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Thermal Design of the Fast-On-Orbit Recording of Transient Events (FORTE) Satellite[1]

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ABSTRACT

Analytical tools were used to design a thermal control system for the FORTE satellite. An overall spacecraft thermal model was developed to provide boundary temperatures for detailed thermal models of the FORTE instruments. The thermal design will be presented and thermal model results discussed.

INTRODUCTION

The FORTE satellite is a collaborative effort between Los Alamos and Sandia National Laboratories as part of the DOE's space-based nonproliferation program. The mission of FORTE is the development of a satellite system to detect electro-magnetic pulses such as lightning events. FORTE is a composite structure with a total mass of approximately 180 kg. It operates at a nominal circular orbit of 800 kilometers, with minimum and maximum power dissipation of 11 W and 142 W, respectively. Body mounted solar panels are located on the side surfaces of the octagonal-shaped spacecraft.

The FORTE instruments are attached to three internal decks which are constructed of aluminum honeycomb with thin graphite facesheets. A spacecraft thermal model has been developed using the thermal radiation code TRASYS [1] and the thermal analyzer SINDA [2]. Quasi steady-state temperatures were obtained for both hot and cold worst case orbits. Temperatures calculated from the spacecraft thermal model were implemented as boundary temperatures for detailed models of the Optical Lightning Sensor (OLS) and the FORTE Payload Controller/Data Acquisition System (FPC/DAS) instruments using PATRAN/P-THERMAL [3], COSMOS-M [4], and PCB-Explorer [5]. The FORTE spacecraft thermal design included selective surface materials, multi-layer insulation, and heaters for the batteries.

FORTE SATELLITE DESCRIPTION

A schematic diagram of the FORTE satellite is shown in Figure 1. The satellite has a mass of 180 kg with maximum width and height dimensions of approximately 102 cm and

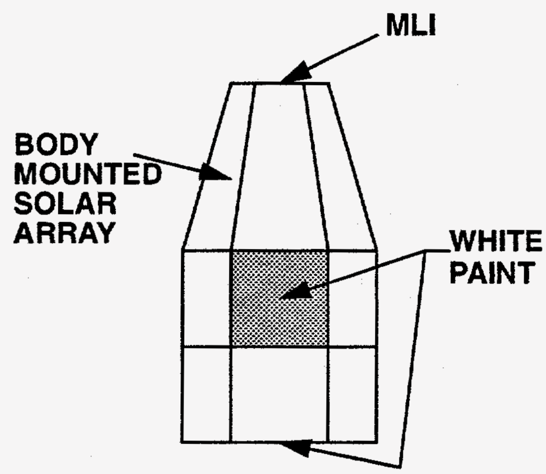

Figure 1. FORTE satellite.

203 cm, respectively. The outer satellite structure is graphite composite (T50/ERL1962, k_{eff}=28W/m-°C, ρ=1661 kg/m^3), with three inner decks on which the FORTE instruments are

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DISCLAIMER

mounted. The bottom and mid-deck decks consist of 2.54 cm thick 5052 aluminum honeycomb (k= 166 W/m-°C, ρ=69 kg/m^3) with 0.076 cm thick graphite facesheets. A 0.00254 cm thick layer of copper flashing was added to the facesheets for electrical grounding purposes. The top deck is 0.635 cm thick 5052 aluminum honeycomb (k= 166 W/m-°C, ρ=50 kg/m^3) with 0.076 cm graphite facesheets and copper flashing.

Table 1: FORTE Component Description.

Component	Mass (kg)	Power (W) Min., Max.
Battery (2)	8.0 ea.	1 ea., 2 ea.
ACDS	2.0	0, 4.65
GPS Rec.	1.6	0, 4.0
PCU	4.0	3.3, 18.0
VHF Rec.	1.8	0.5, 0.7
Scan Wheel	5.6	0, 3.25
EC	2.5	0, 5.0
T-Rods (BX,BY,BZ)	1.0 ea.	0, 1.25 (BY)
FPC/DAS	9.0	0, 31.0
RF	10.5	0, 11.75
TRIG/APW	5.5	0, 24.5
SS Recorder	1.8	0, 3.5
CDMS	5.0	2.15, 3.85
OLS	12.5	0, 22.0
D-Sensor	1.0	0, 2.0
UHF	1.0	3.6, 3.6
S-Band	1.0	0, 1 (ave.)
GPS Ant. (2)	0.2 ea.	0.1 ea., 0.1 ea.
Mag. (3)	0.3 ea.	0, 0

Top views of the instruments located on the bottom, mid, and top decks are shown in Figures 2 through 4. The mass, minimum, and maximum steady-state powers for the components are given in Table 1. The S-Band transmitter is powered on for 15 minutes dissipating 48 W every 12 hours. providing an average power of 1 Watt. The transient power profile was implemented in the thermal model.

