

An Introductory Guide to Variable Conductance Heat Pipe Simulation

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ABSTRACT

Variable Conductance Heat Pipes (VCHPs) are a common element used in spacecraft design, which offer the valuable heat transport capabilities of fixed conductance heat pipes, while reducing heater power demands in cold configurations. For first time users, the proper modeling techniques for simulating a VCHP may not be readily apparent. This paper seeks to familiarize the reader with basic modeling techniques, algorithms, and output parameters using the Gamma-ray Large Area Space Telescope (GLAST) model as an example.

The GLAST model was delivered along with a library file containing a proprietary VCHP routine. However, the HEATPIPE routine found in SINDA/FLUINT proved to be a viable substitute. Understanding the basic algorithm and the parameters affected by each routine, allowed for a detailed comparison of the results produced by the two routines and is discussed herein.

BACKGROUND

The Gamma-ray Large Area Space Telescope (GLAST) includes two instruments, the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The GBM consists of detectors at various inclinations that will re-orient the spacecraft when gamma ray sources are identified at specific locations. The LAT contains sixteen trackers for detailed measurement of the incident gamma rays. Star Trackers on the spacecraft bus will determine the spacecraft pointing direction. Temperature changes must be kept at a minimum to retain the correct alignment between the LAT trackers and Star Trackers due to thermal distortion. To maintain stable temperatures in the various orbits and orientations GLAST will experience during its mission life, the LAT instrument uses a combined twelve VCHPs on its radiators (see Fig. 1). The detailed model for the instrument was delivered using the vendor's proprietary VCHP routine contained in a library file. The GLAST project wanted to eliminate dependence on the vendor's schedule if troubleshooting of the routine was needed, since the code was inaccessible in the compiled library file. The HEATPIPE routine commercially available in SINDA/FLUINT had to be tested for approval as a suitable alternative. An understanding of the physics and modeling of a VCHP was needed to compare parameters vital to verifying the correct behavior and

implementation of the new routine. The evaluations were completed for each of the twelve heat pipes for eighteen different orbital cases to verify replacement of the routine.

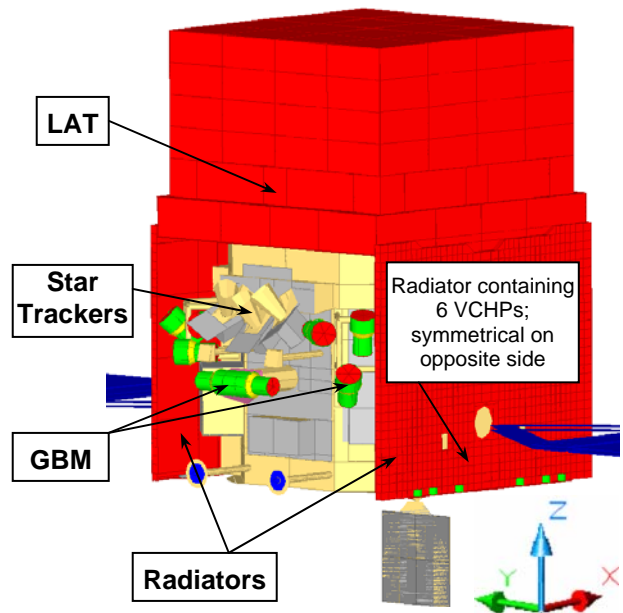


Figure 1 – GLAST Spacecraft

BASIC PHYSICS

Since a VCHP is based on the physics of a Constant Conductance Heat Pipe (CCHP), it is wise to start with the layout of a CCHP. There are three sections of a basic heat pipe with a working fluid enclosed inside the pipe. Various fluids are used in heat pipes and the selected fluid is based upon its saturation temperature and the temperature at which the heat pipe will be functioning. The inside of the pipe has a wick structure, which is in essence just a particular pattern of grooves. Various wick structures can be produced and each has its own particular benefits and drawbacks. Examples of a slab wick structure and an axial wick structure can be seen in Figure 2.

