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IRIS THERMAL BALANCE TEST WITHIN ESTEC LSS

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ABSTRACT

The IRIS thermal balance test has been successfully performed in the ESTEC Large Space Simulator to qualify the thermal design and to validate the thermal mathematical model. Characteristics of the test were the complexity of the set-up required to simulate the Shuttle cargo bay and allowing IRIS mechanism actioning and operation for the first time in the new LSS facility. Details of the test are presented, and test results for IRIS and the LSS facility are described.

INTRODUCTION

IRIS (Italian Research Interim Stage) is the first European launcher to complement the NASA Space Shuttle System with an expendable, spinning solid upper stage, capable of placing satellites into orbits with energy requirements beyond the Shuttle basic capabilities. The system consists of the Airborne Support Equipment (ASE) and the IRIS Spinning Stage (ISS).

The IRIS system is being developed by an Italian industrial team led by the AERITALIA Space Systems Group. The program is being financed by the Italian government through CNR/PSN (National Research Council/National Space Plan) and is now approaching the end of phase C/D.

The IRIS system verification philosophy is based on a three-model approach. One of the models is the Structural/Thermal Model (STM) which was subjected to the structural and thermal test campaign (thermal balance, modal survey, acoustic, spin and deployment, and static tests).

In order to qualify the thermal design and to validate the thermal mathematical models, the system has been tested in two configurations:

- ASE/ISS mode, simulating the IRIS system within the Orbiter cargo bay,
- ISS only mode, simulating the ISS system during the coasting phase after deployment from the Orbiter.

The ASE/ISS mode thermal balance test was performed at the beginning of 1987 in the Large Space Simulator (LSS) at ESTEC-Holland, and was the first test in this new facility.

To facilitate installation of the test article and its operations, and to provide representative Shuttle cargo bay interfaces, a multipurpose IRIS Test Support Hardware (ITSH) was developed by ESTEC and bolted directly to the "seismic structure" of the LSS.

This paper summarizes the characteristics of the IRIS thermal balance test in the LSS. It provides a description of the test article, set-up and facility; a report of the test sequence and events; and a presentation of the test results from both the IRIS and LSS facility point of view.

IRIS SYSTEM

CONFIGURATION

IRIS (ref. 1) is a system to launch satellites, with a maximum mass of 900 kg, from the Space Shuttle (fig.1). It takes the form of an upper stage of the family comprising Boeing IUS, McDonnell Douglas PAM D and PAM A and it covers the lower mass range suitable for scientific satellites and small communications/broadcasting satellites.

The IRIS system consists of two main modules:

- an Airborne Support Equipment (ASE) that is mounted in the Space Shuttle cargo bay. It supports the deployable stage and the payload during ground operations, as well as during launch and ascent up to the on-orbit separation. The ASE is a reusable module with all subsystems needed to fulfil the mission requirements;
- an IRIS Spinning Stage (ISS) that is the deployable and expendable part carrying the payload to be launched. The ISS is spin stabilized and has a solid rocket motor to provide the necessary impulse for payload insertion into transfer orbit.

The reusable ASE consists of a cradle in the form of a truss structure for mounting the deployable stage and its payload inside the Shuttle cargo bay. The cradle takes up 1/8 of the cargo bay length, measures 4.5 m wide, 4.5 m high and 2.1 m deep. It supports the deployable stage through the spin table (at the base of the solid rocket motor) and two restraints attached to the deployable stage payload attach fitting (PAF). The spin table can provide rates between 45 and 100 rpm to the ISS/satellite assembly.

On the cradle are mounted all the avionics which interface with both the Orbiter and the ISS, controlling IRIS functions and monitoring the health status of both IRIS and the satellite. A power supply controls and distributes power to all ASE subsystems, to the ISS and payload until deployment. The on-board computer is responsible for the operating sequence with delivery of commands to the various subsystems.

The cradle also supports the sunshield, which is environmental protection consisting of multilayer insulation of Beta-cloth and aluminized Kapton sheets. The sunshield has a fixed part as well as movable "clamshell" type segments that are opened to allow the ISS deployment. The movable segments are driven by an aeronautical type wiring mechanism with redundant motors and electronic control units.

The thermal environment is controlled using a full insulation approach. In fact, the cradle is also enveloped by multilayer insulation. This means that IRIS is completely insulated with respect to space. The internal environment is thermostatically controlled using ambient heaters attached to the cradle. This solution also provides suitable environmental protection to the ISS module and to the payload.

The ISS consists of a high performance solid rocket motor using a Kevlar case. The case, on one side, interfaces with the spin table and, on the other side, interfaces with the PAF, which is a truncated cone adaptor supporting a honeycomb platform on which are placed all the electronics necessary to fulfil mission requirements of the 45 minute coasting phase. Batteries and power control units control and distribute power to all ISS subsystems; the nutation control subsystem controls the coning of the composite, after deployment; and the electrical sequencing units command and control the preprogrammed mission sequence until final payload separation.

TEST PROGRAM

As described in ref. 2, the verification of the IRIS system is based on several methods such as: test, analysis, similarity, inspection and review of design.

In particular, the test program is the most important part of the overall verification activities oriented to demonstrating that the IRIS design fulfils the performance requirements (qualification) and that the flight hardware/software is identical to the qualified one, free of workmanship defects and is ready to be flown (acceptance).

The models required to carry out the IRIS test program respectively at equipment, subsystem/module and system levels are outlined in fig. 2 with an indication of the relevant test activities.

In particular, the system structural/thermal qualification is performed on a dedicated model (STM) by means of the following tests:

- thermal balance (completed in April 1987)
- modal survey (completed in October 1987)
- acoustic (completed in January 1988)
- spin & deployment (completed in July 1988)
- static (to be completed in December 1988).

The STM is thermally representative of the IRIS system in its operational configuration, including flight standard structural and thermal parts and thermally representative dummies of the electronic equipment, the solid rocket motor and the payload.