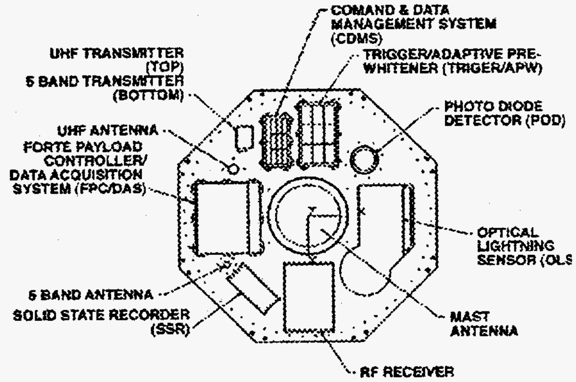

Figure 2. Components on top surface of bottom deck.

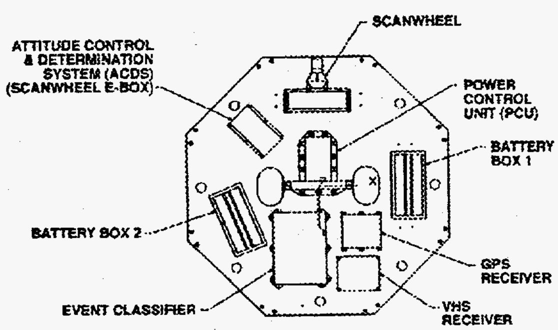

Figure 3. Components on top surface of mid deck.

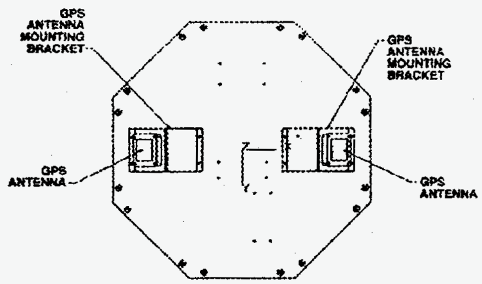

Figure 4. Components on top surface of top deck.

Some components are located on the bottom surfaces of each deck that are not shown in Figure 2 through 4. Namely, S-Band and UHF antennas (bottom deck), two torque rods (mid-deck), and three magnetometers (top deck). Also attached to the bottom deck is a 10 meter long quadrupole antenna.

Solar panels are located on the side surfaces of the satellite structure except for the reaction wheel and antenna panels located opposite each other on the mid-deck. The outer surfaces of these two panels and the bottom deck are coated with Chemglaze A-276 white paint to enhance thermal radiation (see Figure 1). Multi-layer insulation (MLI) covers the outer surface of the top deck. The MLI consists of 20-layers of two-sided aluminized mylar separated by an intervening polyester netting. Eight Watts of makeup heaters are added to the two batteries on the mid-deck to maintain a minimum battery temperature of approximately 0°C during the worst case cold operating orbit.

SPACECRAFT THERMAL MODEL AND RESULTS

A spacecraft geometric model was built using TRASYS which calculates the thermal radiation conductances and orbital heat rates. In the TRASYS analyses, the bottom deck is always nadir facing with the spacecraft velocity in the -y direction. A non-rotating spacecraft is assumed.

The cold and hot orbits analyzed were the noon-midnight orbit (maximum eclipse with beginning of life (BOL) optical properties, and minimum heat rates) and the dusk-dawn orbit (no eclipse with end- of-life (EOL) properties, and maximum heat rates, respectively. The two orbits are shown in Figures 5 and 6. Note that the TRASYS model -y coordinate corresponds to +x in Figures 2 through 4.

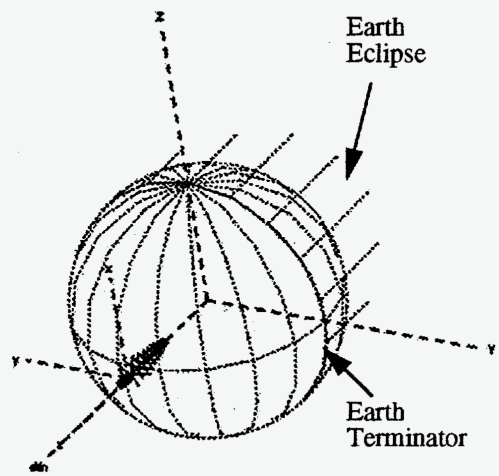

Figure 5. Noon-midnight orbit.

