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LIFE SUPPORT AND INTERNAL THERMAL CONTROL SYSTEM DESIGN FOR THE SPACE STATION *FREEDOM*

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ABSTRACT

A review of the Space Station *Freedom* (S.S. *Freedom*) Environmental Control and Life Support System (ECLSS) as well as the Internal Thermal Control System (ITCS) design, including recent changes resulting from an activity to restructure the program is provided. This review includes the development state of the original S.S. *Freedom* ECLSS through the restructured configuration. This review also includes a special section which addresses the selection of regenerative subsystems for oxygen and water reclamation.

A summary of the original dimension of the S.S. *Freedom* ECLSS and the ITCS is provided with a subsequent update of the "restructured" program detailing the changes in services and altered design solutions, as well as the new proposed timelines for buildup of the ECLSS and ITCS through the currently planned phased-flight configurations. A survey of the present ground development and verification program is given, including both those being executed by the prime contractor, his subcontractors, as well as NASA's Marshall Space Flight Center (MSFC) in-house civil-service test program supporting these activities. Technology issues and proposed risk abatement measures, especially those pertaining to water and oxygen loop closures are summarized. Finally, the subsystems for execution of loop closure for both water and oxygen recovery have been selected. The rationale for these selections is briefly discussed, along with selected data from a set of special comparative tests performed on a competitive set of predevelopment equipment.

1. INTRODUCTION

The S.S. *Freedom* has undergone a number of alterations since the initial request for proposals was sent out to the public sector in 1987. The latest of these has been termed as the restructuring activity. The purpose of this paper is to define the state of the S.S. *Freedom* ECLSS just prior to this change and to separately discuss the recent restructuring changes which have led to the current state of design. A summary of the subsystem groups which make up the ECLSS is provided with a brief discussion of these groups. The current design approach for each subgroup function is outlined. Specifics of how these designs have been altered, orbital buildup phasing, and the resulting test and programmatic rescheduling attendant to these alterations, as they relate to the ECLSS, are included. Also, selections of the components to be used for both water and oxygen recovery were made just prior to restructuring. An outline of how these selections were made, especially regarding the use of recent comparative test data, is addressed. This includes highlights of the more important criteria, critical data, and how it was used in the final engineering adjudications.

The latest ITCS configuration is also defined in its post-restructuring state. This new configuration includes some recent changes made as a result of other activities.

2. GENERAL

As an aside, it might be appropriate to define the differentiation between the ECLSS and the ITCS. Early in the S.S. *Freedom* program it was clear, because of the close kinship of the equipment air cooling and the cabin air temperature control, a decision must be made as to where the separation between the ECLSS temperature and humidity control (THC) subsystem group and the ITCS should be drawn. At this time, it was decided that the best demarcation exists at the water-to-air interface. Although even here, the question arose as to who designs the air/liquid heat exchangers. This was determined to be an ECLSS THC responsibility with all liquid components including liquid-to-liquid heat exchangers (and coldplates) being TCS elements. In keeping with this general philosophy, externally mounted equipment which has an ECLSS function (module, gas tankage, etc.) is being separated so that structure/insulation design and analysis is a TCS function and the internal gas thermal condition is an ECLSS responsibility.

3. PRE-RESTRUCTURING ECLSS CONFIGURATION

To define the S.S. *Freedom* ECLSS configuration, the pre-restructuring configuration will be briefly discussed. This approach is used, in lieu of simply giving the restructured configuration, first because few significant alterations to the ECLSS were made during restructuring, and secondly, for completeness since the recent pre-restructure configuration (and possibly the most ambitious ECLSS concept) has not been documented in the open literature.

An overall composite diagram of the pre-restructured S.S. *Freedom* ECLSS is given in figure 1. From this diagram one can see, by noting the intersecting lines between the various subsystem groups, the highly interactive nature of the various ECLSS subsystems. In some form nearly all subsystem groups of the THC, atmosphere control and supply (ACS), air revitalization (AR), fire detection and suppression (FDS), water recovery and management (WRM), and the waste management (WM) communicate with one another.

The THC can be divided into the cabin air temperature/humidity and ventilation control functions, the avionics cooling function, and the refrigerator/freezers. Temperature and humidity control is achieved using an orbiter-derived condensing heat exchanger and liquid/air separator cooling unit design. The cool dry air leaving this arrangement feeds

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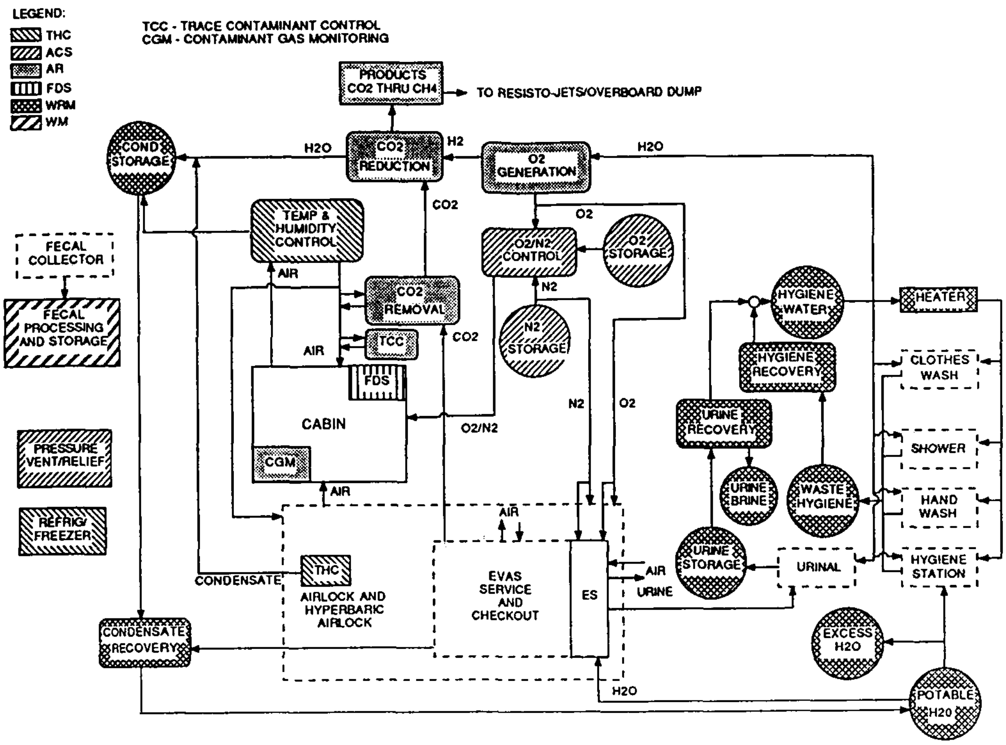

Figure 1. ECLSS functional overview (AC) (prestructure).

ceiling-mounted air registers flowing down the module height to a series of floor registers which return the air to the cooling unit. The required closed-hatch cabin air ventilation flowrates are maintained by such an arrangement. An intermodule flow is created by shunting a 140 cfm flowrate from the habitation/laboratory (HAB/LAB) through the contiguous U.S. modules. Adjacent logistic, airlock, and international modules draw from this clean air stream by using the nodes as plenums, thus, a so-called series/parallel intermodule ventilation (IMV) air flow arrangement is established. The IMV air has been conditioned by both addition of makeup oxygen and nitrogen as well as removal of CO_2 and other trace contaminants. The avionics cooling loop utilizes a central liquid/air heat exchanger to reject heat from an air stream flowing in parallel through the module racks. The flow to each rack is controlled by individual valves. The total flow to the racks is modulated to provide only the needed flow while maintaining the proper flow through individual racks by use of a variable speed fan. Finally, the THC provides freezers and refrigerators which control to 0.6 °C and –29 °C (–20 °F and 35 °F), respectively, for food, film, and specimen storage.

