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Present Capabilities and Extension Possibilities of the Spacelab Thermal Control System

E. Vallerani,* P.L. Degli Esposti,† and B. Sessions‡
Aeritalia, Torino, Italy

The paper is presented in two parts. The first describes the design features of the Spacelab thermal control system, while the second outlines the extension possibilities of the system to comply with the expected evolutionary steps leading from the Spacelab of today to the space stations of tomorrow. The purpose of the Spacelab thermal control system is to insure environmental control of the pressurized Spacelab module and keep the temperatures of the equipment and experiments mounted in the module and on the pallet within the prescribed limits. The design and development philosophy is briefly recalled through a discussion of the mathematical models developed and the results obtained, as well as of the tests performed to support and validate the design. Studies for the extension of Spacelab thermal control system capabilities and performance are presented. These studies have the following main objectives: increase the heat rejection capabilities by adding a radiator; and explore the expected evolution of the basic control loops in the light of increased requirements dictated by the autonomous use of Spacelab, leading to the buildup of future modular space stations.

Introduction

DEVELOPMENT of the European Space Laboratory, Spacelab, to be used over the next decade for scientific and technological space research in conjunction with the Space Shuttle, is a cooperative program between the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). The Spacelab has been conceived with an extremely flexible design to allow the performance of a large variety of experiments in space while achieving best utilization of the payload capabilities of the Space Shuttle. Brought into orbit by the Orbiter, for missions lasting from 7 up to 30 days, Spacelab will offer the international community of users an efficient and versatile general-purpose means to conduct the next generation of manned space research and space exploration activities.

The Spacelab is formed from two basic elements, the "pressurized module" and the "unpressurized pallet." The "module" is a cylindrical compartment that provides to the experimenters and equipment sea-level Earth conditions. Inside the module standard elements for the experiments support, such as floor, racks, airlocks, heat exchanger, cold plates, as well as basic services such as power, environmental control, and data management, are provided. The "pallet" is a platform to support experiments directly exposed to the space environments. These two basic elements, designed with a modular concept, can be used separately or in conjunction, giving rise to different configurations.

The thermal control subsystem (TCS) together with the environmental control and life support subsystem (ECLS) form the Spacelab environmental control subsystem (ECS). The environmental control subsystem provides different services for Spacelab and its experiments including: pressurization of environment inside the module, removal of contaminants, cooling of module- and pallet-mounted equipment, passive thermal control of module and pallet, airlock reconditioning, and several emergency functions such as smoke detection, fire extinguishing, and overpressure and negative pressure protection for the module.

The thermal control subsystem (TCS) is subdivided in turn into two sections, the active thermal control section (ATCS) and the passive thermal control section (PTCS). The former consisting of two coolant loops that transfer heat generated by Spacelab subsystems and experiments from the module and pallet to the Orbiter heat rejection system and the latter formed by thermal insulation covers protecting the module external structure and the pallet segments, as well as the utility lines and other externally mounted subsystem equipment.

Part I—"The Present"

ATCS Fluid Loops Functions and Description

The basic function of the active thermal control system (ATCS) is the transfer of all the heat loads generated inside the module and on the pallet by Spacelab subsystems, experiments, equipment, and by the metabolic processes associated with the crew, to the Orbiter heat rejection system that radiates the heat to space. The ATCS is limited in the amount of heat (8.5 kW) that can continuously be transferred to the Orbiter payload heat exchanger. For short periods (15 min every 3 h) higher peak heat loads (up to 12.4 kW) can be accommodated by storage of heat via heat capacitors and rejected at a later time.

According to the Spacelab flight configurations obtained by combinations of the module and the pallets, different ATCS configurations, are foreseen; the three basic ones are module only, module-pallet, and pallet only. The basic components used in all of the configurations are identical and have been designed to optimize their overall performance for different environmental and operational conditions.

Module-Pallet Mode

The configuration module-pallet (Fig. 1) is the most complex and utilizes two basic loops: water inside the module and freon on the pallets (in the module only and pallet only modes these loops are operated separately). The main cooling loop inside the module, operated with water for safety reasons (nominal mass flow 227 kg/h), collects the heat from three

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*Technical Director, Space Sector.
†Chief Thermal Engineer.
‡Thermal Study Manager.