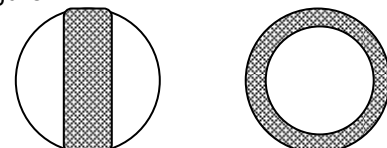


Figure 2 – Examples of a Slab Wick and Axial Wick

The liquid form of the fluid is contained in the wick, whereas the evaporated form of the liquid occupies the remaining free space inside the pipe. The evaporator section of a heat pipe is co-located with the source that requires heat removal. Heat from the source causes the working fluid to evaporate and move into the free volume of the pipe. The vapor then moves through the adiabatic section, sometimes called the transport section, by means of natural convection to the condenser section of the heat pipe. The condenser is co-located with a radiator or other colder section of the spacecraft and heat is rejected as the vapor condenses back into liquid form in the wick structure. The pressure of the vapor forces the condensate to remain in the grooves, which then provide capillary action to move the liquid back to the evaporator section. Figure 3 shows a diagram of the basic CCHP network.

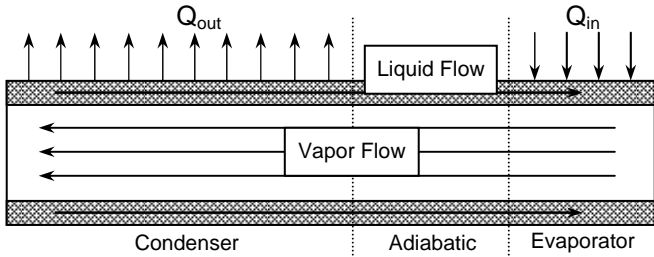


Figure 3 – Basic CCHP Network Diagram

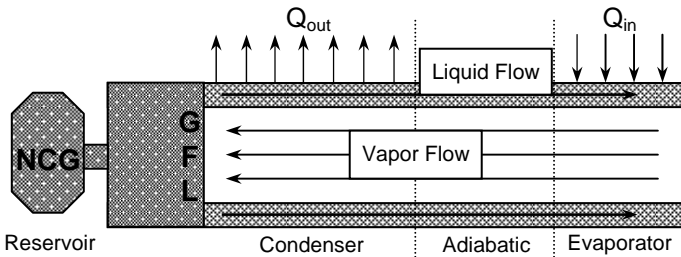


Figure 4 – Basic VCHP Network Diagram

A VCHP uses the same pipe layout as a CCHP, but has a reservoir of non-condensable gas (NCG) attached to the condenser end of the heat pipe. A heater is also located on the reservoir with the heater sensor located at the evaporator end of the pipe. The NCG is used to dynamically change the condenser length of the pipe according to the desired temperature of the evaporator. Using the heater control, the NCG can be expanded into the pipe or withdrawn back into the reservoir as necessary. When the NCG is occupying part of the pipe, it effectively shuts down condensation in that section by driving the working fluid back up the pipe. A wall of gas known as the gas front location (GFL) exists in the pipe at the location where the partial pressures of the working fluid and the NCG on the reservoir side are in balance with the saturation pressure on the evaporator side. If the evaporator gets too cold because too much heat is being removed, the sensor will apply more heat to the reservoir. As the reservoir and NCG heats up, the gas expands into the pipe and reduces the

length of the condenser, subsequently lessening the available area for heat transfer from the warmer vapor to the cooler surroundings. If the evaporator then gets too hot, the sensor will reduce the reservoir heater power, cooling the reservoir, and the NCG will retreat back into the reservoir giving a larger area for heat transfer in the condenser. Figure 4 shows a diagram of the basic VCHP network.

MODELING A VCHP

Most VCHP routines are top-level routines, in that certain assumptions are made to reduce their complexity. In reality, the gas front location is not a flat front, but for modeling purposes, it is simpler to make this assumption. It is also assumed that no condensation occurs on the NCG side of the gas front and therefore no heat transfer occurs in that section of the pipe, even though that may not be the case in actuality. The specific wick structure is also neglected and the cross-sectional area of the pipe is designated as the free space of the vapor only. These assumptions allow the modeling of the VCHP in a thermal analyzer to be reduced to a simple node/conductor network (see Fig. 5) along with other specified parameters.

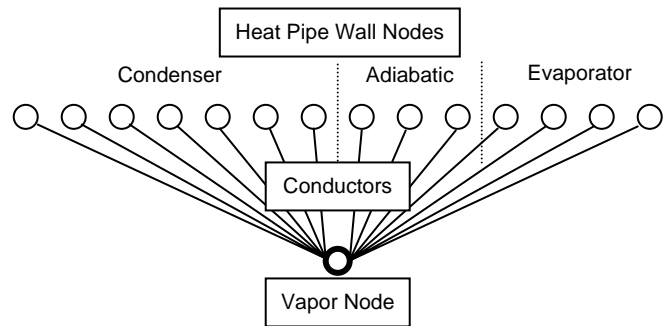


Figure 5 – Heat Pipe Node/Conductor Network

The thermal analyzer software, SINDA/FLUINT contains a HEATPIPE subroutine that can be used to model VCHPs. The call to the HEATPIPE routine in SINDA requires that various parameters be initialized. Table 1 contains descriptions for the routine parameters. Detailed explanations of the parameters as well as examples can be found in the Cullimore & Ring SINDA/FLUINT manual, section 7.7.9.

```
CALL HEATPIPE('SMN',NODE,Ac,AI,Diam,Hcond
+
,Hevap,Vres,Tres,EMgas,IDwork,IDgas,QLpipe)
```