The ACS consists of an internal module two-gas/total pressure control system and an externally mounted gas storage and supply unit. The latter stores the oxygen and nitrogen in a supercritical state. Upon demand, gas is extracted from the storage system and pressurized in a set of intermediate tanks where it can be discharged at high pressure to various use points at preselected rates and thermal state conditions by special externally mounted pressure control and distribution assemblies. The internal two-gas/total pressure control system takes gas from the external pressure control system acting on it to maintain the pressure in the multielement S.S. *Freedom* assembly (or a single module) at partial pressure levels preselected at 21% oxygen, 79% nitrogen with a total pressure of 103 kPa (14.7 psia), or Earth sea level conditions. This system uses a computerized feedback control concept which incorporates a multi-output mass spectrometer (MS) with appropriate valving to provide oxygen and nitrogen partial pressures. This arrangement utilizes a computer algorithm for control of input gas amounts/rates. In addition to this information, the MS outputs the water vapor, carbon dioxide, hydrogen, and methane partial pressure levels in module displays. This device is known as the major constituent analyzer (MCA) and is part of a larger unit referred to as the atmosphere composition monitor assembly (ACMA).

The AR consists of CO_2 removal, trace contaminant control and monitoring, as well as oxygen recovery subsystem functions. The trace contaminant monitor (TCM) function is provided by the TCM within the ACMA. This device utilizes a gas chromatograph/MS combination to provide near real-time readings of airborne gaseous contaminants from an atomic mass unit (AMU) of 24 to 250. Because of the inherent limits of this device at low AMU numbers, it is supplemented by a separate infrared type CO specific monitor. Augmenting these devices for contaminant monitoring is a particulate monitor which utilizes a laser scattering principle dectector to assess the level of solids contamination (note: other air and water monitors, not part of the ECLSS, are located in the manned system's environmental health subsystem). CO_2 removal is achieved by use of four-bed molecular sieves. This unit is so named because it uses four beds to achieve its function, two are needed to adsorb CO_2 with one active continuously while the other removal bed is being desorped. The other two beds in the unit are filled with another type of molecular sieve material and silica gel desiccants to protect the two CO_2 adsorbent beds, since CO_2 adsorbent material is susceptible to moisture degradation. Finally, Sabatier CO_2 reduction and water electrolysis units are provided to allow metabolically generated CO_2 to be reclaimed to a useable form. The Sabatier uses a reactor to elevate the incoming gas mixture of CO_2 and hydrogen, from the electrolyzer, to burn into water and methane (some CO_2 is a residual byproduct) using heat and ruthenium on an alumina catalyst bed. The generation of oxygen is achieved by using an electrolysis process which evaporates hygiene quality water through a membrane into the electrochemical cells, which utilize a KOH liquid electrolyte. The oxygen thus created is fed directly into the cabin atmosphere, and the hydrogen is supplied to the Sabatier. Any excess carbon dioxide, hydrogen, and/or methane are used as propulsive gases in the resistojets.

The FDS consists of an array of smoke and fire detectors as well as fixed and hand-held fire extinguishers. The S.S. *Freedom* will utilize, for the first time in a U.S. spacecraft, CO_2 as the fire suppressant media. A central set of bottles which house the CO_2 will distribute it to the affected equipment racks as required by an automatic activation system (which can be armed to work in an automated fashion, especially when unattended S.S. *Freedom* operations occur or in a crew intervention mode if desired when astronauts are aboard). In the event of a small fire, the crew has available hand-held bottles to combat fires as they deem suitable. Incipient smoke detection is achieved by photoelectric type sensors strategically located in the racks and outlet air ducting of the avionics loop. Ultraviolet (UV) and visible spectrum light detectors are located in the open cabin to detect flames not readily detected via the avionics mounted units.

The WRM subsystem group consists of two basic water recovery subsystem loops, one being the potable and the other being the hygiene. The hygiene loop is fed by a urine recovery device which outputs its water to the incoming wastewater side of the hygiene loop, in effect causing urine water to be processed twice. As part of the urine recovery loop, upstream of the processor a pretreatment function is also performed. The WRM design incorporates both storage and distribution of water to the various end use points. Hygiene water is returned to the manned systems clothes washer urine flush, and the shower with potable quality water supplied the drinking station and hygiene stations. The WRM also includes real-time monitoring and control to assure delivery of only acceptable quality water from the recovery loops. Multiple tanks in the potable loop allow the process output water to be separated into that being tested for water quality, that currently being processed, that already approved for use, that which is being held on standby, and that actually being used. This four-tank arrangement allows holding the water for a microbial check, which requires 48 hours to accomplish. However, this requirement has recently been removed, so this aspect of the WRM design is under reassessment. Separate tankage is located in the nodes to store potable quality water generated in the orbiter fuel cells during its frequent visits to the S.S. *Freedom*. The recovery loop designs are similar in that both the potable and hygiene recovery subsystems utilize multifiltration (MF) units. These units are composed of prefilters and temperature elevation sections to kill the micro-organisms. This is achieved by holding incoming contaminated water at 121 °C (250 °F) for 20 minutes before entering the next phase of the MF. The next step passes the waste water through unibeds which contains both carbonaceous material for organic contaminant filtering as well as ion exchange resin for metals filtering. Within this bed, biocide resins are also housed to protect especially susceptible portions of this bed from micro-organism growth. Because early experience has shown that the stringent organic water quality standard is difficult to meet, an additional post-MF polishing unit called the volatile removal assembly is used. This unit is tailored to remove small molecular weight and volatile organics. Urine is pretreated with sulphuric acid to stabilize the chemistry of this waste in the urine receptacle. Just prior to processing, oxone biocide is added to further pretreat the urine to prevent microbe buildup. The urine water recovery unit is a vapor compression distillation system (VCDS), which utilizes a rotating drum to create an artificial gravity whereby pretreated urine deposited in a thin film on the drum inner wall can be retained by this force mechanism, while water is evaporated from the urine stream by subjecting the film to a vacuum. The heat of evaporation is recovered as the water vapor is pumped out of the unit by the compressor through an annulus around the drum. The lowered pressure created by the flow resistance of the exiting vapor thus causes the water to reach its condensation state point. Makeup urine is added to replace the evaporated water, and, as the water poor brine continues to be deposited on the drum inner wall in this fashion, a 25% solids concentration is reached. At this time, the brine tank is removed and stored for later return to Earth. A new tank is added, and the VCDS loop is then recharged with new pretreated urine and the process repeated.

