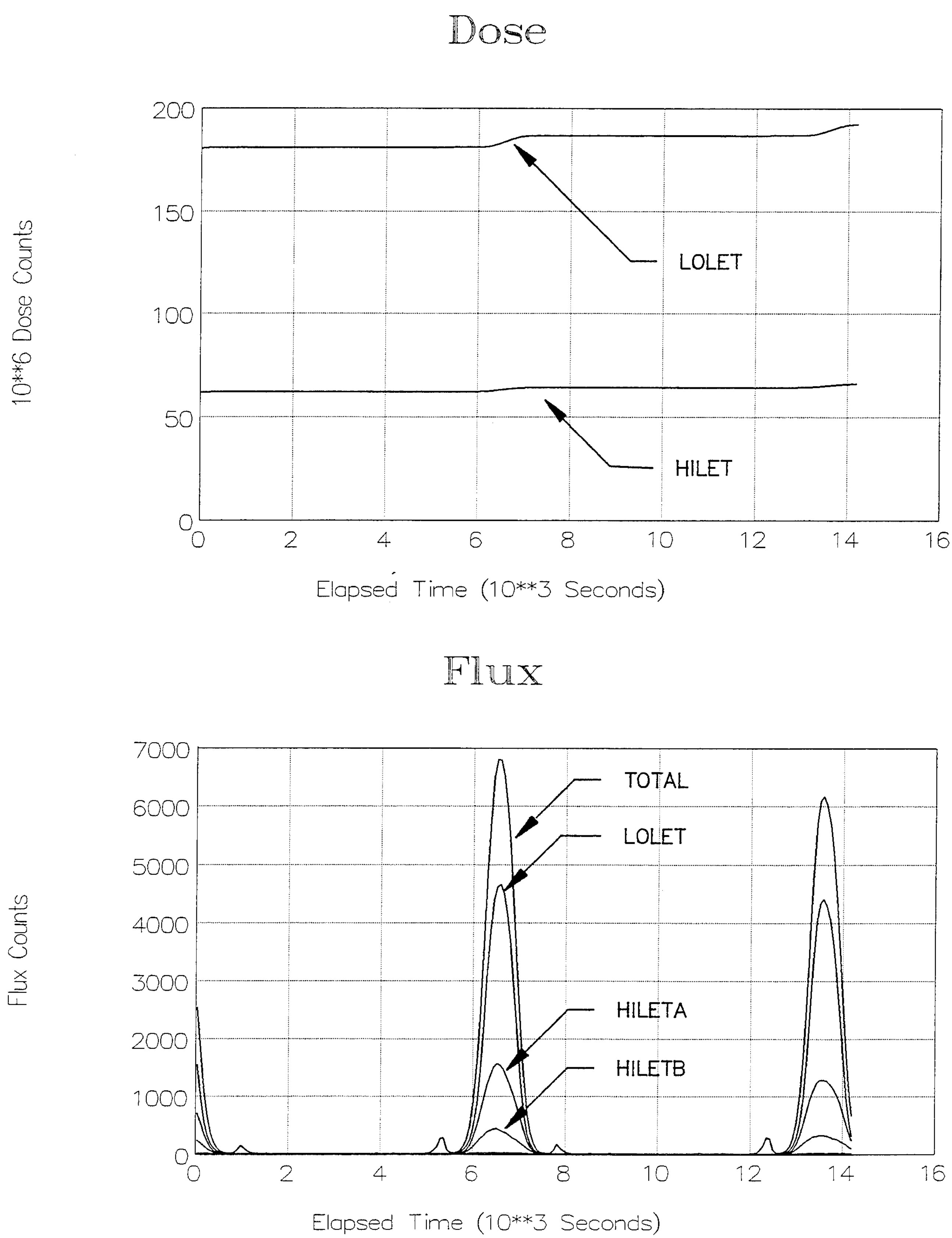
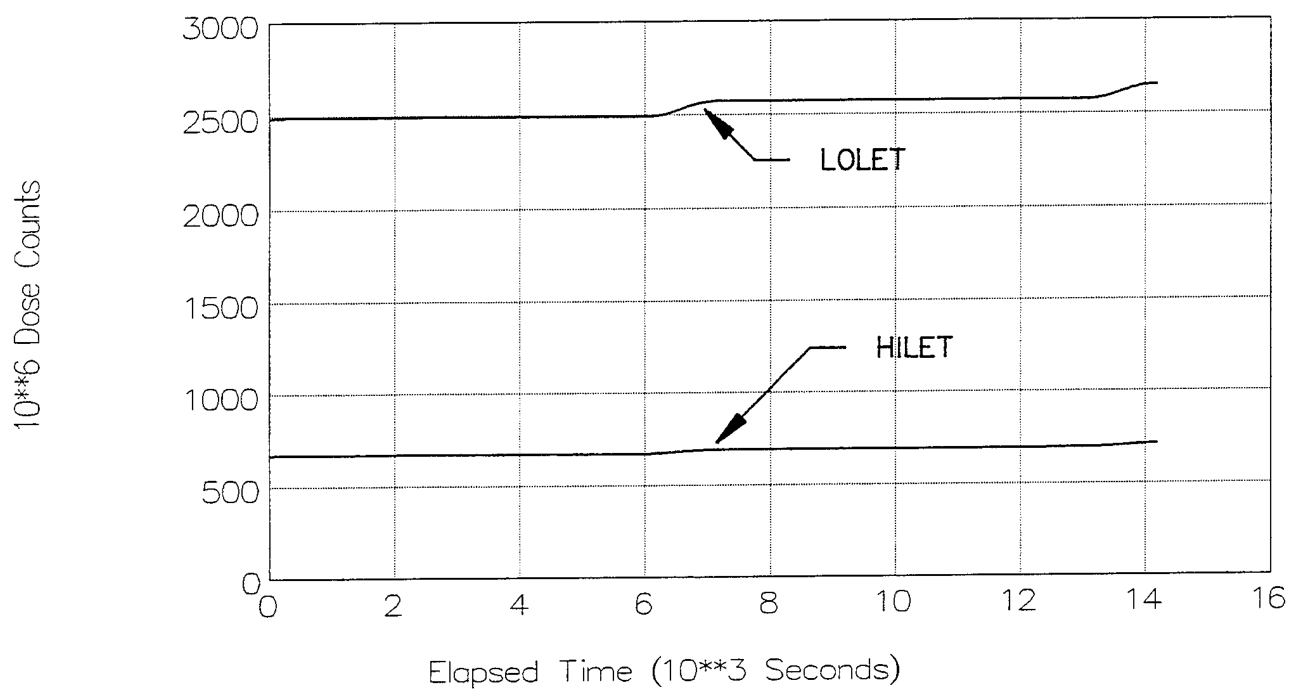