Table 1 – HEATPIPE Routine Parameter Descriptions

Parameter	Description
SMN	Submodel name containing the vapor node and conductors, in single quotations
NODE	Vapor node number
Ac	Reference to an array containing the integer identifiers of the vapor node-wall node conductors

Al	Reference to an array containing the floating point heat pipe segment lengths for each wall node
Diam	Heat pipe diameter (diameter of vapor space only)
Hcond	Heat transfer coefficient for condensing sections
Hevap	Heat transfer coefficient for evaporating sections
Vres	Volume of the VCHP reservoir
Tres	Temperature of the VCHP reservoir
EMgas	Mass of the non-condensable gas in the VCHP (also called gas charge)
IDwork	Integer identifier of the working fluid (SINDA has some library fluids such as "717" for ammonia)
IDgas	Integer identifier of the NCG (FPROP DATA BLOCKS can designate the gas - only need gas molecular weight for the routine)
QLpipe	Returned power-length product for the pipe

First a submodel must be chosen for all the VCHP parameters. This can be an existing submodel or one designated specifically for the heat pipe.

Secondly, all the nodes must be specified in the submodel's NODE DATA block. A VCHP requires that a unique node number be used for the vapor node, all wall nodes (condenser, adiabatic, and evaporator sections), the reservoir, and the transition tube connecting the reservoir to the heat pipe. The transition tube node acts as a wall node, but normally has a distinct cross-sectional area and conductor value. The wall nodes can be divided in any manner that the analyst chooses; however, more condenser nodes per length of pipe are preferred compared to the adiabatic and evaporator sections. Smaller lengths per condenser node are desirable because the gas front location can cause large gradients across the condenser section of the pipe and more resolution may be required.

Next, the conductors must be specified in the CONDUCTOR DATA block for the submodel that was chosen. Conductor numbers and values should be input for the conduction along the wall of the pipe (i.e. wall node to wall node conduction) as well as the conduction between each wall node and the vapor node. The conductor numbers designated for the wall node to vapor node conduction will be the integer identifiers used in the "Ac" array for the call to HEATPIPE.

The conductor number and node length arrays must be detailed in the submodel's ARRAY DATA block next. The arrays are given a number as their identifier and it should be noted again that the "Ac" array contains the conductor numbers, not the conductor values, for the wall node to vapor node conductors. The "Al" array consisting of the node lengths can have either numerical

values or register names, where the registers are initialized to a particular value.

Finally, the actual call to HEATPIPE is made in the VARIABLES 1 block of the submodel. Some of the parameters can be either numerical values or register names. The registers must be initialized to the desired value in the REGISTER DATA block. Any reservoir heater logic should also be contained in VARIABLES 1.

Actual examples of the call to HEATPIPE and the VCHP parameters are useful for understanding how to model the heat pipes. The GLAST thermal model is used to illustrate the correct modeling techniques. An example of a HEATPIPE call appears as follows:

```
CALL HEATPIPE('HPSET1',101,A8,A14,DVM,HCOND
+
,HEVAP,VRES,T1499,GMASS,717,8728,VTEST)
```

The register names DVM, HCOND, HEVAP, VRES, and GMASS are all initialized in REGISTER DATA and even the nodal length array, A14, contains register names. Since the design required twelve VCHPs, the registers allow for easy manipulation of the parameters when completing trade studies to test the performance of various heat pipe configurations. The "717" identifier is for ammonia in SINDA's working fluid data base; all necessary data, such as saturation temperature-pressure (T_{SAT}/P_{SAT}) relationships, are contained within SINDA libraries. The number "8728" identifies a NCG created with an FPROP DATA block, which contains multiple parameters, but the molecular weight is the only information used by the HEATPIPE routine in SINDA. However, it should be noted that other routines, if used, especially related to FLUINT, might require factual values and some parameters require at least dummy values for SINDA to run properly.

