AIAA 93-2825
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Pradeep Bhandari and Steven Bard
Jet Propulsion Laboratory
Pasadena, CA

AIAA 28th Thermophysics Conference
July **6-9,** 1993 **/** Orlando, FL

THERMAL SYSTEMS DESIGN AND ANALYSIS FOR A 10 K SORPTION CRYOCOOLER FLIGHT EXPERIMENT

Pradeep Bhandari* and Steven Bard**
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Abstract

The design, analysis and predicted performance of the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) is described from a thermal perspective. BETSCE is a shuttle side-wall mounted cryogenic technology demonstration experiment planned for launch in November 1994. BETSCE uses a significant amount of power (about 500 W peak) and the resultant heat must be rejected passively with radiators, as BETSCE has no access to the active cooling capability of the shuttle. It was a major challenge to design and configure the individual hardware assemblies, with their relatively large radiators, to enable them to reject their heat while satisfying numerous severe shuttle-imposed constraints. This paper is a useful case study of a small shuttle payload that needs to reject relatively high heat loads passively in a highly constrained thermal environment. The design approach described is consistent with today's era of "faster, better, cheaper" small-scale space missions.

Introduction

The Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) is an element of the Shuttle Pallet Satellite (SPAS 111) mission of payloads for the Strategic Defense Initiative Organization (SDIO) planned for launch in November 1994. BETSCE is designed to demonstrate and characterize the performance of 10 K sorption cryocooler technology in a microgravity space environment. This technology offers the potential for highly reliable, long-life (> 10 years), vibration-free cryogenic cooling of infrared sensors on future astronomy, earth-observation, and surveillance satellite systems. [1-4]

The BETSCE instrument is mounted on the shuttle side wall on a Get-Away Special (GAS) adapter beam. Unlike typical small shuttle side-wall mounted experiments, BETSCE dissipates a significant amount of power (over 500 W peak). Because it has no access to the shuttle active cooling capability, the resultant heat must be rejected passively to space and the shuttle bay via radiative heat transfer from BETSCE's radiator panels.

Due to the program's severe schedule and budget constraints, the quick-turnaround thermal design and analysis approach developed here provides a useful case study consistent with today's era of "faster, better, and cheaper" small-scale space missions.

Because of the relatively warm temperature of the heat sinks (-15 to 0°C) during the nominal earth viewing orientation of the shuttle bay, BETSCE requires relatively large radiators. It was a major challenge to design and configure the individual hardware assemblies and subsystems (with their corresponding radiators) to enable them to reject their heat as well as satisfy various shuttle imposed constraints like center of gravity (e. g.) relative to the GAS beam, total mass, available real estate in the shuttle bay, and imposing minimum constraints on neighboring payloads to allow maximum manifest flexibility. Also, orientation excursions from the nominal earth pointed case to direct views of space or sun had to be accommodated. The baseline design is to cover the radiators with silver/teflon tape or white paint in order to provide the optimum thermo-optical properties to accommodate the various potential thermal sources/sinks interacting with these radiators.

This paper presents a thermal case study of a shuttle

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* Member Technical Staff, instrument and Experiments Thermal and Fluids Engineering Group

** BETSCE Task Manager, Member AIAA

side-wall mounted experiment that needs to reject high heat loads (over 500 W) passively in a highly constrained thermal environment. The design, analysis and predicted performance of BETSCE will be described from the thermal perspective. Various thermal system models of varying degree of detail were constructed to come up with a practical and workable design in a very short time and constrained budget. These models varied from relatively simple closed form hand calculations during the preliminary design phase to more detailed SINDA[5] and TRASYS[6] thermal analyzer models in the latter stages of design. Details of these models and their corresponding predictions will be discussed.

BETSCE Configuration and Basic Operation

"The BETSCE instrument has been organized into four major hardware assemblies, as shown in Figure 1: the sorbent bed assembly, the cryostat, the tank and valve assembly and the control electronics assembly. Alternately heating and cooling of sorbent beds containing metal hydride powders circulates hydrogen in a closed cycle and periodically cools the detector cold head assembly to 10 K on demand. The basic operating cycle is shown in Figure 2. The cold head and the detector heat load simulator (i. e., an electrical heater) are located in the Cryostat Assembly (CA) canister. The three Hughes tactical mechanical coolers (model 7044} 1). which reduce the temperature of the hydrogen below its inversion temperature and provide a continuous standby temperature of about 60 to 70 K. are mounted on an aluminum baseplate in the CA. This baseplate in turn is thermally attached to the four radiator fins which reject the coolers' heat. The cooler bodies are located within the CA canister.