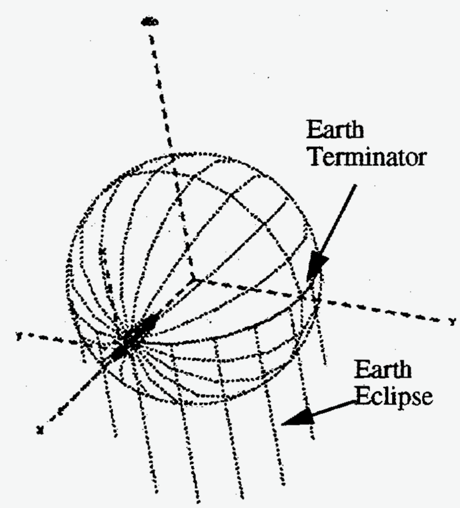

Figure 6. Dusk-dawn orbit.

For the hot orbit, Figure 6, one side of the spacecraft is always illuminated by the sun. Thus, separate hot orbit analyses were performed with either the +x or -x axes (+y and -y in Figures 2 through 4) of the spacecraft parallel to the solar vector. In the cold orbit, the spacecraft is in the earth's shadow approximately thirty percent of the ninety minute orbit. The parameters used in TRASYS for the hot and cold orbits are summarized in Table 2.

Table 2: Orbit Parameters.

Parameter	Noon-Midnight	Dusk-Dawn
Direct Solar (W/m^2)	1323	1419
Earthshine (W/m^2)	214	259
Earth Albedo	0.275	0.375
A-276 paint	α=0.2,ε=0.8	α=0.5,ε=0.8
β-cloth	α=0.2,ε=0.9	α=0.4,ε=0.8
MLI	ε^*=0.05	ε^*=0.02

The SINDA spacecraft thermal model consists of 254 nodes and 2197 thermal conductances. An effective thermal conductivity was used for the graphite material (average of the longitudinal and transverse values). The through-honeycomb thermal conductivity was determined by the ratio of the aluminum honeycomb density relative to a solid aluminum material. The transverse heat conduction in the honeycomb was assumed to be small relative to the through-thickness heat conduction and was thus neglected.

Because the graphite facesheet has a much lower thermal conductivity than aluminum, transverse heat conduction is significantly reduced. Suggestions to improve the transverse heat conduction included using aluminum facesheets instead of graphite, which would increase the deck mass, or using a graphite material that has a much higher thermal conductivity. But such materials are typically expensive. The alternative was to move some of the electronics boxes on the top surfaces of the bottom and mid decks to sides of the spacecraft which do not receive direct solar heating during the dusk-dawn orbit.

The FPC/DAS relocated and reoriented so that the larger side of the box was attached to the bottom deck. This enabled the high power memory and power supply modules to be directly adjacent to the deck. This reduced the thermal resistance from the modules to the deck.

The components are screwed to the decks via inserts glued in the decks. For structural integrity, the inserts were designed such that the components were elevated 0.076 cm above the deck surface. Thus, the only contact area between the components and the deck is where the screws are located. In order to improve heat conduction from the components to the decks, a thermally conductive elastomer was inserted between the standoff areas of the component and the deck. Since the pressure induced by the screws is highest near the screws and around the periphery of the component, a 2.54 cm wide contact width was assumed around the perimeter of the box. In the actual box designs, the bottom surfaces of the boxes will be flat thus enabling more contact area.

Quasi-steady temperatures were obtained for the noon-midnight and dusk-dawn orbits. The cold orbit predictions were obtained for 10 orbits at which time quasi-steady state temperatures were obtained. For the hot orbit, temperatures were calculated for 30 orbits. This allows the UHF transmitter to be turned on four times (every 12 hours). The overall minimum and maximum temperature results are given in Table 3 and represent component/deck interface temperatures.