The WM consists of a unit for fecal collection, storage, and return. This unit is termed a biodegradation cup principle device. The unit simply stores the fecal matter in bags which can breathe the human/fecal gaseous products, consequently, the name biodegradation. The process is initiated by the crewmember opening the lid of the commode. Fecal matter is entrained from the crewman by air drawn through small holes around the periphery of the commode seat by a compressor located under the unit. This air exits through individual bags or cups which can pass air but not liquid. This air stream is filtered through a packed bed of charcoal for odor and contaminant removal before being exhausted into the cabin. The cup, located at the top of a long plastic cylinder canister, which is capable of storing about 40 compressed bags of fecal matter, receives the bolus. After the crewman has finished, the entire canister and bag of fecal matter are rotated into the compact position. A cap housed in the unit is then dispensed over the top of the cup and a piston is used to compact the cup and fecal matter into a small volume for storage. When the canister is filled with compacted fecal filled cups, it is replaced with an empty canister and the full canister stored for return to Earth. A urine receptacle is mounted to this unit to allow easy access by the crew to minimize urine excrement into the WM.

4. RESTRUCTURING

4.1 General

The S.S. *Freedom* has passed the preliminary design review (PDR) and other budget/resource reduction exercises including ones called turbo, work budget review, and the most recent Congressional restructure within the last year. The impacts due to these efforts have necessitated a second requirement review and PDR, the first just completed and the second to be held later this year. The status of the S.S. *Freedom* ECLSS design at the first PDR (3) has been outlined previously.

The recent period of time since the initial PDR has been spent in an effort to scale down the overall space station to meet reduced funding allocations and allow an earlier date for a functional space station configuration. The first major steps taken to resolve this issue were the work budget review (WBR) and the turbo resource reduction activities. These activities were aimed at cutting back power, weight, and volume to reduce space station resources, cost, overall size, and to maintain the assembly sequence within the allotted number of shuttle missions. The turbo/WBR activities resulted in a slightly modified ECLSS configuration with respect to the AR and WRM subsystems. The post-turbo/WBR space station design was presented to Congress which then directed NASA to perform a 90-day restructure effort to reduce costs further to better align with projected congressional budgetary constraints. Top level impacts resulting from the most recent restructure effort include the size reduction of both the U.S. built HAB and LAB modules from 12.1 to 8.2 m (40 to 27 linear feet), and rephasing of the program to include an early man-tended capability (MTC) supported by the shuttle and a later permanently manned configuration (PMC) which would support a four-person full-time crew.

4.2 ECLS System Overview

The S.S. *Freedom* design varies widely between the two major milestone configurations of the assembly sequence (MTC and PMC). The MTC configuration is shown in figure 2 and consists of a pressurized docking adapter (PDA), resource node, LAB module, airlock, and minipressurized logistics module (not shown). The MTC configuration will be manned only when the orbiter is docked. Currently, the extended duration orbiter (EDO) is being developed to support the MTC configuration for periods of up to 16 on-orbit days. Services of both the orbiter and the space station will be utilized to maintain a liveable working environment. The orbiter will attach to the pressurized docking adapter which will provide a passage way for crew and materials to the space station. There will be air interchange between the orbiter and space station in a manner similar to that which is implemented on Spacelab module missions.

The PMC configuration for S.S. *Freedom* (fig. 3) constitutes the phase at which the space station will be permanently manned while claiming resupply logistics from shuttle missions. The PMC configuration consists of U.S. built HAB and LAB modules, two laboratory modules built by the European and Japanese space agencies, two resource nodes, two pressurized docking adapters, a pressurized logistics module (PLM), and airlock (AL), and a new addition to the S.S. *Freedom* program: an assured crew rescue vehicle (ACRV). The ACRV has replaced a leg of redundancy for crew safety. It is an expendable escape vehicle in which the crew may return safely to Earth in case of an emergency on orbit. An eight-man crew capability (EMCC) configuration (fig. 4) is not currently in the program budget, but scars for this capability are retained within the current PMC design in the event an upgrade is desired later.

Functional attributes of ECLSS hardware have been discussed in earlier papers (1,2) and basically remain the same within the new design. ECLSS equipment is distributed throughout the pressurized elements so that operation may continue in the event of a single module loss. In addition to this centralized approach, the equipment is functionally distributed to maximize utility, hence minimizing resource resupply requirements.

The S.S. *Freedom* restructure effort resulted in several ECLSS hardware changes. During the MTC configuration, several capabilities present within the old design will not be available including the delay of water processing and the delay of trace contaminant monitoring as well as the removal of oxygen loop closure. The water used by the crew for ingestion and by experiments will be obtained by resupply utilizing orbiter fuel cell water. This essentially opens the water loop during the MTC phase of the program. In addition, there will be no CO_2 reduction or O_2 generation during MTC. Crew-produced carbon dioxide will be vented to space and oxygen will be supplied from tanks. Other changes at MTC include the delay of a refrigerator/freezer and automated contaminant monitoring until the PMC timeframe. As the program phases to the PMC configuration, the water loop becomes closed and water is recycled for use. One significant change in the WRM design eliminates the use of separate potable and hygiene loops. All reclaimed urine, hygiene waste, and condensate water will be mixed together and processed to provide a quality of water suitable for crew ingestion and hygiene use. The oxygen recovery loop will remain open throughout the PMC configuration causing a resupply penalty over the previous design.

Several unique differences between the previous S.S. *Freedom* configuration and the present design are noteworthy. First, there is no "racetrack" configuration, therefore the air flow distribution path between modules is altered. The addition of the ACRV has allowed use of this vehicle for crew escape in view of redundancy allowing less hardware. This presents a significant savings to the S.S. *Freedom* ECLSS in the area of weight and volume over the previous design.

Internal module layouts for S.S. *Freedom* have not changed significantly with the redesign effort. Both of the U.S. modules consist of four rows of racks (floor, ceiling, port, and starboard) which are used to house space station equipment and experiments. Most of the ECLSS equipment will be located within these rack banks. There are four standoffs (one behind each rack bank) which are used to provide services to the individual racks (plumbing, air, water, etc.). All cabin and avionics air distribution ducts are also located within the standoff region. Utilities provided to the rack are supplied by cables and flex hoses through the standoff which serves as the fulcrum for the rack pivot to maintain utility services when the racks are pivoted for maintenance purposes. A central crossover region is provided to route cables, ducting, and plumbing between adjacent standoffs in the modules.

4.3 ECLS Subsystem Overview

The S.S. *Freedom* ECLSS is divided into six major subsystem groupings. These include the THC, ACS, AR, FDS, WRM, and WM subsystems. The following sections depict the integrated design effort. Some of the subsystems have changed while others have remained fairly consistent with the previous design. The functional schematic of the restructured ECLSS is shown in figure 5.