The Sorbent Bed Assembly (SBA) includes the hydride beds and their respective radiators which reject their heat to the external sinks. The Tank and Valve Assembly ('TVA) contains all the valves and the plumbing which flow the working fluid (hydrogen) through appropriate subsystems during the various phases of the operating cycle. The valves and plumbing are attached to the TVA top and bottom plates which serve as its support structures.; the top plate serves as its radiator too. The Control Electronics Assembly (CEA) contains all the electronics necessary to switch valves, heaters, cryocoolers, etc. based on time, temperature and pressure readings. The CEA radiator (an inclined and tapered plate) is thermally attached to the electronics box and serves to dissipate its heat to the external sinks. The entire assembly is mounted on the BETSCE main mounting plate which attaches to a GAS beam, which in turn is attached to the sidewall of the shuttle structure.

Instrument Power Dissipation

Table 1 lists the normal power dissipation of the various subsystems, excluding the heat of absorption of the hydride beds when they react with the hydrogen; it also excludes the power to the supplemental heaters. The total peak power of about 500 W is rejected to the external sinks by BETSCE's radiators. This large power dissipation combined with the relatively warm sink temperatures lead to the need for large radiator areas. The SBA radiators and hydride beds have been designed to provide sufficient heat loss areas and equivalent thermal masses to ensure that they dissipate the heats of absorption of the hydrogen within their temperature (and pressure) limits. These limits are dictated by the cold head in order to produce and maintain liquid and solid hydrogen during various phases of the operating cycle. Similarly, the SBA heaters arc sired to provide sufficient power to heat up and desorb hydrogen from the hydride beds in a relatively short time during the recharge phase of the operating cycle, when the hydrogen is being recycled back to the hydrogen storage tank from the hydride beds.

Thermal Environment

Shuttle Orientations

Since BETSCE is an element of the SPAS III mission, and is mounted on the sidewall of the shuttle, it was designed to be able to accommodate all the possible orientations of the shuttle which are required by the SPAS III free-flyer. It was also designed to tolerate the minimum shuttle bay orientation required by the shuttle itself for any payload[7]. The following list contains the orientations of the shuttle bay +Z axis which BETSCE is designed to accommodate:

Continuous, for the entire flight; all possible yaw angles:

- pointed towards earth ($+Z_{lv}$) for β angles from O to 90°

- Passive Thermal Control (PTC) for β angles from 60 to 90°
- pointed opposite to velocity vector ($-Z_{vv}$); all possible β angles (O to 90°)
- pointed towards deep space

Short term transients:

- 1/2 hour direct solar view followed by recovery to $+Z_{lv}$ or $-Z_{vv}$ view

The β angle is defined to be the angle between the orbital plane and the sun-earth vector. Figure 3 pictorially shows some examples of the continuous orientations of the shuttle for which BETSCE is designed. The orientations shown in this figure are a subset 01 the entire list of orientations described earlier. Note that the earth oriented (+2,1,) and PTC cases are labeled warm. The $-Z_{vv}$ cases are labeled hot for the extreme situations of low β angles and cold for high β angles. The reason the $-Z_{vv}$ case with low β angles is considered hot is that for about 1/4 of the orbit the payload bay has a direct view of the sun with a cosine variation in solar flux. The reason for the $-Z_{vv}$ case with high β angles being considered cold is that the payload bay has a tangential view of the sun. If BETSCE is located in a bay next to the bulkhead nearest to the earth, then the heat input from the earth will he blocked. This latter case is what lead to the addition of thermostatically controlled supplemental healers to provide maximum flexibility in BETSCE's mounting bay location and the ability to accommodate an extremely wide range of possible orientations imposed by SPAS 111 or other sister payloads.

Neighbor Payload Constraints

BETSCE's radiators require a relatively clear view outside the shuttle payload bay to function properly. Payloads adjacent to BETSCE would seriously impair the effectiveness of its radiators. At the time BETSCE was being designed the shuttle payload manifest was not completely well defined. Hence the mounting location of BETSCE and other companion payloads which would be in the shuttle bay were not known. The 01 II% concrete information available was that the SPAS Ill pallet would be in the shuttle bay and that BETSCE would be side wall mounted on a GAS beam. Since there is an infinite variety of the types of payloads that can be launched in the shuttle, it would be impossible to design BETSCE to tolerate every possible payload. However, some information was known about the typical payload which would be manifested along with SPAS 111 types of payloads. Therefore, it was decided to design BETSCE to accommodate the most probable types of payloads which would be potentially flown along with SPAS 111. With this in mind the following constraints were set in the Payload Integration Plan (PIP) on the types of payloads BETSCE would be able to tolerate in its immediate neighborhood:

1) Payloads in the same bay as BETSCE should be small, to allow BETSCE radiators a 145° clear field-of-view across the bay. 2) Payloads in bays adjacent to BETSCE which fill the entire bay should have their outer surfaces covered with white outer layer insulation, or not be warmer than O"C. obviously, preferred features of' other payloads would be smaller and more distant payloads or deployable payloads in bays near BETSCE. In the context of the above discussion a bay in the shuttle is defined to be bounded by the axial length occupied by a GAS beam (about 1.4 m).