The results in Table 3 indicate that the components, except for one of the magnetometers, are above their non-operating temperature limit of -40°C. However, a mounting modification of the magnetometer will help to increase its low-end temperature above -40°C. Other concerns are the maximum temperature predictions for the scan wheel. The scan wheel maximum temperature is 58°C (manufacturer limit of 60°C). However, the hot orbit scenario orients the scan wheel aperture always normal to the sun vector. Thus, the scan wheel receives direct solar heating for a long period of time. When the spacecraft is rotated 180° from the sun vector during the hot orbit, the scan wheel maximum temperature decreased to 21°C. The maximum temperatures for the S-Band and UHF transmitters, 52°C and 54°C, respectively, occur during the 48 Watt 15 minute power-on by the UHF.

Table 3: Overall Component Temperatures.

Component	Minimum Temp. (C)	Maximum Temp. (C)
Battery (2)	-0.6	31.3
ACDS	-18.9	39.5
GPS Rec.	-16.1	42.3
PCU	-7.9	47.6
VHF Rec.	-14.5	41.5
Scan Wheel	-14.8	58.0
EC	-18.1	39.3
Torque Rods	-20.2	54.7
FPC/DAS	-15.0	35.7
RF	-16.4	42.8
TRIG/APW	-16.2	42.3
SS Recorder	-22.4	33.7
CDMS	-14.6	43.3
OLS	-12.3	29.5
D-Sensor	-13.7	32.4
UHF	-15.7	53.5
S-Band	-16.9	52.1
GPS Ant. (2)	-38.9	14.8
Mag. (3)	-42.0	14.0

Even though the FPC/DAS and OLS maximum temperatures were approximately 36°C and 30°C, there is concern on the temperatures of the internal electronics modules. The memory and power supply modules located in the DAS section of the FPC/DAS dissipates a peak power of 34 W. Also, two modules in the OLS produce nominal powers of 3 and 4 W. Thus, detailed thermal models were constructed for the DAS and the OLS.

DAS THERMAL MODEL

The DAS is located on the bottom half of the FPC/DAS instrument and is housed in an aluminum box that adjoins the FPC as shown in Figure 7. The FPC/DAS box has width, length, and height dimensions of 26 cm, 28 cm, and 17 cm, respectively. The double-sided high power memory board consists of high speed analog to digital converters, amplifiers, and flat pack grid arrays all contained on a 25 cm by 25 cm board. The mass of the memory board is 2.3 kg. The memory and power supply boards are supported by an aluminum strongback as shown in Figure 8. The DAS memory module and an accompanying power module are capable of producing 34 W of peak power. To address the consequence of this power dissipation, a thermal model of the DAS strongback and a detailed thermal model of the memory board were developed using the finite element codes COSMOS-M and PCB Explorer.

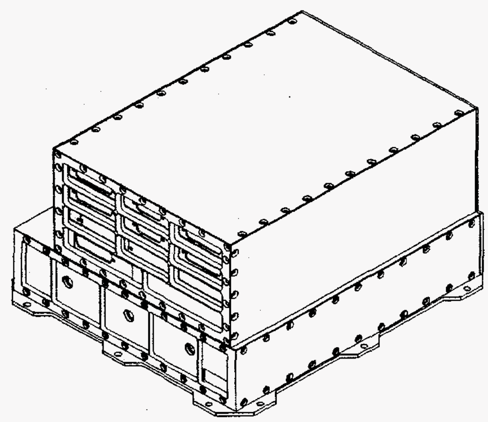

Figure 7. Diagram of FPC/DAS.

Figure 9 shows a one-half symmetric finite element model of the DAS strongback and the calculated steady-state temperature results using COSMOS-M. The deck is located on the -z side of the DAS model shown in Figure 9. The model includes thermal radiation and conduction, and constant material properties. The power module dissipates 9 W that is uniformly distributed with 25 W associated with the memory module as discrete heat sources. The boundary conditions for the thermal model were a 32°C deck temperature and an average surrounding temperature of 30°C. These temperatures were obtained from the spacecraft thermal model (hot orbit and maximum power results).

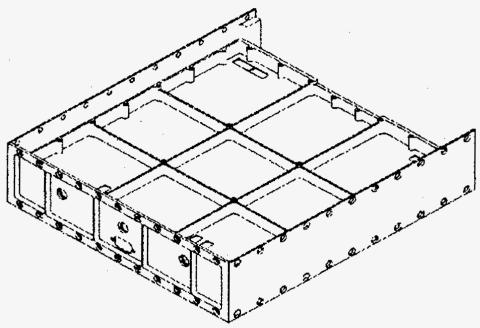

Figure 8. DAS strongback structure.