THERMAL BALANCE TEST DESCRIPTION

TEST PHILOSOPHY

The purpose of the IRIS thermal balance test was to qualify the thermal design and to validate the mathematical model.

From a thermal design point of view it was necessary to verify the adequacy of the concept of full insulation (MLI all around IRIS) together with the multilayer insulation composition (verify number of internal aluminized layers). In addition, the behaviour of the ambient heaters had to be checked. The heat transfer from these heaters to the surroundings is via thermal radiation, whereas normally the heater foils are attached directly to the surfaces to be heated.

From a mathematical model point of view it was necessary to verify the model approach of the cradle truss structure, ambient heater representation and the MLI conductivity value.

To achieve these objectives, the most relevant flight phases were identified (see ref. 3). These were the pre-deployment quiescent phase with the flight heaters thermostatically controlled (400 W and 800 W), the worst hot and cold deployment phases with the opening of the sunshield; and a final recovery phase.

In addition to these phases (all transient) two steady state test phases had to be identified in order to:

correlate more easily some aspects of the thermal mathematical model (radiative and linear conductors, geometrical description, etc.),

identify well defined starting points for the transients.

As a general criteria it was attempted to be as close as possible to the flight temperature levels.

The above considerations led to the test sequence shown in fig. 3.

TEST FACILITY AND SET-UP

a) Test Facility

The test was performed in the Large Space Simulator (LSS) of the European Space Research and Technology Center (ESTEC) located at Noordwijk, the Netherlands. The commissioning of this facility took place in 1986 and it was officially inaugurated on January 14, 1987 at which time the IRIS-STM test preparation was underway at ESTEC. The LSS is undoubtedly the foremost installation of its kind in Europe (see ref. 4). This installation is composed of the following main parts:

- **LSS Chamber**

The chamber, with an overall volume of 2150 m^3, consists of two parts:

- the "main chamber", a vertical cylinder 10 m diameter and 15 m heigh,
- the "auxiliary chamber" with a horizontal cone/cylinder 11.5 m diameter and about max. 15 m long.

The two vessels are interfaced by a nozzle 8 m in diameter. The configuration is illustrated in figure 4.

•Shrouds

The inner surface of the main chamber and the nozzle are completely lined with shrouds. The surfaces facing the specimen are painted black and the remaining surfaces are polished. The auxiliary chamber is equipped with baffle (disc) shrouds. Liquid nitrogen is circulated in all shrouds. The achieved temperature during the test was 85 K with a temperature distribution of about 5 degrees celsius.

•Vacuum System

The full, high-vacuum pumping system was used during the test. It is composed of:

- 2 multivane pumps
- 3 root pumps
- 4 turbo molecular pumps
- 1 L He cryopump for N_2
- 2 cryopanels

The achieved vacuum was 7×10^{-5} Pa with the following profile:

100 Pa (1 mbar) in 2 hours 30 minutes; 3 Pa in 6 hours; 7 x 10-3 Pa in 12 hours; 10^{-4} Pa in 18 hours.

•Sun Simulator

The lamp house of the sun simulator is equipped with 19 Xenon lamps of 20 kW each. Its transfer optic is put in a nitrogen environment to avoid ozone production and corrosion. A quartz window 1.08 m in diameter and 82 mm thick provides the interface between the vacuum chamber and the lamp house. The light beam coming from the lamp house is projected onto a collimation mirror 7.2 m in diameter that is suspended at the rear of the auxiliary chamber, and from there illuminates the test volume with a 6 m diameter parallel beam in the reference plane.

The sun simulator was used at two levels of sun intensity:

- 400 W/m^2 achieved with 4 lamps,
- 1420 W/m^2 achieved with 13 lamps.

The measured intensity distribution inside the test volume during the pre-test was within 7%.

The test volume is defined by a cylinder 6 m in diameter and 5 m long centered with respect to the axis of the main chamber.

•Data Handling Facility

The Data Handling Facility consists of two independent systems:

- the thermal data handling system dedicated to handling data from the test subject during thermal testing,
- the facility data handling system dedicated to data handling for thermal test facility control.

The thermal data handling system can provide data acquisition, reduction and presentation of a maximum of 1032 analog sensors and 128 digital sensors. The safety of the test article is assured by the generation of messages and alarm signals when sensors or derived values exceed pre-defined limits. Warning messages and signals are also issued on the basis of extrapolated values.

The reliability of the data handling system is assured by:

- a dual computer system where each computer checks the other
- a dual sensor measurement system
- high redundancy on peripheral equipment
- continuous monitoring of tasks under software control.

Data presentations, on color graphic monitors, terminals and printers, are available in the customer areas and, if needed, anywhere inside or outside ESTEC through the public telephone network (the latter was not used during this test).

By monitoring detailed facility parameters, the facility data handling system provides, both the test operation team and the customer, with fast up-to-data and accurate information on the performance of the facility.

Data are acquired directly from temperature, pressure, flow, solar intensity sensors etc. as well as through digital communication links with the LSS subsystems.

Early warning capabilities, integrated into the system to detect and analyse deviations from the nominal conditions at the earliest moment, ensure a safe and reliable operation of the facility at all times.

Spacecraft sensor information can also be included in the early warning capability. Performance data and warnings are presented in the facility control and data handling areas only.

During the test, 676 sensors were used as follows:

- 473 thermocouples installed on IRIS itself
- 34 thermocouples installed on the ITSH
- 31 voltage measurement channels from calibrated resistances to measure current of flight heaters and guard heaters
- 131 virtual sensors
- 25 power supplies for the infra-red lamps on the ITSH.

b) Test Set-Up

The test article was placed on a dedicated structure called IRIS Test Support Hardware (ITSH) (see ref. 6). This structure allows the test article to be centered within the LSS test volume with the sunshield facing the collimation mirror.