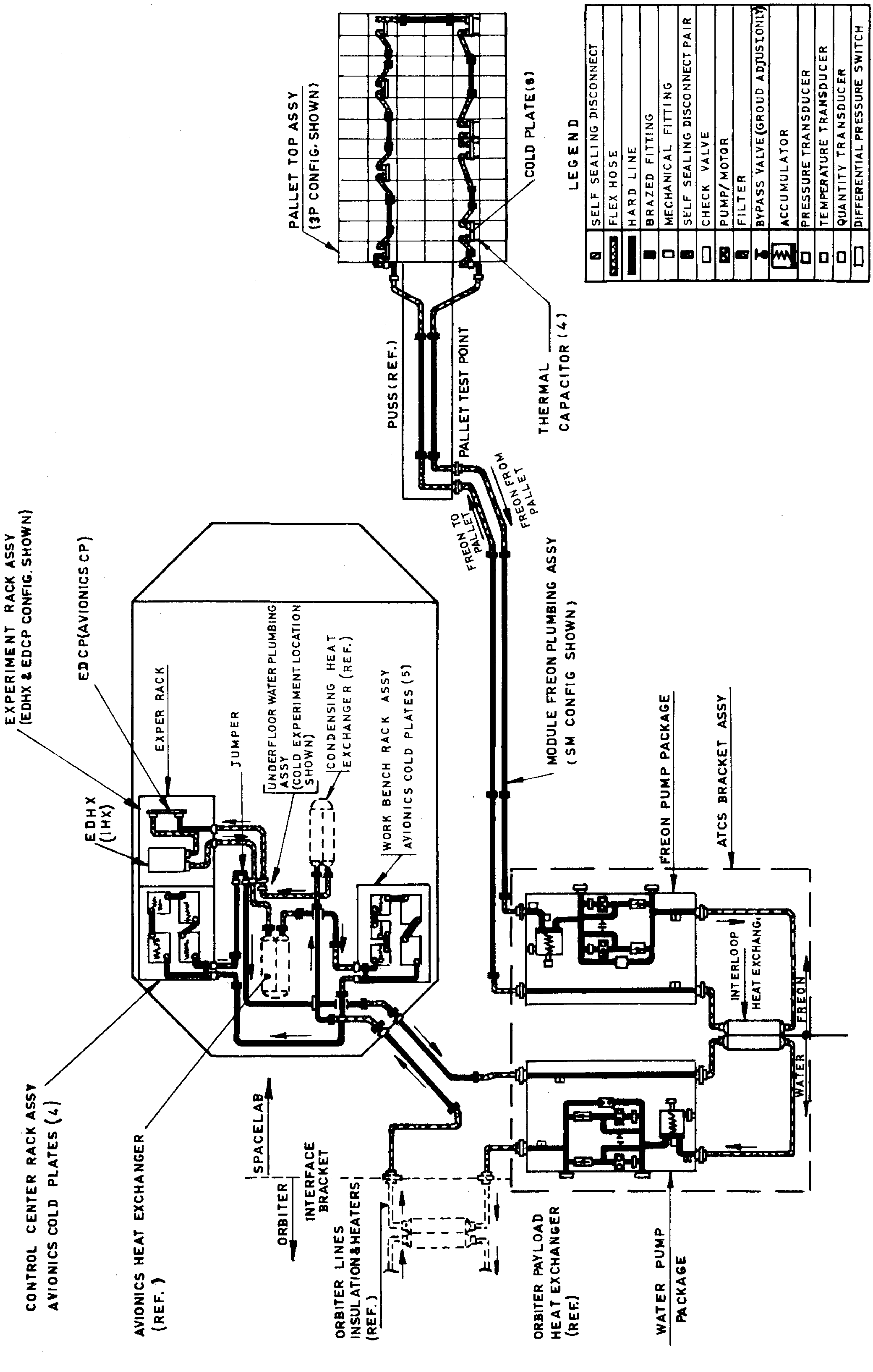

Fig. 1 ATCS schematic module-pallet mode.

auxiliary cooling loops and transfers the total heat to the Orbiter/payload heat exchanger. The auxiliary cooling loops are as follows.

The *cabin air loop* controls the module atmosphere. It interfaces with the main water loop via the condensing heat exchanger. The heat loads in the cabin air loop are originated by the crew total metabolic heat rejection, by module heat leaks to and from the space environment depending on the orbit attitudes (cold case 1200 W out, hot case 1250 W into the module), by heat leaks from the avionics loop through the rack front panels (168 W nominal case), by heat rejected into the loop by subsystems equipment mounted on the subfloor, and finally by heat rejection from experiments mounted on the floor center aisle and inside the airlock (during operations with the inner hatch open) that cannot be readily cooled using the avionics air loop. A maximum continuous heat rejection capability of 1 kW, with a peak up to 3 kW, can be accommodated in total by the cabin air loop. The forced air flow within the module (5-12 m/min) provides an adjustment of the cabin air temperature in the range from 18°C to 27°C selected by the crew, with an automatic control to within ±1°C. The mean radiant temperature of the interior of the module does not exceed 30°C and the temperature of unprotected surfaces of possible crew contact do not exceed 45°C.