BASIC COMPUTATIONAL ALGORITHM

Some VCHP computational algorithms use the ideal gas equation as its basis for deriving the gas front location and subsequently adjusting the conductor values to solve the temperature network for the next timestep. It should be noted that the HEATPIPE routine in SINDA/FLUINT uses tabular data for the specified working fluid pressure-temperature-specific volume relations instead of the ideal gas assumption.

A quick overview of the algorithm will help with having a "big picture" of the process during the detailed explanation. The ideal gas equation can be adjusted to solve for the amount of gas in the pipe given a set of wall temperatures, conductors, and the specified dimensions of the pipe and reservoir. This calculated amount of gas is then compared with the actual gas charge that is contained in the heat pipe to determine if the correct gas front location has been used. The process is repeated with a new estimate of the GFL to determine whether the calculated amount of gas

matches the real gas charge within a specified tolerance.

A generic ideal gas-based computational algorithm begins with solving the ideal gas equation for the amount of NCG, NR.

$$PV = NRT \rightarrow NR_{NCG} = PV/T$$

The NCG will be contained in some combination of the reservoir volume and the heat pipe volume of the section that is shut down, depending on the gas front location.

$$NR_{NCG} = P_{NCG} * V_{RES} / T_{RES} + P_{NCG} * V_{HP} / T_{HP}$$

The pressure of the NCG in the reservoir and the closed section of the heat pipe is derived from assuming there is a force balance of the non-condensable gas and working fluid vapor pressures at the gas front location. At a given set of temperatures and conductor values, the force of the pressure on the NCG side of the GFL will equal the pressure force on the vapor side of the GFL. The partial pressure of the NCG is equal to the pressure of the working fluid vapor on the open side of the GFL minus the partial pressure of the working fluid vapor that is mixed with the NCG.

$$P_{NCG} = P_{VAP} - P_{WF_RES}$$

The partial pressure of the working fluid on the reservoir side of the GFL, P_{WF_RES} , is derived from the reservoir temperature, T_{RES} , and the working fluid T_{SAT}/P_{SAT} relationship contained in a SINDA library file. The pressure of the working fluid on the evaporator side of the GFL, P_{VAP} , is derived from the saturation temperature-pressure relations for the working fluid. The saturation temperature is calculated by performing an energy balance on the vapor node. The system is assumed to be static at a particular timestep with the heat entering the vapor node equaling the heat leaving.

$$Q_{IN} = Q_{OUT}$$

$$Q_{IN} - Q_{OUT} = 0.0 = \sum\{G_{(i)} * (T_{VAP} - T_{WALL(i)})\}$$

Only the wall nodes and conductors in the open section of the heat pipe (no NCG) have to be calculated since no heat transfer will occur where there is NCG. SINDA technically sets the conductors in the closed section of the heat pipe to a very small non-zero value to prevent errors for the sum of conductors, but the heat transfer for those conductors is negligible.

$$\sum\{G_{(i)} * T_{VAP}\} = \sum\{G_{(i)} * T_{WALL(i)}\}$$

$$T_{VAP} * \sum\{G_{(i)}\} = \sum\{G_{(i)} * T_{WALL(i)}\}$$

$$T_{VAP} = \sum\{G_{(i)} * T_{WALL(i)}\} / \sum\{G_{(i)}\}$$

The saturation pressure of the working fluid vapor is returned using the working fluid T_{SAT}/P_{SAT} relationship again.

$$P_{NCG} * V_{HP} / T_{HP} = P_{NCG} * \sum\{AX/T_{WALL(i)}\} = NR_{HP}$$

The mass of the NCG in the pipe is calculated by summing the amount of gas in each nodal section length up to the GFL. For example, imagine the GFL is located somewhere in the third condenser wall node from the reservoir. The amount of NCG in the pipe would equal:

$$(i.e.) \quad NR_{HP} = P_{NCG} * [(AL_{(1)} / T_{WALL(1)}) + (AL_{(2)} / T_{WALL(2)}) + (AX_{(3)} / T_{WALL(3)})]$$

The volume used for the last slice of the closed section of the pipe is proportional to the distance the GFL extends into that wall node length. Figure 6 depicts the important parameters used by the VCHP algorithm. There is a conductor, G, for every wall node to the vapor node, however, only a sample has been shown.