4.3.1 Temperature and Humidity Control (THC)

S.S. *Freedom* module and resource node THC is provided by condensing heat exchangers outfitted with air bypass controls based on sensed air temperatures/set points (fig. 6). The redesign effort resulted in smaller modules/heat loads, hence a smaller condensing heat exchanger was baselined. The previous heat exchanger had a 6,500 W (22,197 Btu/h) capacity and has been reduced to 3,500 W (11,952 Btu/h) for the new design. Node temperature control is similar to that of the main module with the exception of the cupola/integrated avionics cooling requirements. A study is currently on-going to determine which temperature control scheme (single versus multizone) is applicable for the node/cupola configuration. The condensing heat exchangers outfitted for both modules and nodes are common within the current design. The PLM THC has a combined cabin air/avionics coolant loop which requires a considerably smaller heat exchanger. The cabin fans are sized to maintain heat rejection while operating at the reduced 70.3 kPa (10.2 psia) pressure while the orbiter is docked to the space station at MTC.

The new design has necessitated a change in the IMV design due to the loss of the racetrack configuration. The new S.S. *Freedom* layout precludes series/parallel flow as an option, hence a parallel flow is the baseline design. Within this approach, the resource nodes are still used as a plenum to

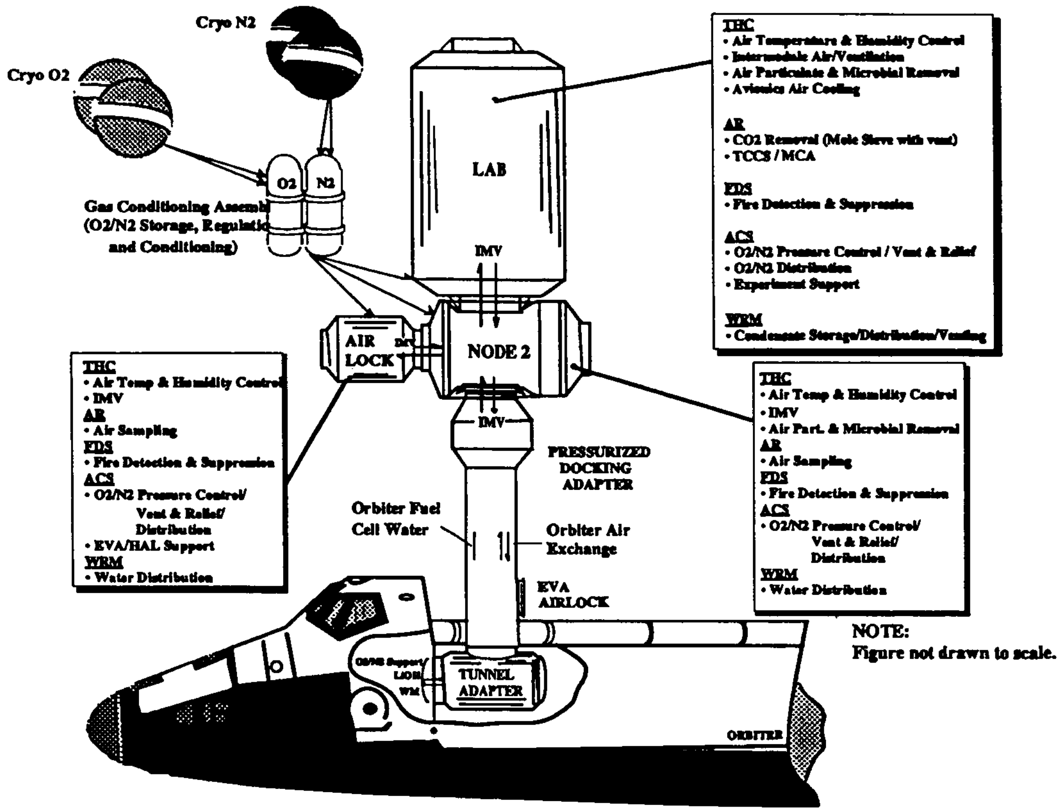

Figure 2. S.S. *Freedom* MTC subsystem functions.

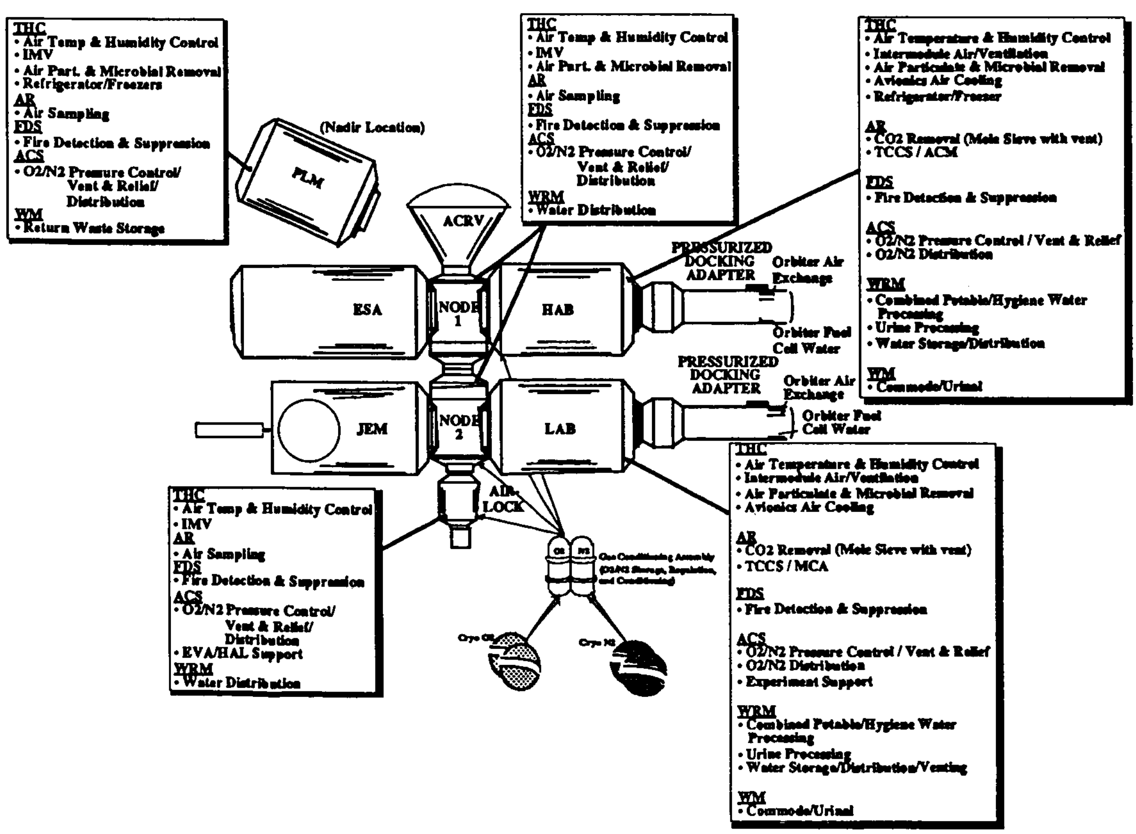

Figure 3. S.S. *Freedom* PMC subsystem functions.