Effective Sinks Temperatures

Table 2 shows integrated average (i. e., over an entire orbit of the earth) equivalent sink temperatures for various thermal control surfaces used on BETSCE radiators. The equivalent sink temperature calculated for any surface is the temperature level when it is at steady state equilibrium with the external environment when the surface does not have any internal heat dissipation. This sink temperature can then be used for computing the operating temperature of a surface when it is dissipating energy. The sink temperature represents the net effect of' the external environment and is the boundary temperature to which the surf rface rejects its internal heat. The main function of Table 2 is to illustrate the relatively large sink temperatures for the radiating surfaces of BETSCE, which lead to the need for relatively large radiating areas. Two types of external sinks arc present for the BETSCE radiators: the shuttle payload bay itself (possibly containing other payloads) and the sinks outside the payload bay (earth, space). The BETSCE surfaces interact with both types of sinks: the TVA and the CEA radiators predominantly view the sink within the shuttle, whereas the SBA and the CA radiators predominantly view those outside the shuttle bay.

Note that Silver/Teflon is in general superior to white paints (ZOT and S13-G/LO-1) in terms of having a lower sink temperature. However, white paint was used for the SBA because the higher operating temperature requirements preclude use of Silver/Teflon, and for the TVA because the relatively complicated surface shapes are more easily coated with paint than with tapes. It is interesting to note that Silver/Teflon's sink temperature is much lower with a direct solar view than a direct earth view because of the very low α_s. Note that the Table 2 values are integrated orbital average temperatures presented solely to illustrate relative differences of different thermal control surface coatings for various orientations and locations. in reality, some of the orbits like the $-Z_{vv}$ are highly transient in terms of environmental inputs, and the thermal math models constructed were transient in nature to account for this. The models did not use sink temperatures; the actual environmental beat inputs were used instead for calculating surface temperatures.

Thermal Design Approach and Constraints

The thermal system design and initial analysis were performed iteratively and in parallel, in contrast to a series approach typically used in the design of large and expensive spacecraft. "This approach was necessitated by several constraints like power, mass, center of gravity (e.g.), use of available and proven technology, and of course cost and schedule.

Figure I shows the shuttle coordinate system. The entire BETSCE system is mounted on a **GAS** beam which is about 1.4 m (4.5 feet) wide in the X_o direction and 0.6 m (2 feet) tall in the Z_o direction. The BETSCE mounting plate is about 4 feet tall and about the same width as the **GAS** beam. The interface agreement with the shuttle organization constrains the weight of the GAS beam mounted payload to be less than 363 kg (800 lb) and the maximum e.g. offset in the Y_o direct ion to be -29.8 cm (- I 1.75 inches) from the GAS beam front face's center, Since all the BETSCE equipment is overhanging from the GAS beam in the $-Y_o$ direction, this e.g. offset was very constraining in terms of configuring the equipment on the mounting plate. "To minimize structural mass of the mounting plate, a design goal of about 10 cm (4 inches) was set for the maximum Z_o c.g. offset. The maximum peak current draw for the entire BETSCE system was based on a fuse rating of 35 A which translates to a maximum peak power draw of 980 W at nominal voltage of 28 V.

Thermal Design

Design Overview

In general, an attempt was made to thermally isolate each subsystem from other subsystems. This was done primarily because the overall system and each subsystem were being designed iteratively, and the design requirements, configuration and shuttle attitudes were often changing. This approach minimized the effect of changes in each subsystem affecting the design of other subsystems. For example, the backsides of the sorbent bed radiators, the bed mounting brackets, and the cryostat radiators are all covered with multi-layer insulation (MLI) to minimize their thermal coupling to the rest of the system. Hence, this thermal design is not optimized for mass, area, power, etc. The general approach taken in each phase of the design process was to develop a workable design as rapidly as possible within the design constraints, and to then move on to the next phase.

The thermal design was made as flexible as possible in terms of accommodating the various shuttle orientations required by SPAS III, meeting the minimum requirements of the shuttle itself, and in minimizing the constraints imposed by BETSCE on the neighboring payloads. This was particularly true for the cold orientations where all the subsystems are designed to tolerate deep space-like orientations for indefinite. periods by using actively controlled heaters, as described later.

The radiators for the sorbent beds are mounted at the shuttle sill level (i. e., adjacent to the open payload bay doors). This is the highest level possible in the shuttle Z_o direction for GAS beam mounted payloads and enables the lowest possible operating temperature. These beds and their radiators are also oriented with their axis parallel to the X_o direction in order to minimize the overhanging moment (i .e., the $-Y_o$ direction e.g. offset) which was a strong system design constraint. The cryostat radiator is designed with four fins (as shown in Figure 1). The opening is located at the same Z_o level as the sorbent bed radiators to maximize its view to the cold sink while minimizing its e.g. offset in the Z_o direction. This is because the heavier components of the CA are below the CA radiator (i. e., at a lower Z_o level).