The *avionics air loop* provides conditioning for the equipment located in the subsystem and experiment racks. It interfaces with the water loop via the avionics heat exchanger. This loop is separated from the habitable volume in the module by sealing of the racks. An avionics fan assembly establishes the air flow through the ducting system and the racks; air is ducted through the avionic heat exchanger and from there into the supply ducts routed under the main floor. Air enters the rack interiors through diffusers, at the bottom, and after cooling equipment (surface cooling for open equipment and ducted cooling for enclosed equipment), is sucked through the return ducts inside the racks into return ducts under the main floor. A nominal continuous heat rejection capability of 4 kW with a peak up to 10 kW can be accommodated in total by the avionics air loop. The avionics air loop flow enters the racks at a nominal temperature of 22°C and can reach up to 40°C at the outlet; for peak loads it can increase up to 50°C. The avionics air loop inlet temperatures are dependent, for a particular set of operating conditions, on the heat loads of the avionics loop as well as of the cabin loop, and on the outlet temperature at the Orbiter payload heat exchanger.

The *experiment fluid loop* interfaces with the main water loop via the experiment heat exchanger and can be installed in the water loop either upstream of the avionic heat exchanger or downstream of the subsystems cold plates. Liquids allowed in manned spacecraft can be used on the experiment side as an alternative to water. This loop provides thermal control of experiment equipment with up to 4 kW of power dissipation.

A fourth loop, the *freon cooling loop,* is connected in the module-pallet mode to the main loop via the interloop heat exchanger to collect the heat generated on the pallets. The freon loop collects heat from the experiment and subsystem equipment located on the pallet by means of eight standrd experiment cold plates; up to four thermal capacitors are mounted on the cold plates to accommodate the peak heat loads. A change is under investigation to accommodate up to 13 standard cold plates located on the pallet.

The freon loop nominal mass flow is 1368 kg/h with a maximum rejection capability of 8.27 kW. The cooling capability available for experiments is dependent on the Orbiter heat rejection capability and on the heat loads acting on the water loop; it depends also on the loads in the freon loop due to subsystem packages located on the first standard experiment cold plate on each pallet, as well as on the heat leaks to and from the pallet structure and to and from the space environment.

ATCS Component Functions and Description

As outlined in the description of the ATCS fluid loop, several standard components have been utilized.

Experiment and Interloop Heat Exchangers

The heat exchangers consist of a brazed assembly of stainless steel plates and closure tubes with nickel fins, with brackets and headings welded on the assembly. A counterflow design, once folded, with 15 fin layers per side has been adopted. Guiding blades at the inlet headings, at both sides, are introduced to improve the heat-transfer effectiveness. The nominal transfer capability of the heat exchanger is 4 kW.

Cold Plates

The cold plate is an element designed to transfer heat, from the electronic equipment and/or thermal capacitors mounted on it, to the water or freon loops. Several types of cold plates similar in design but different in dimensions and configurations have been designed and developed (two types of standard pallet cold plates and three types of avionic cold plates). The cold plate consists of a brazed assembly of stainless steel face sheets, bosses and closure tubes, and internal nickel fins. The nominal heat rejection capability of the standard cold plate is 1 kW each. A grid hold pattern 70×70 mm is provided for mounting electrical components and/or thermal capacitor elements. The mounted components are bolted through the cold plate holes, with or without a filler on the contact surface, and attached to the main spacecraft structure.

Thermal Capacitor

The thermal capacitor is an element designed to store heat loads resulting from transient overcharges in the fluid loops. The heat accumulated in the capacitor, through a phase change process, is returned into the loop at a later time when the heat-transfer balance allows it. The capacitors consist of an aluminum structure containing a very large number of independent small square cavities partially filled with the phase change material (n-Heneicosane). Thermal capacitors are designed for a nominal heat storage capacity of 0.25 kWh each with an input of 1 kW and a phase change temperature range of 39-40.5°C.