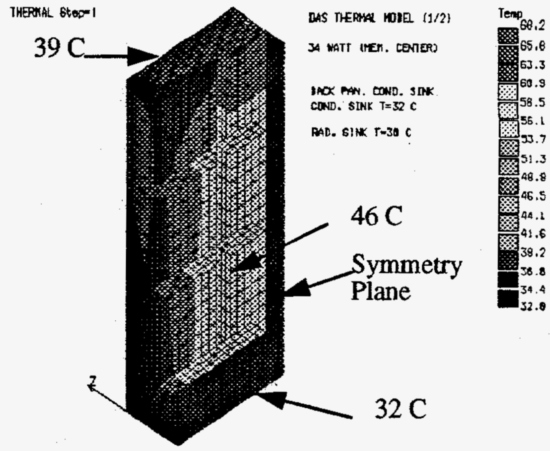

Figure 9. Strongback finite element mesh and steady-state temperatures.

The results in Figure 9 indicate strongback temperatures ranging from 32°C to 39°C at the outer region to 46°C in the inner region. The results from the DAS thermal model were used as boundary temperatures for the detailed memory board model. A detailed thermal model was developed for the memory board using PCB Explorer to calculate junction and board temperatures. Because of symmetry, only one half of the module was modeled.

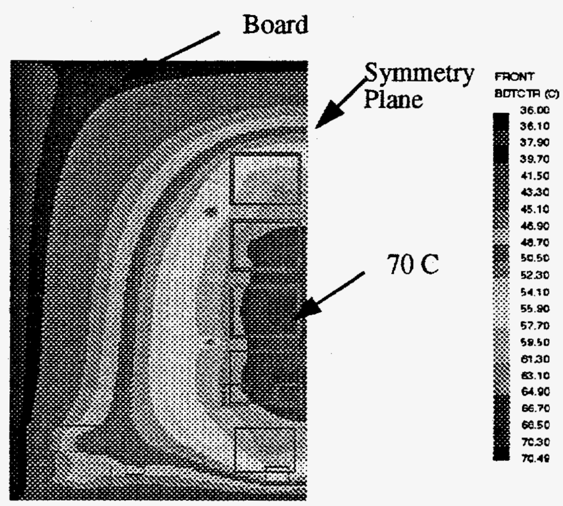

Figure 10. Memory board steady-state temperatures.

Results from the initial analyses verified that localized heat sinks were needed. The in-board heat sinks are plated through vias attached to ground and thermal planes. A thermally conductive adhesive is used between the component and the in-board heat sink. The board temperatures are shown in Figure 10 and the junction temperatures in Figure 11. The maximum board temperature was 70°C (Figure 10) and the maximum junction temperature was 87°C. Without the in-board heat sinks, the maximum junction temperature was 120°C.

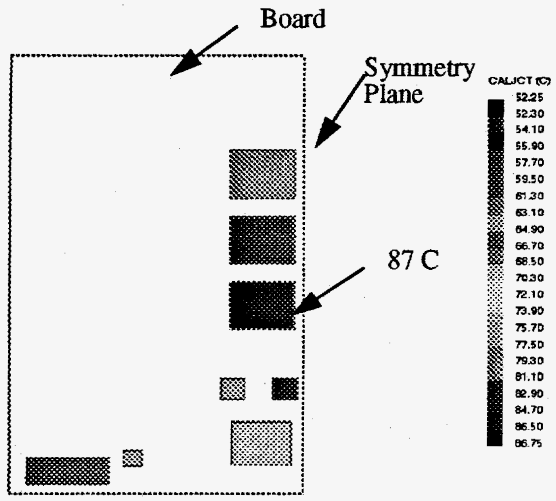

Figure 11. Calculated memory board junction temperatures.

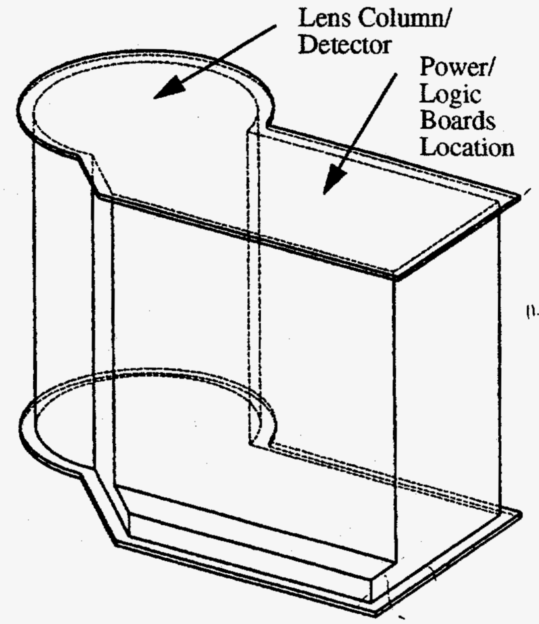

Figure 11. OLS aluminum housing.