The electronics radiator is inclined to maximize its view to the external cold sink while minimizing the system c. g. offset in the $-Y_o$ direction. The main radiator fin of the cryostat and the electronics radiator are both tapered to optimize their mass and minimize their e.g. offsets.

Components in the electronics box were distributed as evenly as possible to minimize hot spots, Interface connections within the box have a typical density of 1 screw per linear inch to minimize the contact resistance. Indium sheets are also used at each interface to further minimize temperature gradients.

The relatively unpopulated area of the main mounting plate in the bottom right quadrant (see Figure 1) is covered with Ml.]. This minimizes the heater power required to prevent the Tank and Valve Assembly (TVA) bottom plate from getting too cold, because the TVA bottom plate is mounted on, and intimately in contact with the main mounting plate (Figure 4). Eight out of the eleven solenoid operated valves which are typically on for the longest time (less than 1 to 2 hours), are located on the top TVA plate. The TVA top plate and the valves are painted with S 13-G/1,0-l white paint to maximize their heat loss capability. The three remaining valves are located on the bottom plate because they are not powered on for more than a few minutes, and their thermal mass is adequate to minimize their temperature rise.

Valve Overheat Protection

Each of the 11 BETSCE solenoid valves contain two coils; one for initial activation (72 W for < 1 sec) and another to provide holding power (7.2 W). If a hardware or software fault prevented shutoff of the initial activation coil to any valve, the resulting temperature rise due to the coil power dissipation may cause hydrogen trapped in nearby plumbing lines to pressurize above the maximum design operating pressure of 13.8 MPa (2000 psia). To meet the shuttle safety requirement of providing two-fault tolerance to this [wcrhcat-caused pressure hazard, two thermostatic switches set to open at 95°C were added in series to the initial activation coil circuits for each valve. For further protection, two additional thermostatic switches were similarly added to the holding coil circuits for 6 of the valves, The remaining 5 valves are connected to large enough relief volumes to prevent the pressure from ever rising to above 13.8 MPa. Thus, a total of 34 Elmwood Series 3200 space-qualified thermostatic switches are used.

It is very possible that a detailed analysis would show that additional thermostats could be eliminated because it may not be possible for the average temperature in any trapped plumbing volume to exceed the 105°C level used to derive the maximum operating pressure value of 13.8 MPa. However, the analysis may be difficult, time-consuming and not as fully convincing as required for a shuttle safety related issue. It was much easier and less expensive to implement a brute-force solution by using 34 thermostatic switches.

The thermostatic switches arc mounted by screws to aluminum blocks that saddle the tube stubs connected to each valve. Iridium sheets are placed at the interface of the saddles and tube stubs to improve thermal contact. Under normal operating conditions when there is no valve coil stuck on. the valve case temperature is expected to never exceed 75°C, thus providing sufficient margin to the thermostatic switch set-point temperature of 95°C.

Supplemental Heaters

The very cold temperatures resulting from the highly unlikely worst-case cold orientation (see Table 2) would significantly impair BETSCE's performance. To insure proper performance under these extreme cold conditions, active. thermal control using electrical heaters and thermostatic switches have been built in to each subsystem. These heaters were sized by assuming a worst case continuous orientation of the shuttle +Z axis towards deep space. Also, to avoid any potential for overheating due to runaway heaters, two-fault tolerant thermostat switch circuits have been used (i. e., 3 thermostats in series).

Note that the temperature of the hydrogen tank in the TVA is passively controlled without the use of supplemental beaters by its radiative thermal links to the surrounding top and bottom TVA plates. and to the warm electronics below it. Both sides of the TVA top plate and the hydrogen tank are coated with white paint (S 13-G/LO-1) to maximize the radiative thermal coupling.

'1'able 4 summarizes the locations and powers for the BETSCE supplemental heaters. The total supplemental heater peak power is about 380 W. It is unlikely that these heaters will ever be operated because of the low probability that this cold orientation and extreme mounting location near the bulkhead will actually occur.

Thermal Analysis

Overview

l-he following mixed bag approach was used for the thermal analysis: (1) band calculations using closed form approximations[8], standard handbook data[9], (2.) simple few node PC models, and (3) detailed TRASYS/SINDA models on the VAX minicomputer. Thermophysical properties were extracted from Reference 10,

Subsystem Models

Several subsystem models were constructed, each accounting, for the interaction of that subsystem with the rest of the system and including worst case blockages, heat inputs and losses, etc. These were constructed for both worst case hot and cold, such that each subsystem model was effectively individually integrated with the rest of the system. Each subsystem model was run individually to predict temperatures for that subsystem. This approach was in contrast to having, one super "system-model" which would be run for each prediction: this was primarily warranted by time constraints and the fact that the separate subsystems were being designed and analyzed in parallel. These models are relevant only for the external and system level interfaces of BETSCE. The internal thermal details of each subsystem were modeled separately by each subsystem's cognizant engineers, and are not described in this paper.