Water and Freon Pump Packages

Water and freon pump packages consist of two redundant flow paths made up of an inlet filter, an electrically powered centrifugal fluid pump, a manual bypass valve, and a reverse-flow check valve. The inlet pressure and temperature of the fluid supplied to the package are monitored by a pressure and a temperature sensor. The pump inlet pressure is established by a nitrogen charged accumulator. The system fluid quantity is monitored by a quantity sensor relating the accumulator bellows position to system fluid quantity. A delta pressure switch monitors the pressure rise across the parallel redundant loops (filter, pump to check valve) to enable early assessment of any problem in these flow paths. The instrumentation (sensor and switches) and pumps are interfaced by a control box mounted integral to the package; ac power to the pumps is introduced through two separate connectors feeding through externally operated relays. The instrumentation power supply is a conditioned dc signal fed directly through the control box and then through a harness to the instrumentation. Should the pressure rise across a flow path (filter/pump/check valve) drop below 0.28 kg/cm^2 (3.5 psi) the delta pressure switch contacts open, providing a signal of the low pressure, and the operation of the package is shifted manually to the parallel flow loop to permit continuation of the mission.

Plumbing

The plumbing is a combination of hard and flexible lines. Stainless steel lines are used with induction brazed fittings for

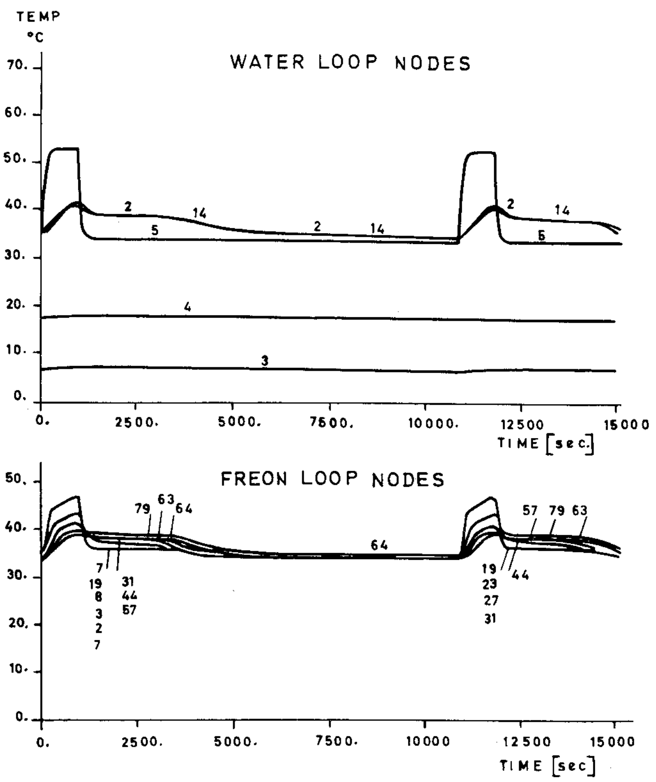

Fig. 2 ATCS thermal model results, module-pallet mode.

unbreakable joints and quick disconnectors or MC fittings for the breakable joints.

PTCS High-Performance Insulation Covers

Functions and Description

The Spacelab passive thermal control subsystem is designed to provide thermal insulation of the module structure, pallet structure, and mounted equipment as well as the utilities. The entire module surface is protected by a cover tailored to wrap the cylinder and the cone surfaces. The cover is shaped to protect all the surface protuberances such as the main support and keel fittings and to insure the continuity of insulation at the interfaces with the tunnel and the top airlock. The forward cone cover is supported by a tentlike structure that allows the creation of a thermal protection compartment for some Spacelab components such as the gas storage tanks and the ATCS assembly, including water and freon pump packages, interloop heat exchanger, cold plates, and thermal capacitors. Special collars are designed to insure the overlapping of the covers at the major interfaces between cylinders, cylinder-cones, and airlocks.

The design approach for the thermal covers is quite advanced; multilayer high-performance insulation blankets are used, with double goldized kapton sheets and dacron net separators protected externally by a teflon coated fiberglass cloth and by a double goldized kapton sheet reinforced with nomex inside. The multilayer insulation provides an efficient barrier to heat transfer through the multiple reflection path created between the layers of the cover. The blankets have a modular shape with overlap joints to minimize the heat loss. All of the blankets are initially made in a flat pattern and then put into shape on the module structure. Positive venting provisions are included in each blanket. Electrical continuity across each blanket and along the outer skin of the blankets is also provided by special design features.