Figure 22. Dose and Flux Plots for the D3 Channel for 8/7/94, Starting at 2321:25.

Dose



Flux

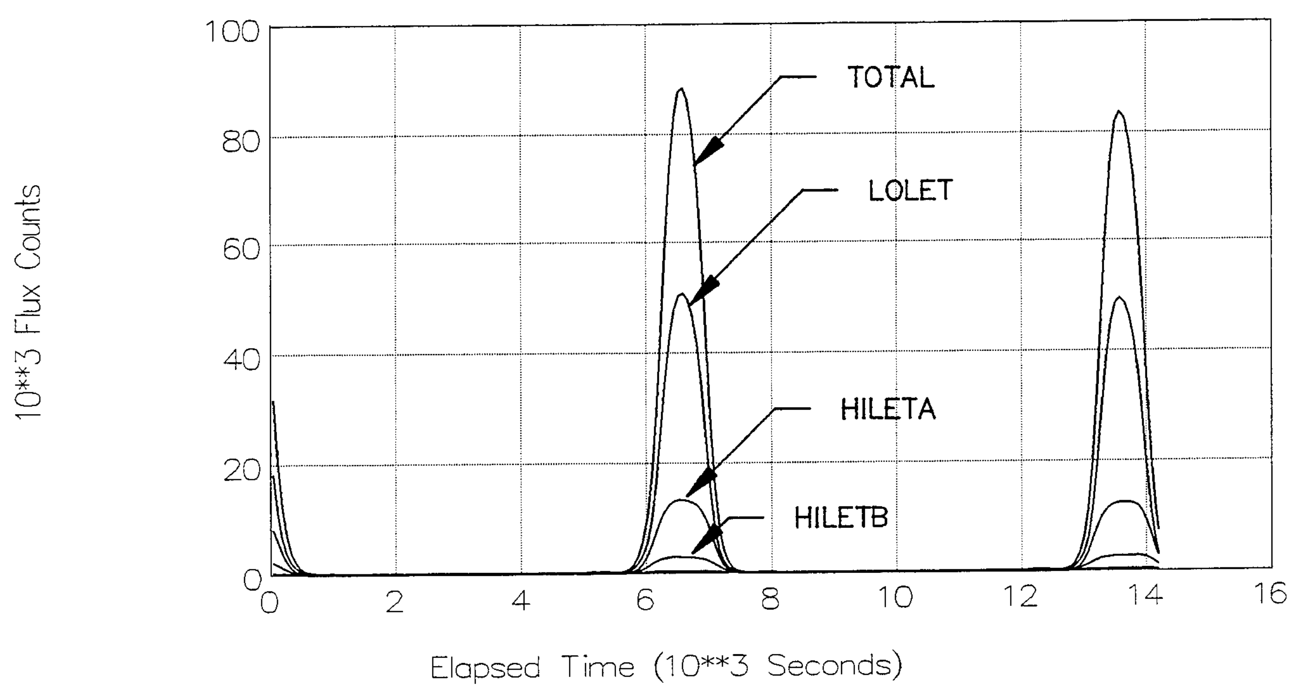


Figure 23. Dose and Flux Plots for the D4 Channel for 8/7/94, Starting at 2321:25.