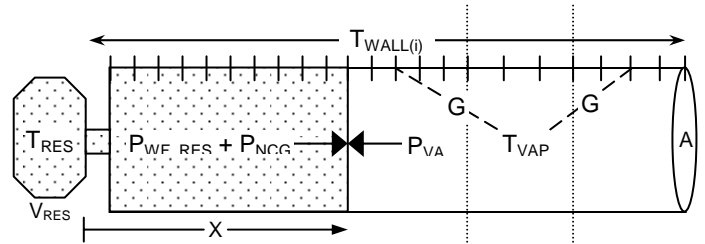


Figure 6 – VCHP Algorithm Parameters

The calculated NR_{NCG} value is compared with the actual gas charge and if they differ by more than the tolerated value, a new NR_{NCG} value will be calculated with a different gas front length. Once the gas front is calculated within an acceptable difference, the conductors are corrected, the vapor node temperature is calculated, and wall node temperatures are updated.

EXAMPLE RESULTS AND COMPARISONS

Understanding how the HEATPIPE routine affected the heat pipe node/conductor network was important for the comparison to the proprietary VCHP routine. Specific parameters can be output for each timestep to help diagnose whether or not the pipe is performing as it should. The important factors to observe are the timestep, vapor node temperature, reservoir temperature, sensing temperature, heater on/off status, gas front location, the wall node temperatures, and the wall node to vapor node conductor values.

Most of the parameters are direct outputs such as temperatures and conductors, but heater status will require some logic unless pure reservoir heat is desired. The gas front location can be calculated by SINDA using

the HPGLOC routine if the HEATPIPE routine was used to solve the VCHP network. However, since comparison to a proprietary VCHP routine needed to be completed, user logic was added to solve for the gas front for each timestep that was outputted. This ensured that all the parameters were calculated the same way for comparison purposes.

The data was post-processed and contrasted in Microsoft Excel, but the sheer volume of information did not support manual management of the data. Eighteen orbital cases with twelve heat pipes each, run with both VCHP routines, generated too much data to be practical to manually import and manipulate in Excel. A Visual Basic (VB) program was written to import all the heat pipe data sheets for each case into an Excel template file and save it according to the orbit filename. Charts and graphs were created in the Excel template to compare vapor node temperatures, wall node temperatures, and gas front locations for any heat pipe and timestep that was requested. VB macros and other Excel logic had been internalized in the Excel template to change all relevant graphs and charts with the least amount of cell operation. Other VB macros were designed to export the graphs from Excel and import them into Microsoft Power Point to compare all heat pipes from all orbital cases in one place.

The cold mission cases provided more difficult conditions for the VCHPs to control and were the focal point of the evaluation of the HEATPIPE routine in SINDA. The mission case B00MZC is used as an example and has: a beta angle of 0° , the $-Z$ side of the spacecraft oriented towards the sun, BOL properties, and a 575 km orbit altitude.