Integrated System Model

A detailed transient thermal model o! the entire system was constructed after the system design was completed. This model used the subsystem thermal models as building blocks. It was composed of two parts: a geometric math model using the TRASYS[6] software and a lumped capacity resistance-capacitance network model using the SINDA[5] thermal analyzer. The TRASYS model had about 20 surfaces to represent the primary external surfaces of BETSCE, whereas the SINDA model had about 40 nodes to represent the important thermal zones of each subsystem. About 20 solid conductors connect various parts of the BETSCE system in the SINDA model, The TRASYS model was integrated with a separate detailed TRASYS model of the shuttle bay and run in various relevant shuttle orientations. These runs produced the net radiation couplings (RADKs) between BETSCE surfaces, and between BETSCE surfaces and shuttle payload bay surfaces. They also provided the net orbital environmental heat inputs to each BETSCE surface. These RADKs and environmental heat inputs were then integrated with the basic BETSCE SINDA model and the detailed model of the shuttle bay to provide temperature versus time histories for the sorption cooler operating cycle. These runs were made to analytically confirm that the BETSCE thermal design will maintain operating temperatures of interfaces within their allowable limits. The analyses also provide the time required for the system to cool down before the next sorption-desorption cycle can be started.

Thermal Predictions and Key Assumptions

The thermal models were used to make predictions for the important BETSCE interfaces and these are summarized in Table 3. These predictions account for all extreme steady state and transient thermal conditions t'or the shuttle orientations which BETSCE has been designed to accommodate, as described earlier. The predictions are for the end of the i' day mission when any thermal "ratcheting" would have reached its maximum level. This is particularly relevant for the $-Z_{vv}$ orientations for low β angles. These predictions assume that the power to the replacement beaters is available throughout the flight immediately after the payload bay doors are first open, i.e., these heaters will at all times ensure minimum temperature levels required for each subsystem's normal operation. They also assume normal operation of the valves, i.e., they are not malfunctioning in terms of their power being turned on indefinitely due to a software or hardware malfunction. They account for the thermal coupling between the shuttle internal structure and the GAS beam/BETSCE mounting plate by using the worst-case value for the thermal design, as specified in Reference 7. It should be noted that even for these extreme all encompassing conditions there is at least a 5°C margin between the predictions and the allowable limits, and the typical margin is greater than 1 0°C for most interfaces.

Thermal/Vacuum Tests

System level thermal /vacuum tests are planned for January 1994. These tests will thermally exercise the hardware to the flight acceptance temperature levels. in addition, they will serve as limited thermal balance tests to validate and calibrate the integrated thermal model.

Summary and Conclusions

The detailed design of the BETSCE spaceflight experiment is complete. BETSCE is designed to accommodate all minimum shuttle thermal requirements, and all possible orientations required of the shuttle by the SPAS III mission. Predicted temperatures fall within the flight allowable limits for all BETSCE interfaces. Thermal vacuum tests are planned to validate and calibrate the system thermal model. The thermal design of BETSCE presented here provides a database which will aid in the design of future small shuttle side-wall mounted experiments that need to reject high heat loads (over 500 W) passively in a highly constrained thermal environment, It also delineates an effective and efficient approach for the thermal design and analysis process involved in relatively low budget and fast paced projects like BETSCE in order to quickly develop a workable design within a highly constrained set of groundrules.

Acknowledgements

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work was sponsored by the Drill liant Eyes Program Office, Strategic Defense Initiative Organization (SD1O), USAF Space and Missile Systems Center (SMC).

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TABLE 1 - BETSCE Normal Power Dissipation
(excluding heats of sorption/desorption and supplemental heaters)

SUBSYSTEM	MAX. POWER (Watts)
Cryostat Assembly	220
Tank & Valve Assembly	[illegible]
Electronics Assembly	40
Sorbent Bed Assembly	180

TABLE 2- BOUNDARY (SINK) TEMPS. FOR VARIOUS SHUTTLE BAY + Z AXIS ORIENTATIONS
($\alpha = 0.1$, $\varepsilon = 0.75$ for Ag/Teflon tape; $\alpha = 0.2$, $\varepsilon = 0.85$ for ZOT white paint)

ORIENTATION (150 nm altitude)	Sink within STS bay, °C (payload bay average)		Sink outside STS bay, °C (external environment average')	
	Ag/Teflon	ZOT	Ag/Teflon	ZOT
Earth-view, $+Z_{lv}$, WARM (no sun)	0	0	-17	-12
Sun-view. HOT (no earth)	100	100	-35	1
Space-view, COLD (no earth or sun)	-130	-130	-269	-269
Opp. to velocity vector, $-Z_{vv}$ $\beta = 0°$, HOT (4th power average)	-5	-5	-61	-47
Opp. to velocity vector, $-Z_{vv}$ $\beta = -90°$, COLD (4th power average)*	-269	-269	-269	-269