Development Philosophy: Analysis and Tests

The development of the Spacelab thermal control system has been based on two foundations—analysis and tests—through which it has been possible to provide the verification

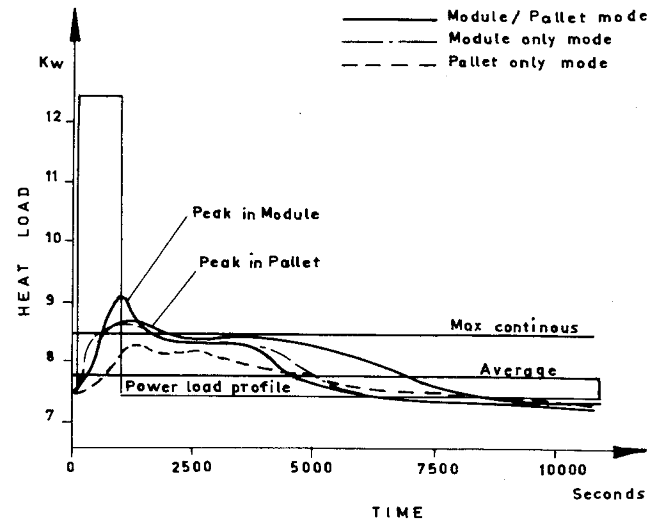

Fig. 3a Heat load profiles at Orbiter payload heat exchanger.

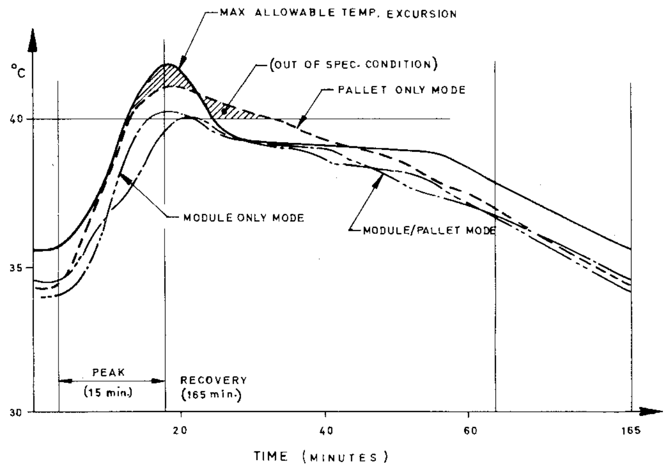

Fig. 3b Fluid return temperature to Orbiter payload heat exchanger.

of the system requirements. The computing and analysis activities have allowed evaluation of the response of the ATCS components and loops to the applied environmental and thermal loads. Steady-state and transient analyses have been performed during the development phase and have been reiterated upon results of the development tests to account for more correct inputs on component performances.[1] The high-performance insulation cover sizing has been done on the basis of extensive analyses supported by development tests that have allowed the definition of the number of sheets to be used to prevent excessive temperature fluctuations of the module and pallet under the applied environmental loads. For the analysis, general purpose and specific computer programs have been utilized, that require the extensive use of large computer facilities. Some of the programs are of a standard type such as SINDA (System Improved Numerical Differencing Analyzer) and LOHARP (Lockheed Heat Rate Computer Program) used for radiation exchange computations; others are programs specifically developed at Aeritalia to solve some of the relevant problems.

The thermal control analysis includes: the environmental analysis, leading to the definition of the thermal inputs imposed on the module and pallet from the specified mission profile; and the thermal analysis, leading to the evaluation of the thermal responses of the component and of the subsystem in terms of temperature histories of the different elements under the specified transient and steady-state thermal load conditions.

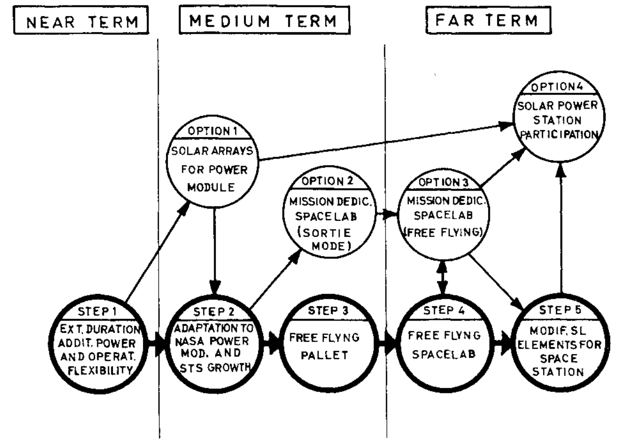

Fig. 4 Spacelab follow-on development approach.