The test set-up also included an additional set of 6 shrouds connected to the liquid nitrogen system of the facility; a Space Shuttle cargo bay simulator; and a gravity compensation system for the opening and closing of the sunshield segments. All these complementary elements were fixed to the ITSH structure. The test set-up is illustrated by the photographs in figures 5, 6 and 7.

• IRIS Test Support Hardware (ITSH)

A special multipurpose structure has been designed to allow thermal tests on large items in the LSS with a representative Space Shuttle interface. ITSH was developed primarily to allow two different IRIS test configurations: in a horizontal position for the thermal balance test described here, and in a vertical position for a thermal vacuum test of the IRIS flight model.

Because of its modular concept, this structure is particularly flexible in use and allows easy adaptations for various test configurations and project specific requirements. The ITSH is illustrated in figure 8.

• IRIS-STM Thermal Balance Test Configuration

In this configuration the ITSH permits the mechanical coupling with split bearings among the five IRIS trunnions (two main fittings, two stabilizer fittings and one keel fitting) onto the stable platform of the LSS chamber, and makes it possible to center the test article in its horizontal position within the solar beam.

The Space Shuttle cargo bay was simulated by means of a cargo bay simulator equivalent in size and thermal properties.

To allow opening/closing of the sunhield, a Gravity Compensation Unit (GCU) is also provided.

• Cargo Bay Simulator

The cargo bay simulator is used to simulate the solar trapping phenomena that occur between the cargo bay walls and the cradle walls.

The cargo bay simulator consists of a light structure holding multilayer insulation of seven layers of Double-sided Aluminized Mylar (DAM) separated by polyester netting material. The insulation is covered on both sides by Single Aluminized Kapton (SAK) and, on the inside facing the test article, by Nomex polyester.

•Additional Shroud System

Suitable cryogenic shrouds cooled by LN_2 are installed under the sunshield plane to avoid the radiative heat exchange between the ITSH base structure and the test article.

•Sunshield Gravity Compensation Unit

The Sunshield Gravity Compensation Unit (GCU) unloads the hinges of the sunshield segments during the test actuations by supporting them in the center of gravity. The GCU allows the automatic adjustment of the compensation weight and of its position with respect to the supporting rails.

•Scaffoldings

To the basic test structure one can easily attach scaffoldings, working platforms as well as access bridges and telescopic stairs to reach the test article during installation and preparation activities in the test facility. All these elements are designed to be installed and removed quickly by two people.

•Thermal Control

For temperature control of the ITSH, 28 infrared lamps (500 W) were fixed to the legs and the base frame of the structure and 7 foil heaters were attached where infrared lamps could not be mounted. Eight additional infrared lamps were installed on the LSS stable platform. During the test the ITSH temperature was maintained at about - 50 degrees celsius. The power used was only 1 kW during the test and about 8 kW during the recovery phase.

• Other ITSH uses

The ITSH is also designed to be used for the IRIS flight model thermal vacuum test. This requires some modifications of the split bearings support legs and additional shroud elements. However, due to the modular concept of the ITSH, it is easily achieved at a minimum of cost.

In the mean time ITSH has also been used for the European Retrievable Carrier (EURECA) thermal balance test with minor adaptations to the basic ITSH elements.

The test set-up was completed by means of photovoltaic cell sensors to automatically control and measure the solar flux; a power supply and control unit to feed the IRIS dummy boxes; a sunshield special test equipment to remotely actuate and control the mechanism; and an observation camera system to control the actuation of the sunshield from outside the chamber.

TEST PREDICTIONS

The thermal mathematical model (see fig. 9) used for the test predictions was basically the one already used in the analysis campaign for the thermal control design definition.

Changes were made to take into account the IRIS test configuration and the test boundary conditions.

The following items of the STM in the thermal configuration were not flight standard:

- the electronics, except for a few exceptions, were thermal dummies
- the motor was empty
- the bolt cutters were inert
- a dummy payload simulating the mass (900 kg) of a nominal payload was included.

The thermal vacuum chamber and the test fixture configuration were considered in the thermal mathematical model. The main implementations are the following:

- The introduction of a cargo bay simulator. This represented a compromise between the worst hot and cold conditions for IRIS in the Space Shuttle cargo bay. The front and the bulkheads were semi-circular; so it was possible to experience worst cold conditions in the cargo bay (high radiative link with space). The simulation of worst hot conditions was permitted by maintaining reduced gaps between the test article and the cylindrical part of the cargo bay simulator. This configuration allowed sun trapping to be simulated.
- The large collimation mirror was considered in the pre-test thermal mathematical model for two reasons: the large dimensions (viewfactor between mirrors and test article around 0.05); and the temperature during the test that was maintained at + 20 C for contamination reasons. It was represented in the thermal mathematical model by a disc (7.1 m in diameter) having the thermo-optical properties of the mirror.
- The chamber was modelled as a sphere of radius 18 m centered on the IRIS axes. It was considered a boundary with the following properties: absorptivity and emissivity equal to 1, temperature of 100 K. The true absorptivity and emissivity of the shroud is 0.9. However, due the large size of the chamber with respect to the ASE, multiple reflections can be ignored.
- The trunnions were made adiabatic by the application of guard heaters on the test fixture side of the attachment interface. All linear conductors between ASE and the cargo bay have therefore been deleted.

In order to perform the test successfully and safely, a set of pre-test temperature and power level predictions were required. All the test phases were analysed except the pump down/cool down and warm up (ref. 5).

The thermal analysis predictions for the two steady states allowed the determination of the ambient heater power level to reach the correct mean temperature range inside the IRIS: 100 W for phase 2 and 60 W for phase 5.

The analyses for the two slow transients gave the duration of the two test phases: 25 hours for phase 3, and 23 hours for phase 6.