* Assumes a worst case cold location of BETSCE behind the bulkhead close to nose (tail) for a nose (tail) local vertical

TABLE 3- BETSCE Thermal Interface Predictions and Limits
(Unless otherwise stated, all temperatures in °C; Operational Values)

COMPONENT	PREDICTED (Max/Min)	ALLOWABLE FLIGHT (Max/Min)
Electronics (radiator base)	50/-10	55/-20
Tank & Valve Assy - top plate	66/- 10	90/-20
Tank & Valve Assy - bot plate	< 66 >-1o	75/-20
Hydrogen tank	55/-10	75/-76
Cryostat (radiator base plate)	60/-1O	65/-40
SBA: High pressure bed radiator	129/-10	177/-30
SBA: Fast abs. bed radiator	48/-2	177/-30
SBA: Low pressure bed radiator	155/-1	177/-30

TABLE 4- BETSCE Supplemental Heater Powers

ZONES	TOTAL HEATER POWER (Watts)	MINIMUM TEMP. REQT. (°C)
Cryostat Assembly	100	-30
Tank & Valve Assembly	90	-10
Electronics Assembly	70	-10
Sorbent Bed Assembly	120	-30/-55

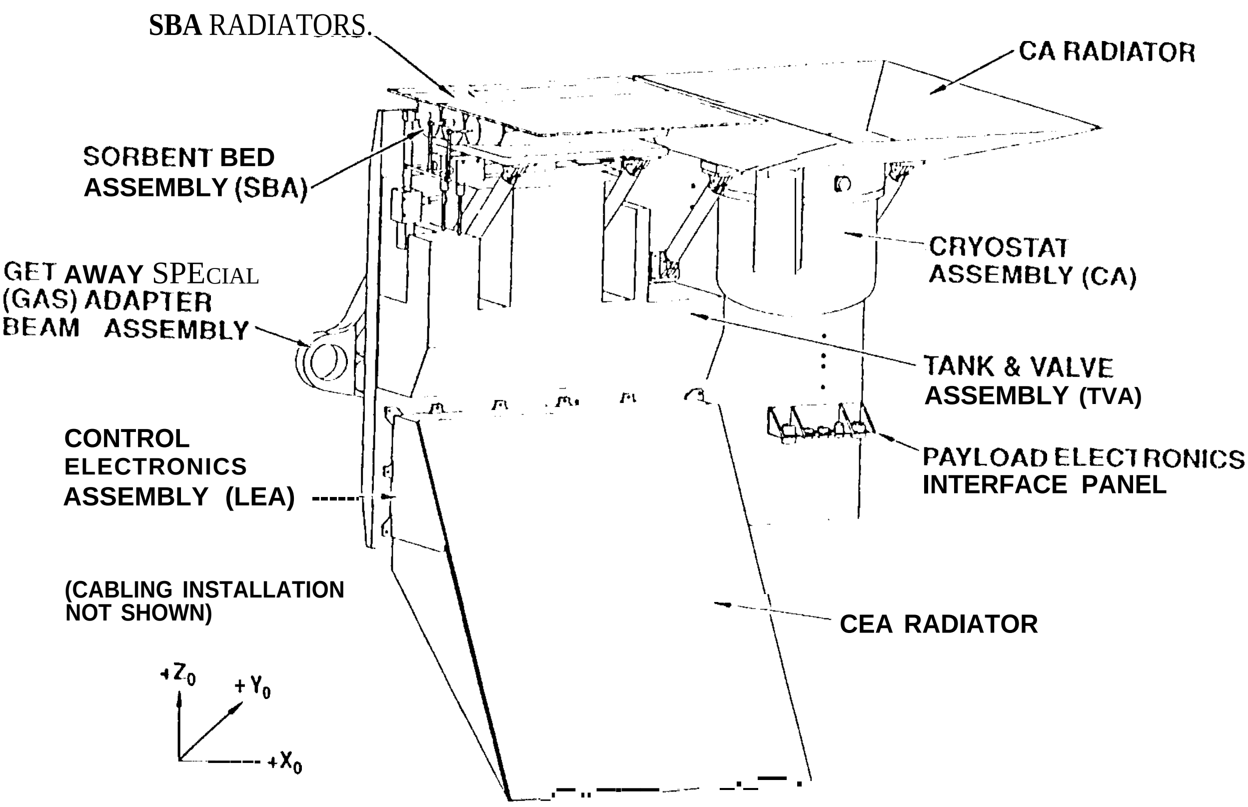

Fig. 1. BETSCE Schematic.