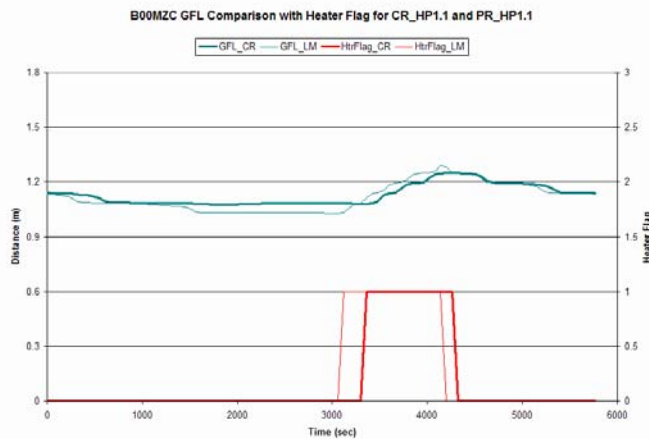


Figure 7 – Heat Pipe 1.1 Gas Front Location

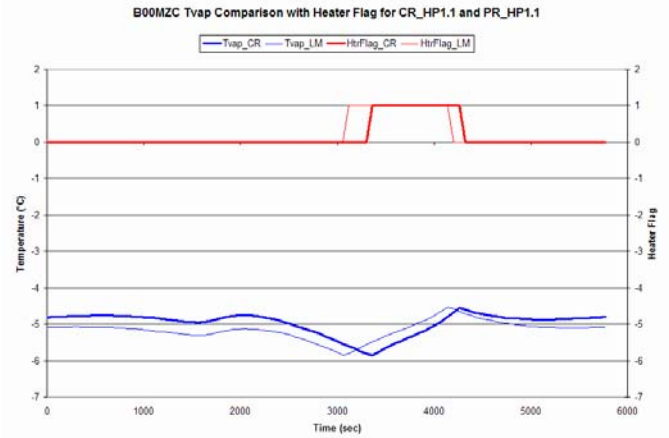


Figure 8 – Heat Pipe 1.1 Vapor Node Temperature

Heat pipe 1.1 is located on the $-X$ side of the $-Y$ radiator of the LAT instrument. The gas front locations in Figure 7 and vapor node temperatures in Figure 8 are not exactly the same throughout the orbit, but are well within modeling uncertainty. Also, the response and trend of the behaviors are consistent. Differences may be related to internal computations performed by SINDA/FLUINT in the HEATPIPE routine that are not necessarily performed in the proprietary code.

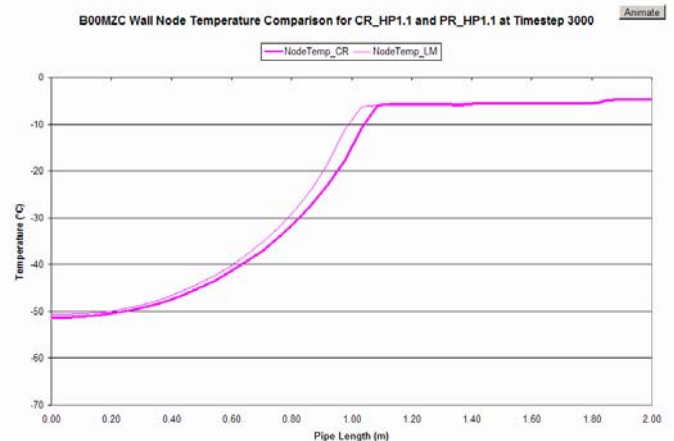


Figure 9 – Heat Pipe 1.1 Wall Node Temperatures

The wall node temperatures are shown for the 3000-second timestep of the 5770-second orbit in Figure 9. The nodes away from the GFL are almost exact matches; the wall nodes in closer proximity to the GFL are affected more by slight changes in the gas front and heater status. The differences in temperature for the nodes surrounding the GFL still fall within modeling uncertainty though.

CONCLUSION

All of the graphs were packaged in the Power Point presentation and examined by the project and the LAT instrument vendor for verification. It was decided to replace the proprietary VCHP routine with the commercially available HEATPIPE routine in SINDA

after all the data was evaluated. The analysis effort sufficiently reduced any future dependency on the vendor for troubleshooting of the routine and possible delays for future version deliveries.

The VCHP modeling knowledge that was gained during the entire process became a beneficial by-product that will assist with future modeling and analysis.

P_{WF-RES}: Partial Pressure of Working Fluid on Reservoir Side of GFL

T_{WALL}: Heat Pipe Wall Node Temperatures

HEATPIPE: SINDA routine used for modeling various heat pipes

HPGLOC: SINDA routine for determining the GFL

ACKNOWLEDGMENTS

I would like to thank Eric Grob (GSFC) and the GLAST project for their support and the opportunity to conduct this analysis for the benefit of the project as well as my own. I would also like to thank Hume Peabody (Swales) for his direction and support through the analysis process.

REFERENCES

In depth explanations of the HEATPIPE and HPGLOC routines can be found in the Cullimore & Ring SINDA/FLUINT manual along with further details concerning the correct setup of the SINDA deck. More information is available on the Gamma-ray Large Area Space Telescope and its science through the GLAST project office. "VCHP Comparisons.ppt" presented to Eric Grob (GSFC) contains the full spectrum of comparisons for each of the twelve heat pipes in all eighteen orbital cases.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

VCHP: Variable Conductance Heat Pipe

GLAST: Gamma-ray Large Area Space Telescope

GBM: Gamma-ray Burst Monitor

LAT: Large Area Telescope

SINDA/FLUINT: Systems Improved Numerical Difference Analyzer and Fluid Integration

CCHP: Constant Conductance Heat Pipe

NCG: Non-Condensable Gas

GFL: Gas Front Location

T_{SAT}/P_{SAT}: Saturation Temperature-Pressure Relationship

V_{RES}: Reservoir Volume

T_{RES}: Reservoir Temperature

T_{VAP}: Working Fluid Vapor Temperature

NR_{NCG}: Mass (Gas Charge) of NCG in VCHP

P_{NCG}: Partial Pressure of NCG

P_{VAP}: Saturation Pressure of Working Fluid Vapor