The analyses for the two deployment phases allowed the evaluation of the thermal behaviour of the operative electronics, particularly the flight-standard ones. To better appreciate the temperature trends the deployment phases were longer than planned in flight.

The analysis for the recovery phase gave an indication of the length of phase required.

It has been found that the general level of temperatures within the ASE is very sensitive to variations in the parameters: solar intensity, flight heater power and MLI conductance. A sensitivity analysis was therefore performed in order to assist in the adjustment, during the test, of the power levels to meet the test objectives. Under the same conditions a double or a half thermal conductance of the MLI gave a variation in temperature of $\pm 10°$ C.

TEST EXECUTION

The test required an intense test preparation and pre-test period of about three months.

Before the proper test execution could start, the following pre-test activities were performed:

- sun simulator calibration two weeks before test article arrival
- calibration (e.g. thermocouples, sun simulator cells)
- pre-test of the ITSH to verify the leak tightness of the specific shrouds, to monitor the cool down of the structure and to check the effectiveness of the heaters; to perform the leak test during video filming and window observation; to check the proper operation of the LSS in the test configuration. This pre-test revealed defects in painting of the ITSH specific shrouds. Repainting was done and the shroud panels successfully retested in time.

The test itself was carried out during February, 1987. The test started on the morning of February 20 and terminated at night on February 27 following the phases as specified in the applicable procedure (ref. 7). The only exception was the deletion of phase 8: "earth facing recovery" because during the previous preparatory phase, with sunshield closing, a failure occurred and the movement stopped at 1/4 of the run.

The failure was due to the unexpected change in the size of a bearing of the GCU system wheel when exposed to the sun flux. In fact, the sunshield closed as soon as the temperature decreased.

Apart from this failure, the test was considered satisfactorily executed from both points of view: LSS performance and IRIS behaviour, as extensively described within ref. 8 and 9.

During the execution of the test, standard mass-spectrometric measurements were performed to monitor the quality of the LSS vacuum. Seven sensors were placed inside the facility during the test to control organic contaminant (hydrocarbon equivalent and ester equivalent). The measured values were less than 1.3×10^{-7} gcm^{-2}.

TEST RESULTS

The test results confirmed a high level of confidence in the ASE/ISS thermal design.

Generally the temperatures of the test were in accordance with the predicted ones.

In the two steady states the internal environment of IRIS was as predicted (temperature level around 15° - 18° C). These results mean that the design of the thermal blankets and the concept of full insulation are acceptable and allow adequate control.

The results from the two slow transients showed that the duration of the 2 phases are 25.5 hours for phase 3, and 21 hours for phase 6. The differences from the prediction are very small: 2% more and 8% less in time respectively. This result confirms the design of the MLI. Moreover, it shows that the ambient heaters work properly and that the thermostat set points are adequate. The location of these thermostats (on the ISS annular plate) is acceptable.

The considerations that arise from the evaluation of the results of the two deployment phases are in accordance with the above statements.

During the hot deployment phase, when the sunshield was open, some items reached relatively high temperature values. They are: the cylindrical structure that connects the SRM and the spin table; the springs; and the clamp band of the separation subsystem. The temperature was around 40° C. This problem led to the reconsideration of the requirements for these items. The temperature excursion, however, was considered acceptable, because the test conditions of this phase were conservative.

As already explained, it was not possible to have information on the recovery time from the hot excursion, owing to the sunshield failure during the closure phase.

Taking into account all of the above considerations, the thermal design of IRIS is considered qualified (see ref. 8).

Suitable test correlations have been performed to compare the test results with the post-test predictions which were updated by introducing actual test boundary conditions (shroud temperatures, heat dissipation, measured thermo-optical properties, power on/off times, etc.). The correlation criteria (delta temperature predicted/measured less than 1.5° C, standard deviation less than 3° C) were reached for all IRIS internal nodes requiring only a few mathematical model modifications. An example of the statistical histogram for phase 2 is shown in fig. 10. Details of the correlations are contained in ref. 10.

CONCLUSIONS

The execution of the Thermal Balance Test allowed the achievement of the stated goals. The thermal design of IRIS has been qualified. The thermal mathematical model has been updated and validated, and is now ready to be used for IRIS payloads.

The cargo bay simulator allowed the creation of the in-cargo bay boundary conditions. This approach gave suitable results, together with the overall test concept.

This first operational test with the LSS was carried out without problems. The facility performed well and good results were obtained, in particular, concerning the stability and uniformity of the solar intensity in the test volume. The facility showed a very good efficiency which resulted in low operational costs.

Interesting facility information was collected for later improvements.

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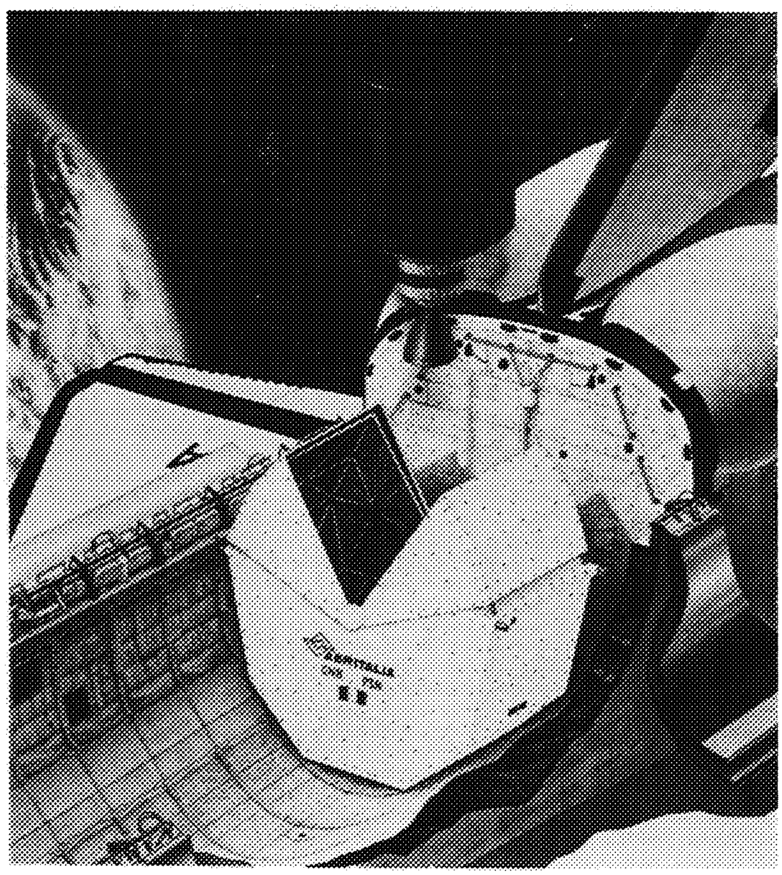