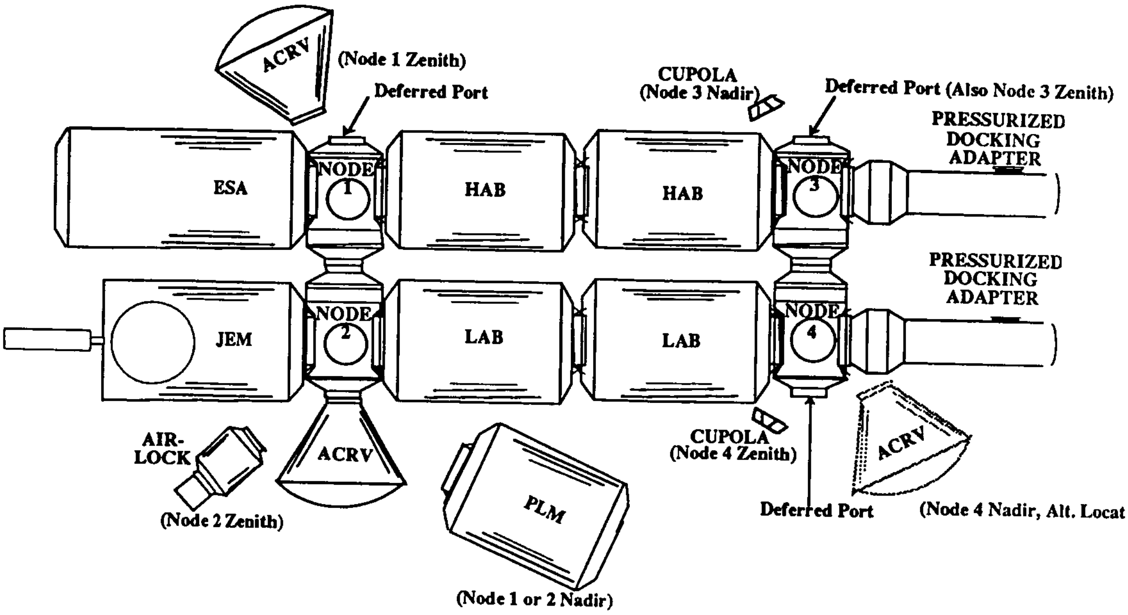

Figure 4. S.S. *Freedom* EMCC flight configuration.

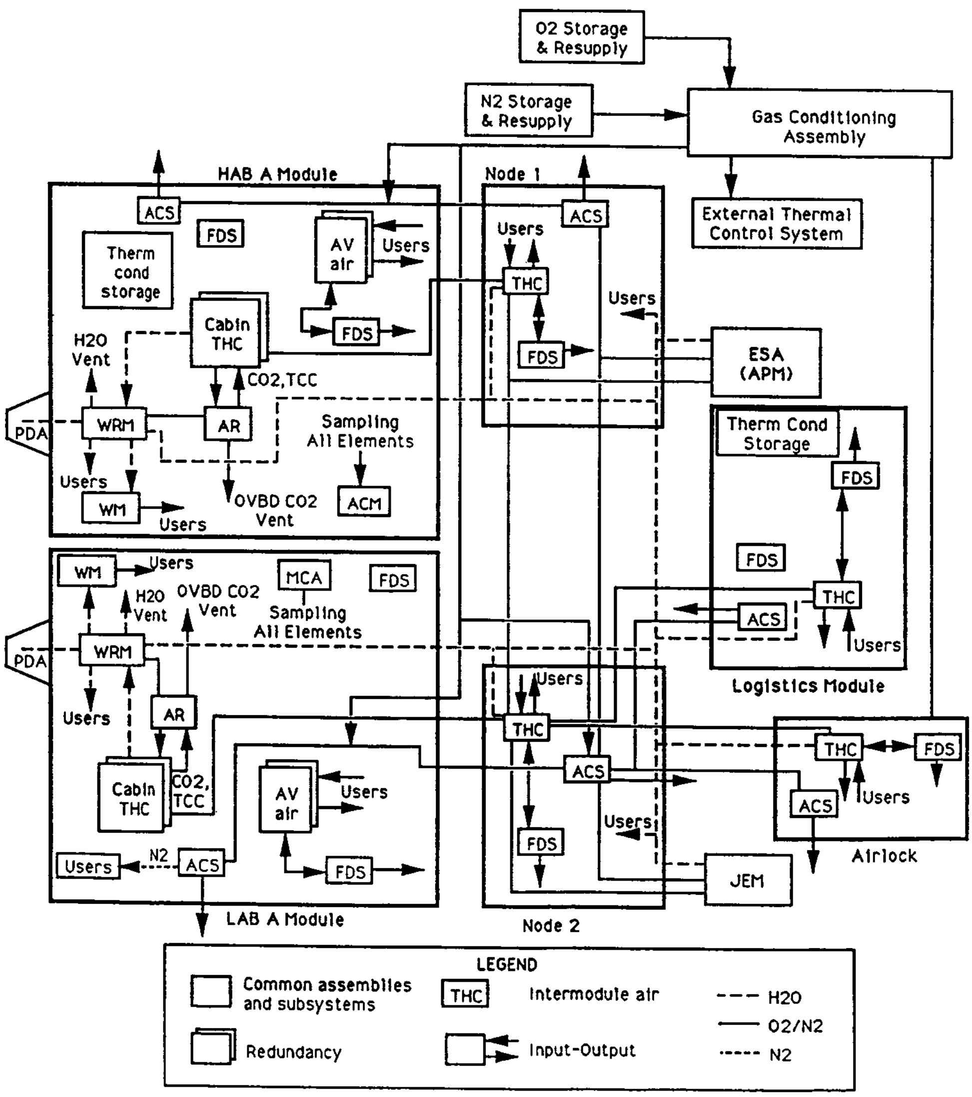

Figure 5. ECLSS integrated functional schematic.

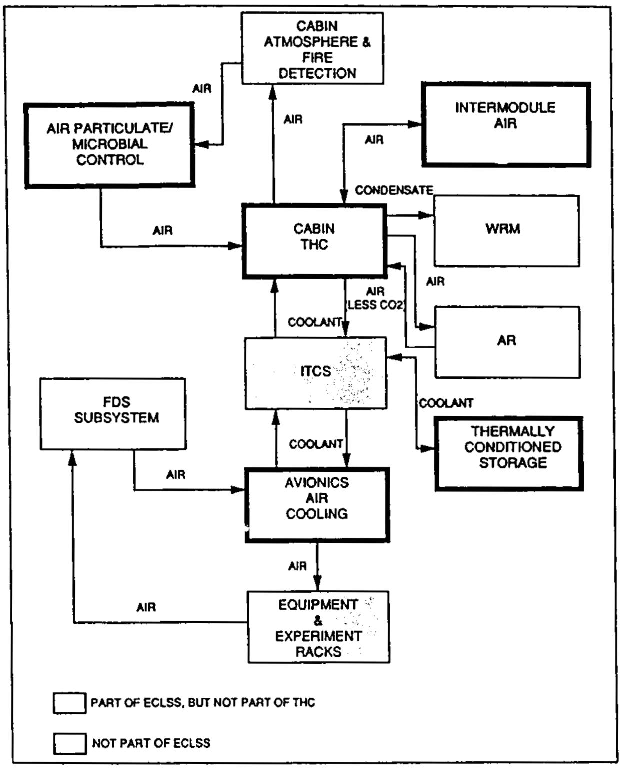

Figure 6. THC functional schematic.

provide air to all adjacently attached elements. Analysis results to date have shown a decreased capacity to remove CO_2 and trace contaminants due to the higher residence time caused by the new flow regime. The IMV function posesproblems for the requirements that state individually selectable temperatures shall be maintained for all pressurized elements. Due to the variation in module/node heat loads, the IMV could pose a significant positive/negative heat load on adjacent elements which inhibits the capability for temperature control. For this reason, the S.S. *Freedom* will nominally be maintained at a common set point temperature.