OLS Sensor/Electronics Thermal Model:

The OLS is located on the +y side of the bottom deck (see Figure 2) opposite the FPC/DAS. The OLS is contained in an aluminum housing and consists of a lens column and optical filter located in the cylindrical section, and supporting electronics in the rectangular section as shown in Figure 11. The OLS is approximately 29 cm high and has a mass of 12.5 kg. The bottom lid of the enclosure has a circular cutout immediately beneath the lens column assembly to allow viewing of the earth. The wall thickness of the rectangular section is 0.152 cm and the cylinder is 0.127 cm thick. The top and bottom covers are 0.152 cm and 0.20 cm thick, respectively.

There are twelve power and logic boards located in the rectangular section which provides power and logic functions in support of the optical detector and the lens column. The boards are screwed into aluminum frames and some of the frames house a single board and are not shielded by an aluminum cover. Other frames enclose a single board through the use of covers on both sides of the frame. The remaining frames enclose a pair of boards between covers.

The power for each board is summarized in Table 4 and the position of each module relative to the lens column is shown in Figure 12. All the boards are nominally 0.132 cm thick. With the exception of the LLS Analog board, each of the boards is a six-layer board with 0.5 ounce (0.01778 cm) thick ground plane. The LLS analog board is a four layer board with a one ounce ground plane.

The OLS lens column and optical filter constitute a very complex assembly as shown in Figure 13. The central housing has multiple shoulders counter-bored into it to house a number of lenses and the optical filter. The filter is mounted halfway up the lens column. The lens column is made of 6061-T6 aluminum and is supported by the threes brackets depicted in Figure 13. These brackets span between the lens column and the two circular rings which attach to the OLS enclosure. Spacers, made of G-10 material, are used between the lens column and the support rings to thermally isolate the lens column from the enclosure.

Table 4: OLS Power and Logic Boards.

Module	Power (W)
PDD Analog	1.17
PDD Power Supply	0.5
Microproces-sor Power Supply	3.08
State of Health	0.5
PDD Digital	0.84
Microproces-sor Timing	3.88
LLS Digital	4.03
LLS Power Supply	2.5
LLS Analog	1.7

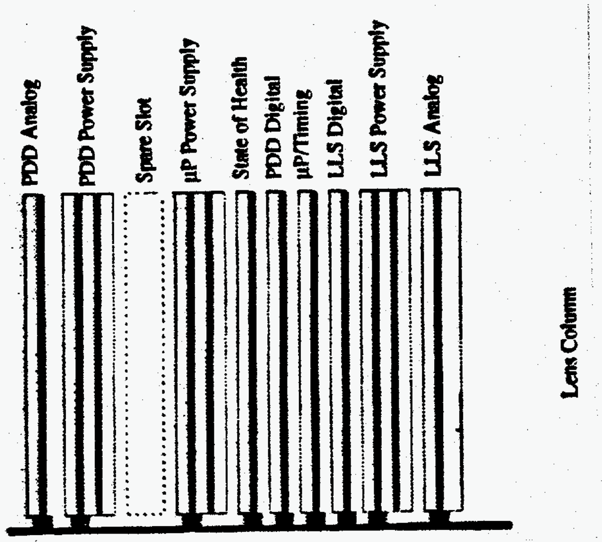

Figure 12. OLS power/logic board layout.

Figure 13. OLS lens assembly and supports.

Figure 14 illustrates a layout of the sensor electronics and adapter ring. The focal plane charged coupled device (CCD) detector and supporting electronic circuit boards are mounted to the lens column and its supports. The detector is mounted to a small circular electronic board known as the CCD board. The CCD board is mounted to the lens column via three screws and an adapter. The digital electronics board is a large circular board which is attached to the amplifier electronics board. In Figure 14, only four standoffs are depicted between the amplifier and the digital boards. There are in fact six standoffs located every 45°, with the exception of the locations of the cutouts shown in the digital board (for electrical connections). The amplifier board is mounted to the middle lens column support ring. The ring has eight stand-offs machined into it on which the amplifier board rests. All three boards are nominally 0.157 cm thick with a 2 ounce copper plane. The power for each of the detector boards are given in Table 5.