Fig. 1 - IRIS in the Space Shuttle

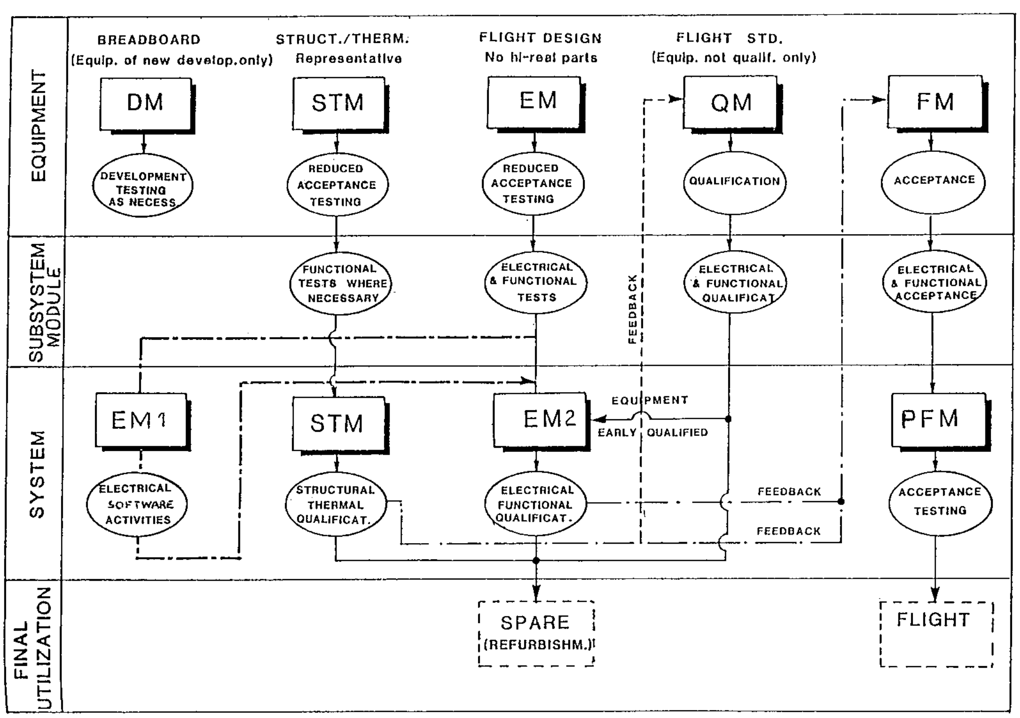

Fig. 2 - Model Philosophy

PHASE NUMBER	1	2	3	4 (1st part)	4 (2nd part)	5	6	7 (1st part)	7 (2nd part)	8
PHASE DESCRIPTION	pump down cool down	earth facing steady state	earth facing cycling	cold active phase	cold active phase	earth facing steady state	earth facing cycling	hot active phase	hot active phase	earth facing recovery
SPACECRAFT ATTITUDE		FLUX	FLUX			FLUX	FLUX	FLUX	FLUX	FLUX
FLUX INTENSITY	zero	400 W/m^2	400 W/m^2	zero	zero	400 W/m^2	400 W/m^2	1420 W/m^2	1420 W/m^2	400 W/m^2
CHAMBER PRESSURE	from ambient to < 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa	< 10^{-3} Pa
SHROUD TEMPERATURE	from ambient to 100 K	100 K	100 K	100 K	100 K	100 K	100 K	100 K	100 K	100 K

Fig. 3 - Test Sequence

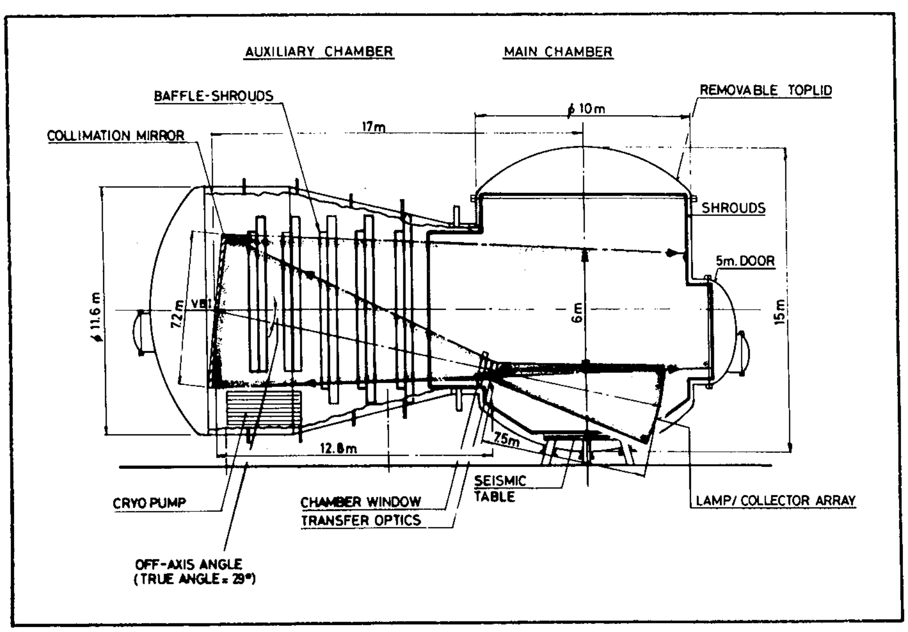

Fig. 4 - Lay-out of the Large Space Simulator (LSS)