Avionics air cooling capability provides air flow for rack mounted equipment, rack experiments, and fire detection purposes. The U.S. HAB and LAB modules have a separate avionics air loop configuration in which a sensible heat exchanger is tied into the ITCS for heat rejection. The heat rejection capability for the avionics cooling systems in all U.S. pressurized modules has been reduced due to the restructure effort (decreased heat loads). The avionics cooling systems within the nodes, airlock, and pressurized logistics module are integrated with the cabin THC due to the substantially lower heat rejection requirements. Currently, a trade study is on-going to determine the most favorable configuration for avionics cooling within the elements. The two options being traded include a single fan/heat exchanger to serve an entire module, or multiple fan/heat exchanger packages to serve the rack banks located in the floor-starboard areas and the ceiling-port areas. The single package is preferable but causes problems with respect to crossover ducts required to route flow from one side of the module to the other. Both options provide an automated flow balancing control concept which utilizes a variable speed fan to accommodate changing heat load distributions. Within the other U.S. pressurized elements, a set fraction of air is taken from downstream of the condensing heat exchanger and routed through racks for cooling/fire detection purposes. All racks are individually regulated by a preset rack intake valve to provide the required airflow and delta pressure. A second valve flow position provides sufficient flow for fire detection when the rack is either in the powered or unpowered mode.

Air particulate control is established by utilizing 0.5-micron high efficiency particulate air (HEPA) and 20-micron coarse filters within the return ducts of the THC system. These filters are required not only for air particulate control, but also microbial control.

The THC also provides a refrigerator/freezer volume to store food and other perishable items. Three units are provided in the HAB; four in the PLM. Each unit will provide a minimum of 0.44 m^3 (16 ft^3) of storage volume. The unit design utilizes a standard vapor compression cycle for cooling.

4.3.2 Atmosphere Control and Supply (ACS)

The ACS subsystem provides for the monitoring, regulation, and control of total pressure, oxygen partial pressure, and other constituents which comprise the atmosphere. A significant change in the design due to restructure involves the method by which oxygen is released into the S.S. *Freedom* atmosphere. Prior to the restructure effort, oxygen and nitrogen were supplied by cryogenic supply tanks during PMC. As the space station evolved to the assembly complete (AC) configuration, the oxygen loop was closed via a water electrolysis unit. In the restructure design, the oxygen supply will remain open from MTC through PMC with supply coming from high pressure gas at MTC and cryogenic boiloff at PMC. This decision to open the air loop permanently was made due to the high degree of complexity involved with interfacing the AR, WRM, and ACS in addition to the fact that cryogenic supply has been proven in earlier spacecraft vehicles. High pressure 6,203 kPa (900 psia) gas storage for oxygen and nitrogen will be handled in accumulators pressurized from the cryogenic supply. This high pressure gas is used in support of experiments which require high flow rates, as well as for repressurization of a module under emergency conditions. Internal and external O_2 and N_2 distribution plumbing is provided to transport oxygen and nitrogen from storage to each element use point. A functional schematic of the ACS is shown in figure 7.

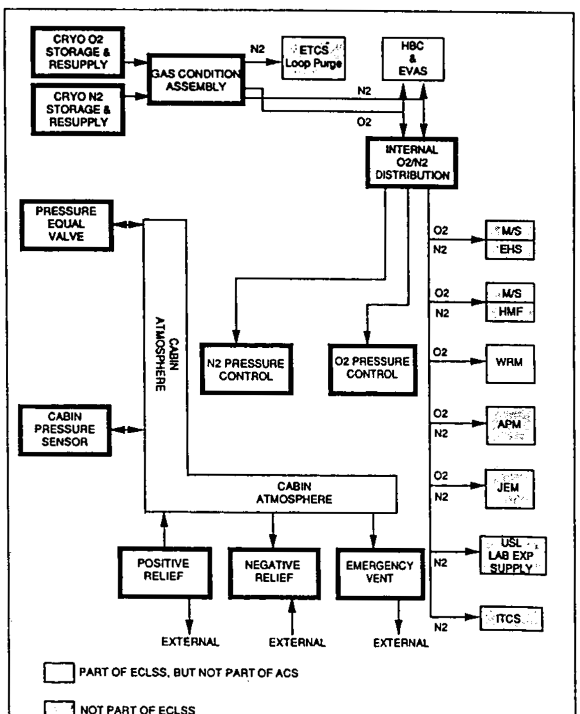

Figure 7. ACS functional schematic.

The baseline O_2/N_2 control concept remains basically unchanged with respect to operational integrity. The data management system (DMS) constantly updates the controller with outputs from the MCA part of AR subsystem. There are two MCA's, one each located in the HAB and LAB modules. Sampling lines are routed from the MCA's to the other pressurized elements of S.S. ***Freedom***. Samples are taken at each sample location at set intervals. The outputs are then sent via the DMS to the controller which uses the inputs to determine if oxygen, nitrogen, or both are required to maintain the cabin atmosphere within required limits. The control scheme used on S.S. *Freedom* is more advanced than that used on the shuttle. The DMS stores output signals from the MCA over set periods of time to determine the "trend" of both ppO_2 and total pressure. Algorithms are then used to determine the correct amount of gas to be supplied based on this trend and events scheduled to occur in the near future (e.g., extra vehicular activities (EVA's), orbiter docking, airlock operations, etc.).

4.3.3 Atmosphere Revitalization (AR)

The AR subsystem revitalizes the space station internal atmosphere. This subsystem underwent significant changes as a result of the space station turbo and restructuring activities. Major functions at MTC and PMC include CO_2 removal, atmosphere monitoring, and trace contaminant control as shown in the AR functional schematic (fig. 8). Closed-loop AR with the addition of CO_2 reduction and oxygen generation hardware has been postponed awaiting the EMCC.