The D3 and D4 flux and dose data are plotted in Figures 22 and 23. The plots show the same characteristics as the D2B plots (the order of the various flux and dose counts is the same), with a large flux count peak from inner belt protons and smaller peaks from outer belt electrons. Since the electron thresholds are 2.5 MeV for D3 and 5.0 MeV for D4, the outer belt electron peaks are weaker for D3 and barely visible (in the graph) for D4. This shows up clearly in the dose plots, where for D4 the only noticeable increase is for the inner belt proton part of the orbit.

The above data, and other data from the first few weeks of operation, show that the Dosimeter is working properly. The flux count and dose accumulation patterns are what is expected for the APEX satellite orbit. Data from near perigee show flux and dose count rates essentially identical to the pre-launch values from the in-flight calibration sources, so all detectors are operating in total depletion and with the correct gain. For the first week of operation the approximate average dose accumulation per orbit (about 1.9 hours) is listed in Table 12 below. Note that the high maximum count rate of the D1B channel (about 800 kHz) results in a significant dead time correction to the accumulated dose counts (the total count has about a 0.7 microsecond dead time for counting; at 800 kHz this gives a dead time factor of 2.27), and this is why the D1B doses are about 74% of the D1A doses. These differences will be eliminated by making the necessary dead time corrections during data processing.

Table 12.
Average Dose - rads(Si)/orbit

Channel	LOLET	HILET	TOTAL	Ratio (B/A)
D1A	525	5.70	531	
D1B	387	5.39	392	0.74
D2A	1.31	2.33	3.64	
D2B	1.10	2.39	3.49	0.96
D3	0.58	1.37	1.95	
D4	0.44	0.90	1.34	

The dose/orbit pattern in Table 12 shows that the thinnest shielding (Dome 1 - D1A and D1B) results in most of the dose coming from electrons (LOLET dose), while the thicker shields of the other three domes result in most of the dose coming from protons (HILET dose). As the APEX orbit precesses to put the apogee/perigee line out of the equatorial plane, the flux/dose patterns seen in Figs. 20 to 23 should change, with more of the dose coming from the outer belt electrons. The Dosimeter should thus provide a significant amount of data on the dose rate distribution of the sampled parts of the radiation belts.

5. SUMMARY

A second generation Dosimeter has been designed to fulfill the need for accurate radiation dose measurements. Two identical Dosimeters, a Protoflight unit and a Backup unit, have been fabricated, tested and calibrated. The Backup Dosimeter was integrated into the payload of the Advanced Photovoltaic and Electronic Experiments (APEX) satellite, as part of the Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) experiment.

APEX was launched shortly after 1430 UT on 8/3/94, with the initial orbit having apogee/perigee in the equatorial plane. The Dosimeter was turned on in Rev. 20, at about 0410 UT on 8/5/94. The initial turn on showed no anomalies, with the Dosimeter operating properly. The Dosimeter was then monitored for several days and proper operation has been verified.

A summary of the second-generation Dosimeter's characteristics is given in Table 13.

Table 13. Summary of Dosimeter Characteristics	
Sensors	6 planar silicon solid-state detectors (SSD's) under 4 aluminum shields
Field of View	2π steradians
Data Fields	For each channel (SSD) counts in 6 deposited energy ranges, and the dose for 2 deposited energy ranges. LOLET counts (0.050 - 1 MeV) HILETA counts (1 - 3 MeV) HILETB counts (3 - 10 MeV) OVERFLOW counts (> 10 MeV) VHILET counts (> 40 or 75 MeV) TOTAL counts (> 0.050 MeV) LOLET dose (0.050 - 1 MeV) HILET dose (1 - 10 MeV)
Output Data Format	272 bits serial, read out as 34 bytes, once per second. A total of 6 readouts is required to obtain all 6 channels. A total of 24 readouts is required to sample all Housekeeping data.
Command Requirements	2-byte commands initiate telemetry packet transmission, reset dose counters, determine PROM/RAM configuration, and upload data to RAM.
Size	5.5" H x 8" W x 9" D plus maximum 3.5" extension in D for Domes, excluding connectors and mounting tabs.
Mass	13.0 lbs
Power	5.5 W Nominal, 8.5 W Maximum
Temperature Range	0°C to +35°C Nominal Operating -10°C to +45°C Maximum Operating -30°C to +60°C Non-Operating

REFERENCES

1. B. Sellers, R. Kelliher, F.A. Hanser, and P.R. Morel, "Design, Fabrication, Calibration, Testing and Satellite Integration of a Space-Radiation Dosimeter," report AFGL-TR-81-0354, AD A113085 (December 1981). Final Report for Contract No. F19628-78-C-0247.

2. P.R. Morel, F.A. Hanser, B. Sellers, J. L. Hunerwadel, R. Cohen, B. Kane and B. Dichter, "Fabricate, Calibrate and Test a Dosimeter for Integration into the CRRES Satellite," Report GL-TR-89-0152, ADA213812 (April 1989). Final Report for Contract No. F19628-82-C-0090.