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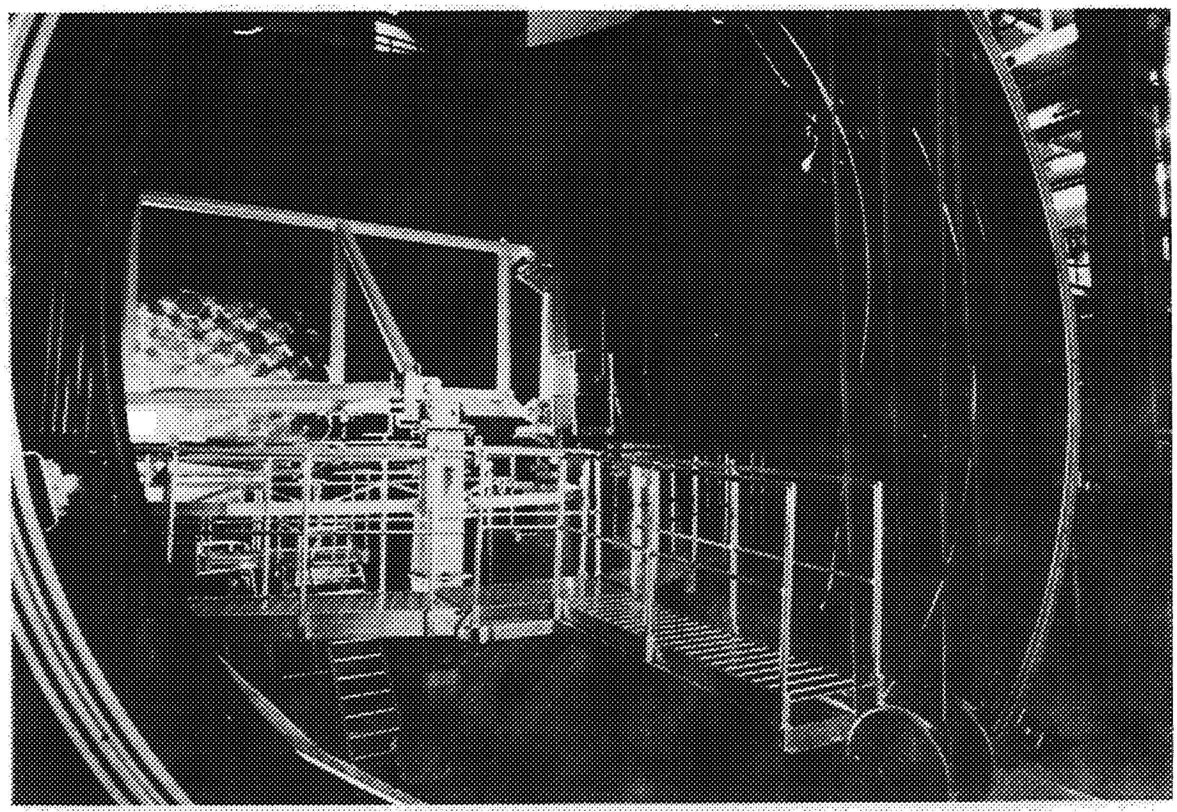