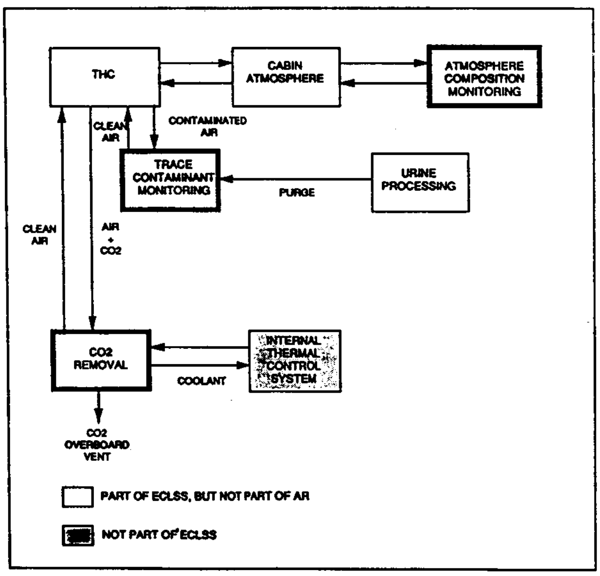

Figure 8. AR functional schematic.

The MTC configuration consists of one open loop AR rack, located in the LAB module, outfitted with a molecular sieve CO_2 removal device, MCA, and trace contaminant control system (TCCS). When the molecular sieve adsorption cycle is complete, the CO_2 will be heated and vacuum desorbed to space. The MCA monitors the cabin O_2, N_2, H_2, CO_2, and CH_4 partial pressures and water vapor content for each element. The TCCS consists of charcoal beds, pre- and postsorbent beds, and a high-temperature catalytic oxidizer to maintain airborne trace contamination levels below specifications. During orbiter docking periods, air exchange between S.S. ***Freedom*** and the orbiter cabin will be provided through the pressurized docking adapter via an IMV fan. The requirement for $ppCO_2$ will be relaxed from 3.0 mmHg to 7.6 mmHg (0.06 psia to 0.15 psia) for the short duration MTC phases. The single AR rack in S.S. ***Freedom*** is zero fault tolerant. Monitoring of particulates and trace contaminants, including carbon monoxide, can be performed manually using the shuttle monitoring systems.

The PMC configuration consists of two open-loop AR racks: one each in the LAB and HAB modules. The only hardware addition to each rack is an ACM. Due to the loss of the race track configuration for PMC, the IMV flow patterns have been altered which affects the $ppCO_2$ levels in attached elements. Attached elements to a HAB or LAB with an active CO_2 removal device (molecular sieve) experience a 0.15 mmHg (0.003 psia) increase in $ppCO_2$ for every two crew persons located in the attached element. The effects cascade throughout the cluster. For example, if two crew members are located in a node attached to the HAB which has an active molecular sieve, the $ppCO_2$ in the node would reach a steady state $ppCO_2$ level 0.15 mmHg (0.003 psia) higher than that in the HAB. Further, if two crew persons are located in the Japanese Experiment Module (JEM) attached to that same node, the JEM $ppCO_2$ level would be 0.30 mmHg (0.006 psia) higher than the HAB. The AR at PMC is single failure tolerant for CO_2 removal, MCA, and TCCS. The ACM functions are zero failure tolerant with backup manual sampling. The ACRV return to Earth provides a third leg of redundancy for emergency situations.

4.3.4 Fire Detection and Suppression (FDS)

The system design remains largely unchanged by the restructuring activities. A functional schematic of the MTC and PMC FDS is shown in figure 9.

Fire detection capability is provided in powered equipment racks, standoffs, and the open cabin environment. Scattering photoelectric smoke detectors are mounted in each powered rack's avionics return ducting, in the avionics air main return manifold, in the cabin air return ducting, and in the standoff ventilation air stream. The duct-mounted smoke detectors utilize a nonintrusive "collar" design with built-in test capability. The collar detector utilizes the air duct for the

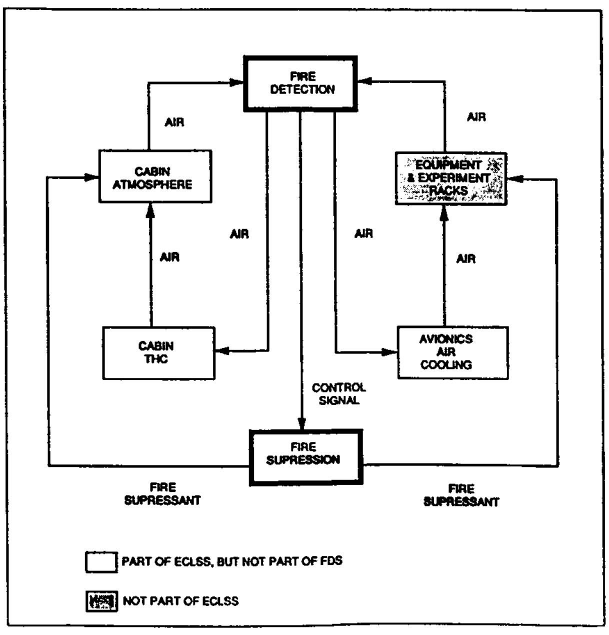

Figure 9. FDS functional schematic.

sample volume. Flame detectors are mounted in the endcone areas to detect open fires in the main cabin volume. The ECLSS PDR baseline rack thermal sensors, designed to monitor rate of heat rise, were deleted from the FDS design. Each rack in the LAB/HAB and each powered rack in the node/PLM contains an FDS panel consisting of a fire indication flag, a port for insertion of a manual extinguisher, and a rack CO_2 release valve manual override.

Recent agreements were reached with the European Space Agency (ESA) and with Work Package 2 (WP02) at JSC to baseline CO_2 as the single S.S. *Freedom* suppressant. Prior to these agreements, ESA had a halon-based design for the *Columbus* module and WP02 had a nitrogen-based system for the hyperbaric chamber (HBC). Each pressurized element (split module, node, airlock, etc.) contains a single CO_2 suppressant tank with distribution lines plumbed to the potential fire locations.The split module tanks are approximately 0.066 m^3 (2.4 ft^3) internal volume while the node/airlock tanks are considerably smaller at 0.014 m^3(0.5 ft^3). CO_2 is stored as saturated vapor at 853 psia (5,879 kPa) and ambient temperature. Upon fire detection in a rack, the rack will be isolated by shutting off the avionics air flow. The tank and rack CO_2 release valves will be opened to allow CO_2 to discharge into the rack volume. Discharge times will be preset for each rack internal packaging configuration based on ground testing. A CO_2 concentration of 50% by volume is required to extinguish a fire. Rack over-pressurization is avoided by utilizing an avionics return flapper valve. Discharge tubing is also routed to all standoff volumes. Cabin fires are suppressed with manual portable CO_2 extinguishers. In the event a fire cannot be suppressed at the rack level, the element will be isolated by ceasing IMV flow and closing hatches prior to venting the element to space vacuum. Unresolved FDS safety issues include stored energy concerns of high pressure CO_2 in the S.S. *Freedom* elements and single-failure tolerance of the suppression system.