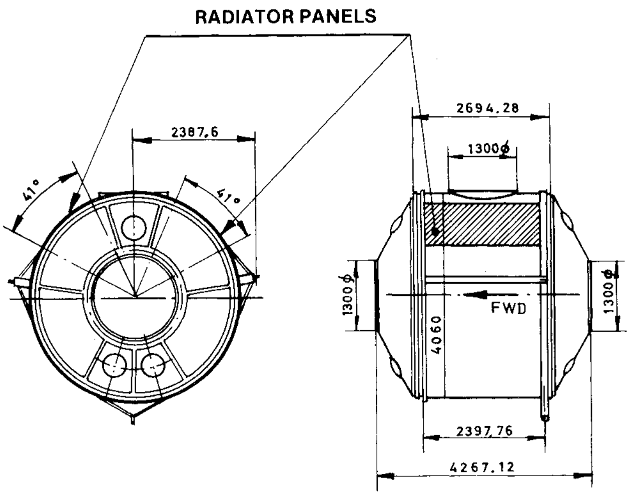

Fig. 5 Short module with radiator panel segments.

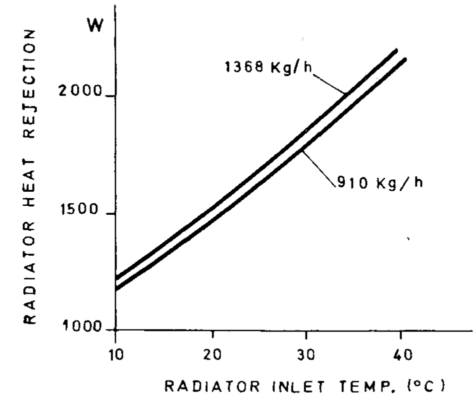

Fig. 6 Short module radiator heat rejection performance.

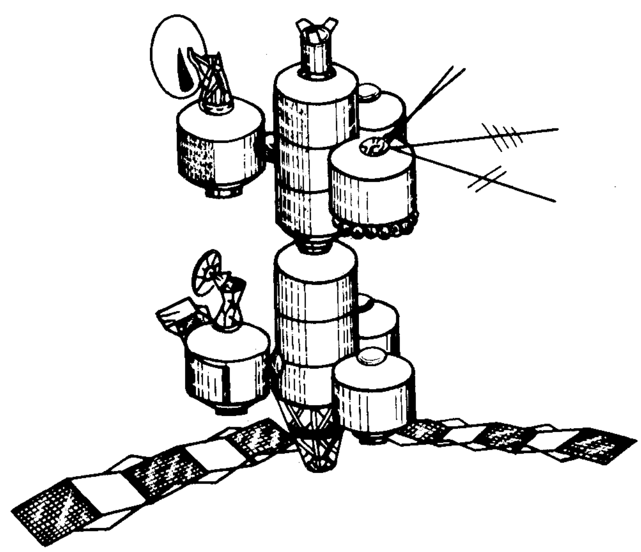

Fig. 7 Spacelab/space station concept.

The testing activities have constituted the support of the design and have provided the validation and verification of the approaches selected. Development tests have been performed at component level first and later at assembly and system levels; the results of these tests have provided the necessary inputs to modify the design of the development units and later on of the qualification units whenever necessary.

ATCS Mathematical Models and Results

The thermal analysis of a complex active thermal control system such as that of the Spacelab, consisting of different fluid cooling loops, internal and external heat sources, needs to be treated with a sophisticated thermal analyzer program such as SINDA capable of defining, under the different thermal loads conditions occurring during the mission, the temperature histories of the various components of the system.

For each of the three basic configurations of the Spacelab active thermal control loops a mathematical model has been developed[2-4]; the models of the various components have been derived on the basis of data available from the design. The various elements of the loop are modeled in terms of analog resistance/capacitance simulators. Significant outputs of thermal analysis are steady and transient temperatures of each node, heat flows between the various nodes, heat rejection to Orbiter payload heat exchanger, and a global energy balance of the system.

Typical temperatures of the key nodes as a function of time, have been computed and some of them (water loop and freon loop) are presented in Fig. 2. Heat load profiles at the Orbiter payload heat exchanger for the three configurations analyzed are shown in Fig. 3a. The transient temperature levels of the fluid delivered to the Orbiter payload heat exchanger during peak/recovery condition for the three configurations are also presented in Fig. 3b.

TCS Components and System Tests

The development tests have been performed at component level and as well at system level by means of a breadboard test. At the component level thermal vacuum, electromagnetic compatibility, vibration, shock, pressure, thermal leak, functional performances tests, have been performed. On the basis of these results the design solutions were modified and improved and the tests have been rerun until satisfactory levels of performances have been achieved.