Fig. 5 - ITSH with dummy load frame inside the LSS

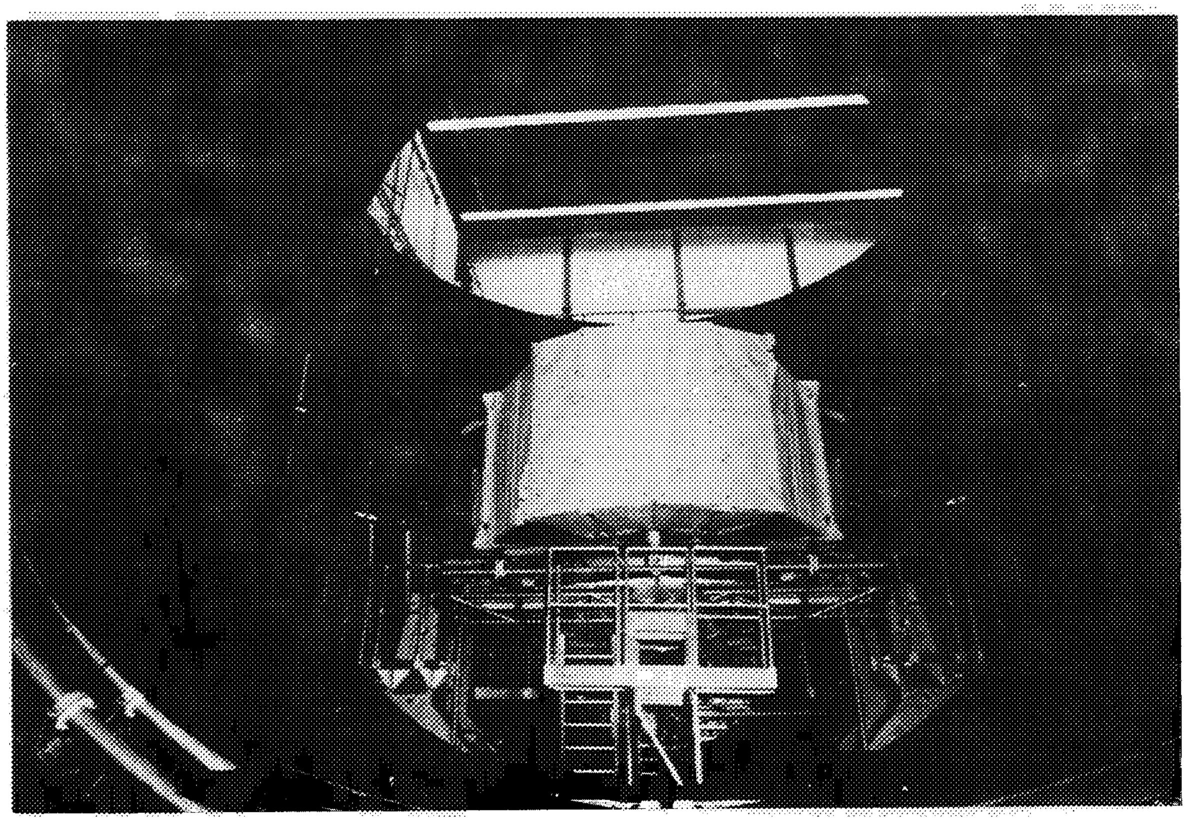

Fig. 6 - Test set-up front view

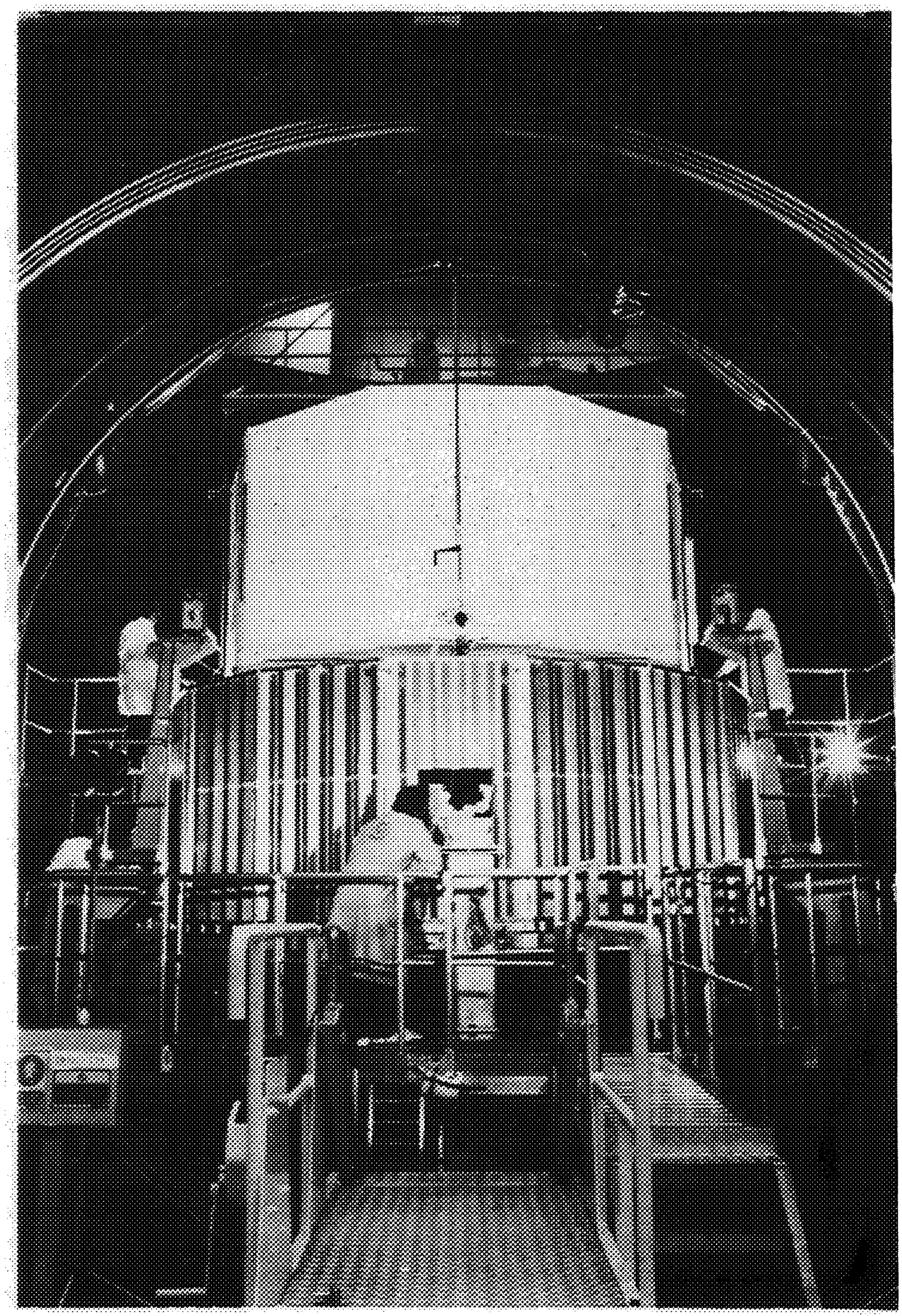

Fig. 7 - Test article installation in the LSS

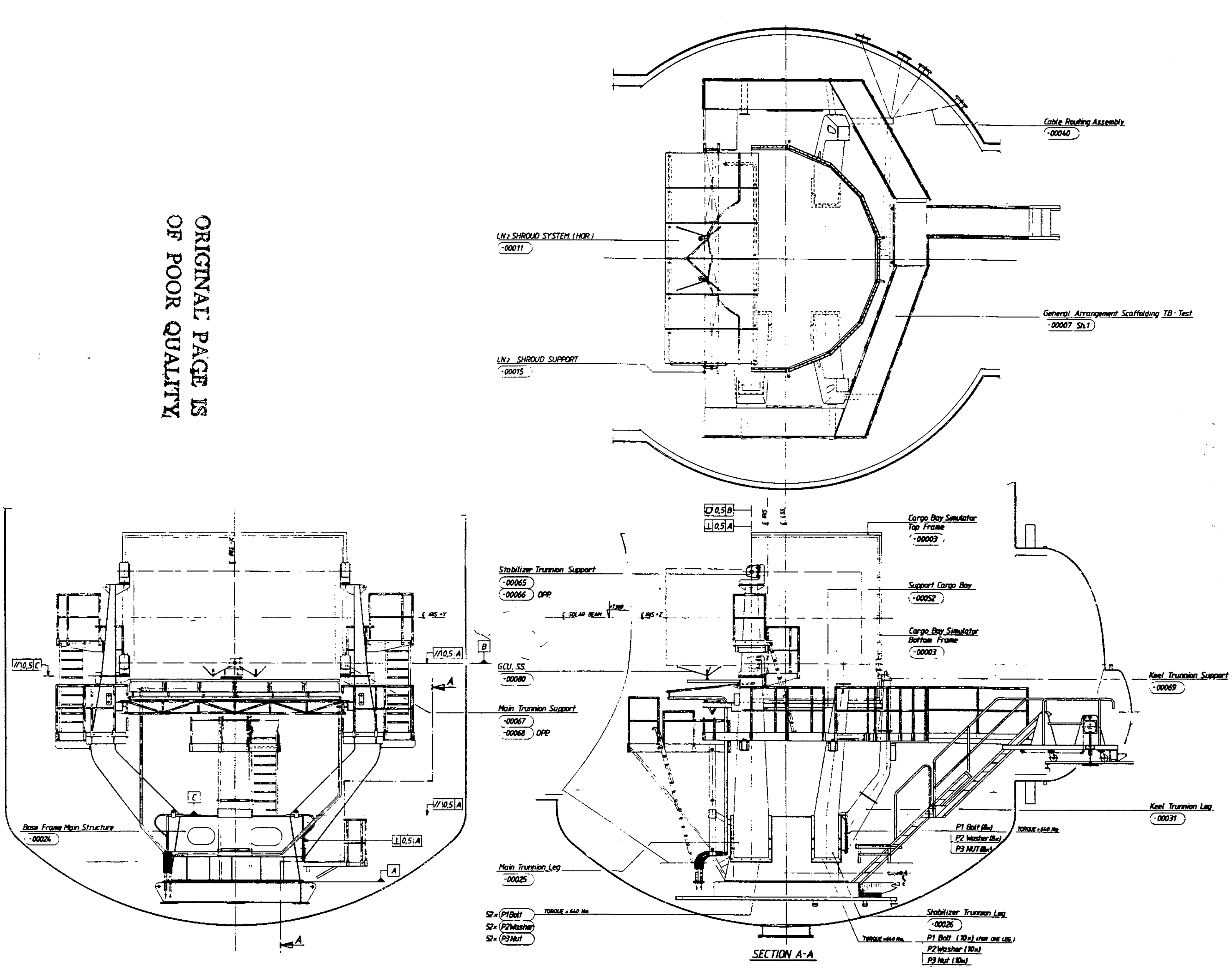