Table 5: Detector Board Power.

Board	Power (W)
CCD	0.150
Amplifier	2.5
Digital	2.5

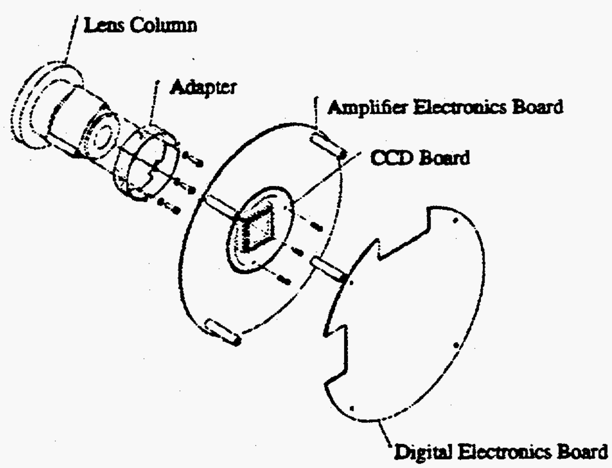

Figure 14. OLS sensor electronics and adapter ring.

A detailed thermal model of the OLS was developed using the finite element mesh generator PATRAN and the thermal model P3/PTHERMAL. The power on each board was assumed to be uniformly distributed with constant thermal properties. Due to the poor thermal path from the bottom of the modules to the deck, provisions were made to screw the board frames to the side wall of the enclosure 2.54 cm to 5.08 cm near the top end of the boards. A thermal conductive elastomer is placed between the mating side surfaces to improve heat conduction.

OLS steady-state temperatures were obtained using boundary temperatures from the hot orbit spacecraft model results. The deck and surrounding temperatures were 30°C and 35°C, respectively. The external surfaces of the OLS housing is coated with Chemglaze Z306 which has an infrared emissivity of 0.8. Temperatures were calculated with thermal radiation from the detector aperture to space neglected in order to obtain a worse-case maximum temperature.

The temperatures in Figure 15 illustrate that the maximum temperatures are recorded by the microprocessor/timing and LLS digital boards having peak temperatures of approximately 71°C. This allows no more than 30°C temperature rise for component junction temperatures to insure that junction temperatures are below 100°C. The board temperatures can be reduced by increasing their frame widths.

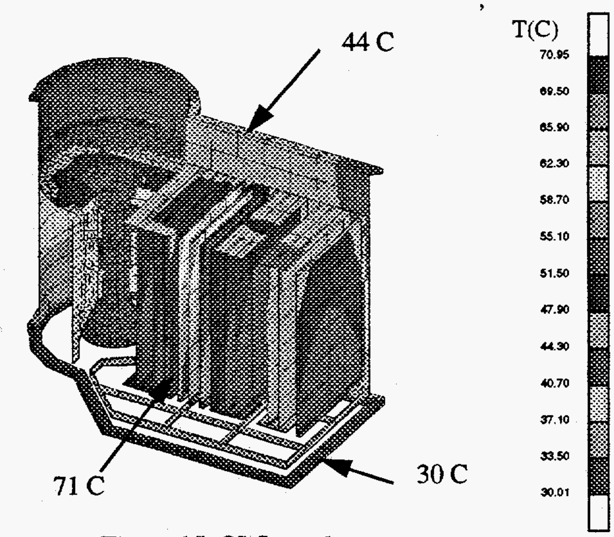

Figure 15. OLS steady-state temperatures.

If needed, schemes for enhancing heat conduction from the electronics chips to the board will be similar to that utilized for the DAS memory board. However, the power distribution of OLS boards will be uniformly distributed.

Summary and Conclusions:

A thermal design has been developed for the FORTE spacecraft using selective surface materials, multi-layer insulation, and battery heaters. The combined use of analytical thermal codes enabled the end-to-end thermal analysis of the FORTE thermal design from the overall spacecraft to component board junction temperatures. The results from the codes provided design changes to insure that adequate temperatures will be maintained throughout the spacecraft.

Component and spacecraft level thermal-vacuum/thermal balance tests will be conducted to benchmark and verify the thermal models.

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