A breadboard test on water and freon loops, to assess the functional and operational performances of the active thermal control fluid loops as a system has been performed.[5] The test article consisted of all of the ATCS components mounted on a test rig reproducing the flight location of each component; real development units were used except for Orbiter payload heat exchanger, condensing heat exchanger, avionics heat exchanger, and payloads, which were simulated. The ATCS ground support equipment (GSE) consisting of water services, freon servicer, signal conditioning and display unit, freon leak detection unit, were considered an integral part of the test article.

The three basic design configurations (module only, module-pallet, pallet only) were separately tested for the nominal design conditions as well as for the extreme operational conditions to check the fluid flow rates, the pressure drop and the temperature levels as well as the other major design parameters. The main objectives of the test were: 1) to establish the capability of the GSE to properly service, check-out, support, purge, and dry the flight loop of the ATCS; 2) to demonstrate the capability of the ATCS fluid loop to accommodate expected ground and flight thermal loads; 3) to verify equipment efficiency; 4) to determine the extreme capabilities of the ATCS design, under off-design conditions; 5) to assess the fluid line leakage, especially at breakable joints; 6) to evaluate the ATCS response to simulate hardware failures and to verify the capability of flight hardware instrumentaion to detect these failures. In addition to the flight instrumentation a special extensive test instrumentation was provided to monitor and record pressures, temperatures, flow rates, and power conditions of the different components.

The overall pressure drop of the fluid loop has been measured as a function of the mean-flow rate for different heat load conditions. Thermal behavior of the fluid loop components has been verified for the extreme steady-state heat load conditions, obtaining extremely good agreement with the theoretical predictions. Investigations of the transient conditions have been made as well by imposing a heat load with a specified peak of 11.5 kW for 15 min and recording the temperature histories of the various components.

Part II—"The Future"

Special studies with the aim of extending Spacelab's ATCS capabilities are currently underway. The special studies together with the follow-on development program form a phased program consisting of a sequence of discrete steps and options (these steps and options are discussed in detail in Ref. 6 divided into three major increments, namely the near-term, medium-term, and far-term alternatives, as shown in Fig. 4.

Near-Term Alternatives

The investigation of the near-term alternatives affecting the extension of the Spacelab ATCS performance and capabilities are receiving special attention. In particular these near-term alternatives include options which improve the Spacelab resources capability in terms of heat rejection considering reduction of electrical power consumption and augmentation in available electrical power and heat rejection. Specific options under investigation for near-term application are: 1) incorporation of throttles into Spacelab liquid loops to match cooling capability to actual mission requirements and save electrical power; 2) modification of the freon loop plumbing for the module-pallet and pallet only configurations to increase the number of cold plates (currently limited by pressure drop considerations) and to add an experiment heat exchanger mounting capability for the pallets; 3) operation of the water loop pumps in parallel to increase flow rate and pump pressure head capacity; and 4) addition of a radiator into the Spacelab ATCS to increase the heat rejection capabilities presently limited by the Orbiter payload dedicated heat exchanger and at the same time allow a reduction in the fluid temperatures of the Spacelab liquid loops. For near-term applications this paper discusses in some detail the last option mentioned, i.e., the Spacelab radiator.

Spacelab Radiator

Although the present Spacelab baseline does not include a space radiator, the capability to add a radiator has been retained to provide additional heat rejection capability prior to availability of increased heat rejection resources of the Orbiter or Orbiter/power module combination, and to offer the Spacelab user a payload dedicated radiator for use as a flexible heat rejection kit, and permit additional heat rejection capabilities for near-, medium- and long-term application potential.

Regarding the near-term applications, a Spacelab module mounted radiator concept has been pursued instead of a pallet mounted radiator due to the following reasons: 1) it satisfies foreseeable user requirements for increased power/heat rejection, i.e., for module-pallet and module only configurations; 2) it does not constrain payload accommodation (e.g., volume, viewing angle, and attitude flexibility); 3) it is decoupled from level III and level IV spacelab integration; and 4) it does not require development of a deployment mechanism.

A modular radiator concept has been developed using a curved radiator panel 1.550 m in width (allowable radiator width between Spacelab/Orbiter attachments and airlock flange) and 2.250 m in length, which radiates from one side only. The short module with two radiator panel segments is shown in Fig. 5.