Fig. 8 - ITSH Thermal Balance Test Arrangement

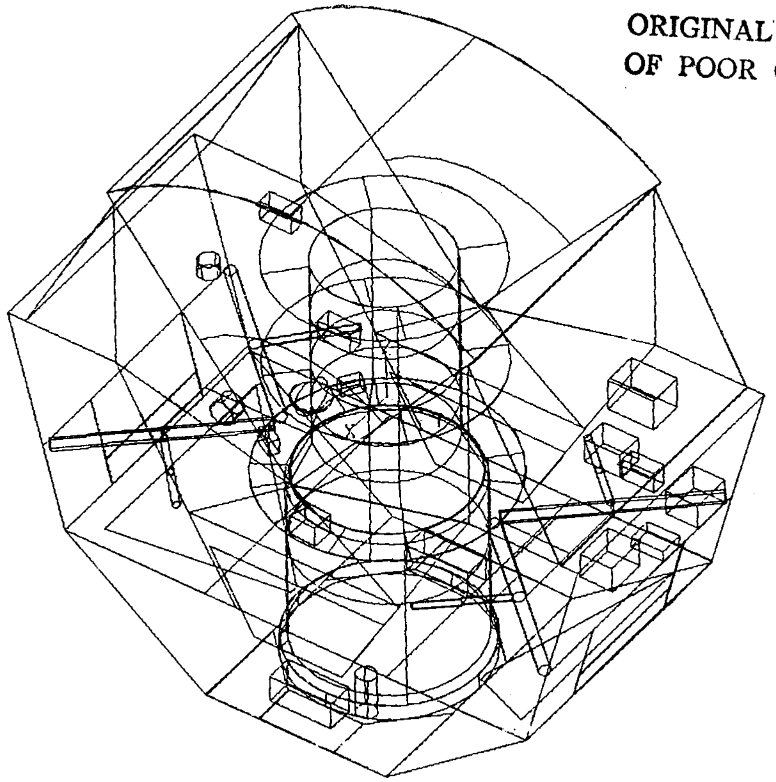

Fig. 9 - IRIS Thermal Mathematical Model

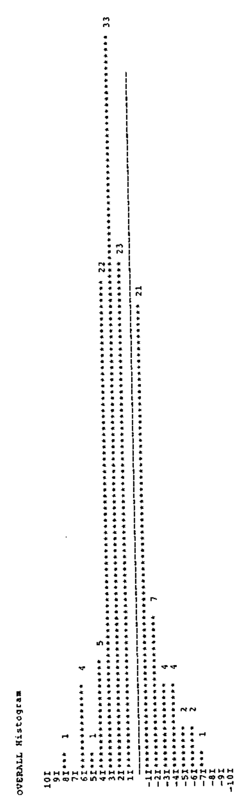

Fig. 10 - IRIS Phase 2 Histogram as elaborated by a statistical program