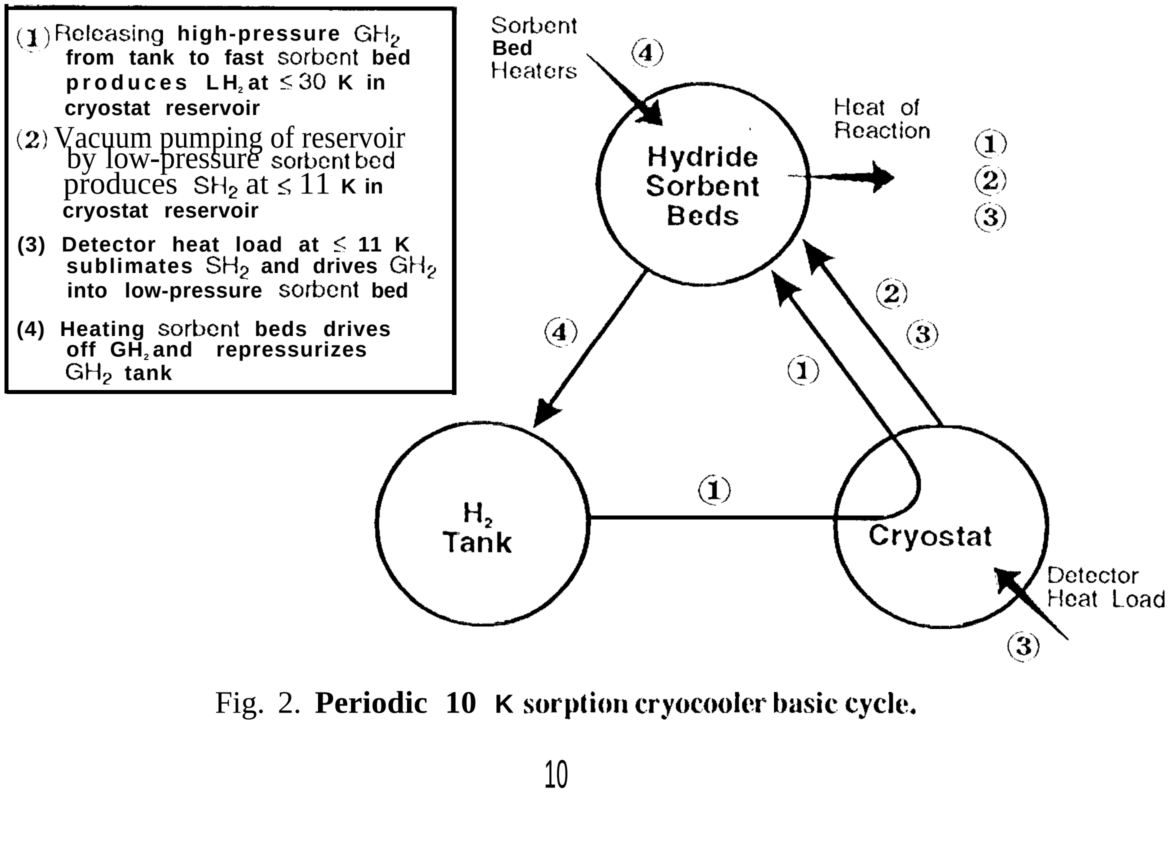

Fig. 2. **Periodic 10 K sorption cryocooler basic cycle.**

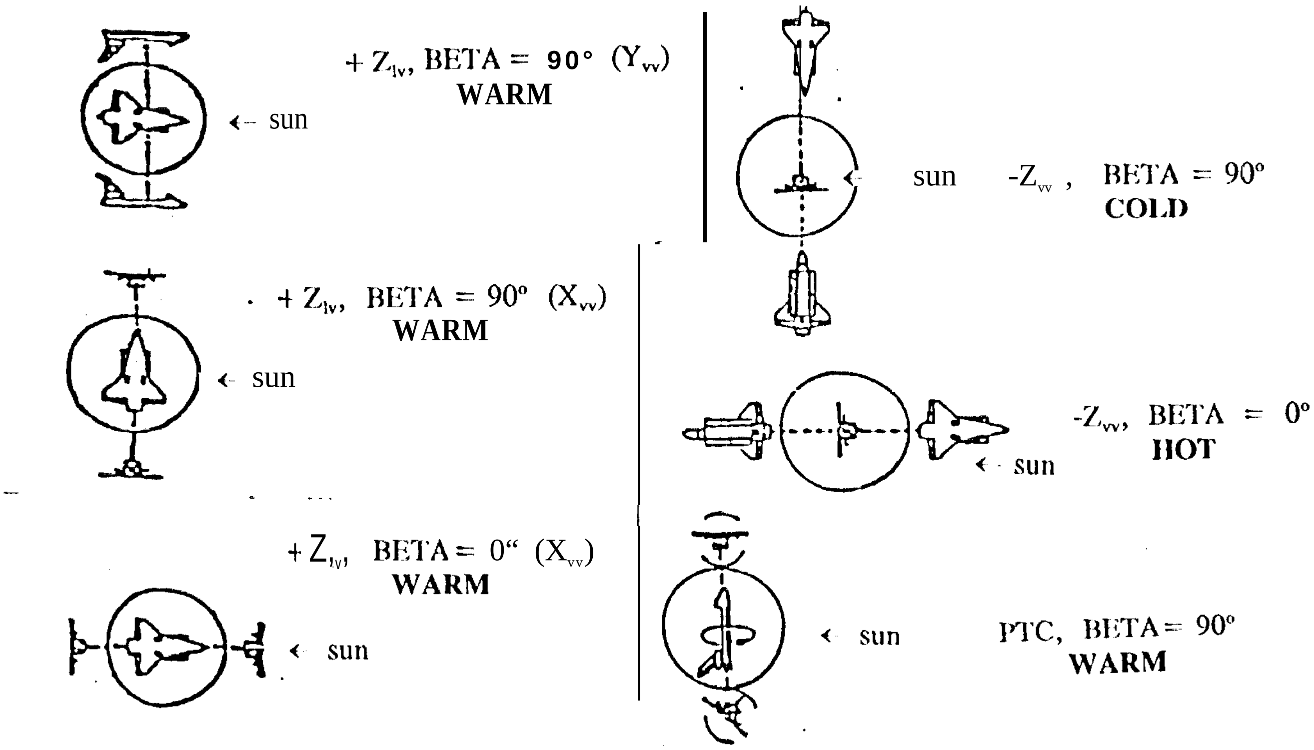