The panel segments consist of a 0.5-mm skin with an extruded integral tube/frame using a parallel serpentine flow path (four passes) to transport freon through the radiator. The frames are seam welded to the radiator skin to provide good thermal contact. At the tube bends, the frames are cut away from the tubes. The use of long extrusions minimizes the number of tubing connections (where required the tubes are connected by brazing). Tube size and routing are the result of heat transfer, pressure drop, weight, and manufacturing considerations. The selected design, four passes with 12.7 mm outer diameter tube (½ in.), provides reasonable pressure drop (11 kPa at 910 kg/h), minimizes weight, and simplifies tube bending and welding.

A preliminary evaluation of the Spacelab short module radiator heat rejection performance is given in Fig. 6 for the basic Spacelab freon loop design flow rates (i.e., 910 to 1368 kg/h). As shown, heat rejection values between 1200 W and 2200 W can be obtained for radiator inlet temperatures of 10°C and 40°C, respectively, using 7.0 m^2 of radiator area (for the Spacelab long module configuration the heat rejection values are approximately double). Detailed radiator studies have been performed and are presented in Ref. 7.

Medium-Term Alternatives

Within the constraints imposed by the Shuttle the near-term alternatives previously described represent the first step to extend the Spacelab TCS capabilities. During the medium-term time period (i.e., 1982/1985), NASA plans to have a power augmentation system/power module in operation which will supply increased electrical power to Spacelab and its payloads, permit higher heat rejection possibilities, and allow extended mission duration. Thus, the medium-term studies are aimed at adjusting/redesigning the Spacelab TCS capabilities so that they are compatible with the augmented capabilities of the Shuttle/power module combination. Some of the medium-term studies include: modular pallet-mounted space radiators with deployment capability, dc gear pumps with speed control to match coolant loop cooling capability to actual mission requirements, use of a single ATCS fluid such as PP50 for the module and pallet fluid loops, addition of thermal control valves to Spacelab fluid loops, pallet-mounted temperature controlled compartments using variable conductance heat pipes and radiator, and development of an experiment cooling loop for special thermal conditioning of Spacelab experiment payloads.

Far-Term Alternatives

Overcoming the constraints imposed by the Shuttle in spite of increased Shuttle capabilities is the primary objective for the medium- and far-term TCS alternatives. Initial steps toward an autonomous Spacelab TCS were identified in the medium-term studies mentioned previously. The trend toward complete autonomy of Spacelab TCS is then continued by the far-term alternatives, in which all of the services needed by the Spacelab and its TCS will be available independently from the Shuttle.

This significant step will allow Spacelab to become a free-flying manned spacecraft allowing considerable reduction of its on-orbit operational cost. In addition, a free-flyer autonomous Spacelab will constitute the basic element to build more complex habitable assemblies up to the creation of small space stations similar to the example shown in Fig. 7.

Conclusions

The development of the Spacelab ATCS has required an extensive amount of design, analysis, and testing that has been performed for all of the ATCS components; these activities culminated in the successful critical design review in Sept. 1977. In parallel with flight hardware delivery initiated on May 1978 and presently in progress, qualification testing is active at component and assembly levels and is expected to be completed in the spring of 1980 (this includes the long-lasting hydraulic endurance tests on pump packages, heat exchangers, and cold plates). In addition, a regenerative heat exchanger control system (RHECS) has recently been added to the water loop inside the module and is presently nearing completion by virtue of an exceptional allocation of resources both at Aeritalia as well as at ERNO.

In the winter of 1979, the prototype of RHECS will be incorporated into the ATCS breadboard test. Thus, the design concept and performance will be verified almost in parallel with the RHECS flight hardware integration at ERNO. This exceptional and challenging end-of-program effort, will close the design and development effort (for the Spacelab phase C/D contract) and we hope will constitute the first of the Spacelab TCS evolutionary steps.

Although the Spacelab was conceived to accommodate a large variety of payloads with considerable flexibility in design, there are some inherent limitations that will require improvements, modifications, and extensions in the light of the evolution of the space activities based on the utilization of the Space Shuttle-Spacelab system. These improvements, modifications, and extensions that will increase the utilization of the Space Shuttle/Spacelab system have been identified and discussed as the near-, medium-, and far-term TCS alternatives. The evolution of the Spacelab toward a progressively increasing degree of autonomy from the Space Shuttle is foreseen. This should lead to the free-flyer concept, a further step toward space stations.

Acknowledgments

The material presented is derived essentially from internal reports that record the progress of the Aeritalia and subcontractor activities; these reports have been prepared by the engineers of the Aeritalia Spacelab Team of which the authors carry the honor and responsibility. Our appreciation goes, therefore, to all of our colleagues who, through their work, have allowed us to present this article. Our thanks go as well to the Aeritalia General Direction and to ESA/ERNO for the authorization to publish the article.

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