Fig. 3. Space shuttle orientations.

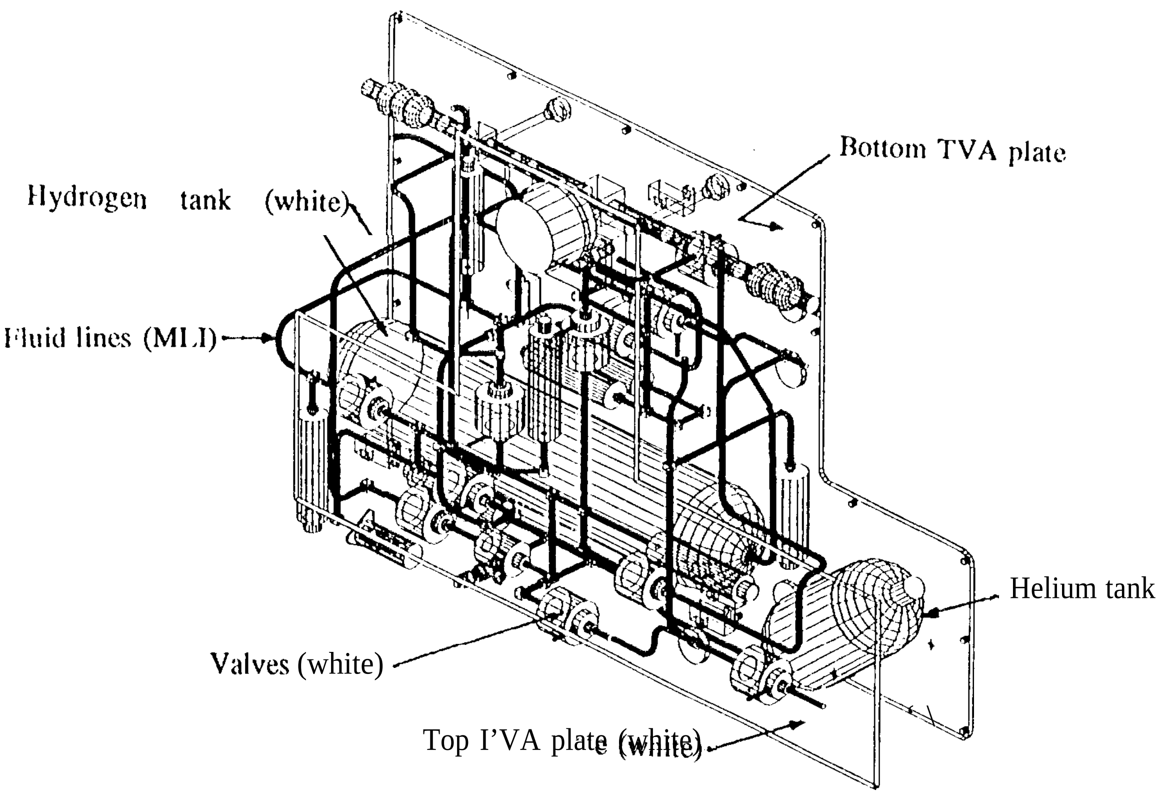

Fig. 4. Tank and Valve Assembly Schematic.