4.3.5 Water Recovery and Management (WRM)

Several major changes have occurred within the WRM during the restructure effort. The previous design consisted of a completely closed water loop with two different grades of water. Potable water was recovered from humidity condensate and CO_2 reduction by-product water and used for human ingestion purposes. Hygiene grade water was recovered from urine distillate, spent shower, hand wash, clothes wash, dish wash, and other end use equipment waste water. The two loops were separated with independent storage tanks and processors for each loop. The new design differs from the MTC to PMC configurations within S.S. *Freedom* evolution.

At MTC, the installed water loop will consist only of hardware to collect humidity from the condensing heat exchanger and vent it overboard. A temporary jumper to transfer fuel cell water from the orbiter to EVAS equipment in the airlock will also be provided. Water for the crew will be supplied onboard the orbiter.

The water loop becomes closed at PMC with the launch of water recovery equipment in the HAB module. The PMC configuration has a single water loop capable of providing potable grade water for all functions required on S.S. *Freedom*. Inputs to this loop include urine distillate, humidity condensate, CO_2 reduction byproduct water (EMCC), waste shower, hand wash, clothes wash, and oral hygiene waters, waste water from the environmental health subsystem (EHS) water quality monitor, EMU waste water, and fuel cell water. Two water processors (one in LAB, one in HAB) based on MF technology supplemented by an oxidative VRA will process the combined waste input to potable water quality specifications.

Another change in the WRM design includes the transfer of orbiter fuel cell water to the space station on a regular basis. This function had been required for ECLSS contingencies in the earlier design. However, the transfer of responsibility from the FMS to the ECLSS for supplying water to scientific experiments has made the WRM dependent on fuel cell water supplied by the orbiter even under nominal conditions. Fuel cell water will be stored separately from reclaimed water for the crew to use in an emergency situation. Other changes in the WRM imposed during the redesign effort include the interfaces for end users/experimenters. The dishwasher has been deleted from the program. A functional schematic of the WRM is shown in figure 10.

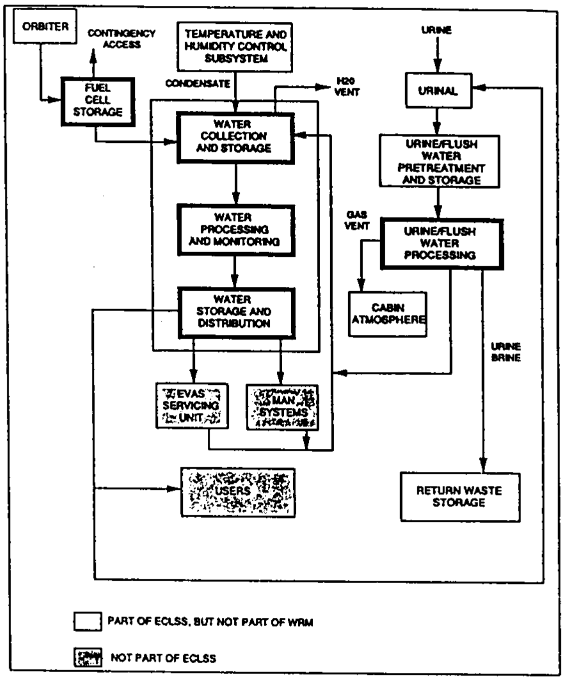

Figure 10. WRM functional schematic.

The current WRM design utilizes two MF/VRA units for water processing, two VCD units for urine processing, and inline process control water quality monitors (PCWQM) for on-line checks of product water quality. Deleted from the design are the hygiene processor and the batch water quality monitor (WQM). The PCWQM tests pH, iodine, turbidity, conductivity, and total organic carbon (TOC). Iodine is detected by ultraviolet absorption (UVA) while the TOC is monitored via infrared (IR) detection. All PCWQM measurements are continually monitored in addition to specific ion content, inorganic constituents, bacteria, ammonia, free and dissolved gas content, color, turbidity, and total bacteria counts. Waste water from all of the various sources is collected in waste storage tanks and fed through the MF processor where the outlet is checked for proper water quality by a PCWQM. If the water is determined to be unacceptable for use, it is diverted back to the waste storage tank for reprocessing. Otherwise, the water is sent to product storage tanks for use throughout the space station.

4.3.6 Waste Management (WM)

There will be no WM hardware on the space station at MTC. The crew will rely on the orbiter capabilities for these functions. At PMC, there will be a commode/urinal located in both the HAB and LAB modules. The commode/urinal design will be common with the chosen design for the EDO. The canisters will be sized for a four-person crew. EDO and S.S. *Freedom* waste management hardware will utilize a manual compaction device, which differs from the previous automated compaction device.

4.4 ECLSS Assembly Sequence

The S.S. *Freedom* restructure activity has not changed the space station assembly sequence drastically with respect to the period through PMC. The integrity of the ECLSS design dictates the design sequence so that the space station can be operational from the launch of the first element through PMC.

The early stages of the assembly between FEL and MTC are heavily outfitted with truss structure and electrical power generation equipment. The gas conditioning assembly (GCA) arrives on the second flight in support of the arrival of the first pressurized element 3 months later. Upon arrival of the first pressurized elements (Space Transportation System (STS) docking adapter and node), the ECLSS will contain THC and ACS within the node and will rely heavily on the orbiter for CO_2 removal and water supplies. Use of high pressure gas from the GCA will be used to resupply the space station with atmosphere maintenance and leakage makeup. The MTC configuration includes the addition of a U.S. LAB module within which active AR/THC units will be located. WRM supply lines are available at MTC, however, hardware related to the recovery of water via a recycle process is delayed until the PMC configuration. The orbiter is present during the active MTC configuration hence the S.S. *Freedom* ECLSS design must be able to withstand long periods during which the space station is unoccupied. The delay of a trace contaminant monitoring system during this period is of some concern during the long periods of space station stagnation. During the MTC operation, the space station will operate at 70.3 kPa (10.2 psia) so that lengthy extravehicular activity (EVA) prebreathe procedures may be avoided. This imposes a significant power penalty upon the THC fans which must circulate more air to produce the equivalent heat rejection at normal operating pressure. A pictorial representation of the space station at MTC along with the associated ECLSS functions is shown in figure 2.

The current assembly sequence calls for the relocation of STS docking adapters to empty docking ports as the other pressurized elements arrive. During this period, the arrival of the cryogenic oxygen and nitrogen replaces the high pressure resupply for atmosphere makeup. Operating pressure on the station for the PMC phase is increased to 101 kPa (14.7 psia). The high pressure gas is used for emergency repressurization and high flowrate experiment users. The addition of the U.S. HAB module includes the remaining ECLSS hardware. By PMC, the ability to recycle is complete with the WRM processing unit. In addition, enhanced storage capability will be used to resupply fuel cell water from the orbiter for use on S.S. *Freedom*. The oxygen loop remains open at PMC relying on cryogenic sources for resupply. The CO_2 is removed from the atmosphere and vented to space. PMC also adds the capability for the crew to shower and wash clothes within the S.S. *Freedom*. The single water loop also provides water to experimenters via the integrated ECLSS/FMS design. One design change incorporated from an earlier redesign activity is the deletion of the dishwasher from the program. A functional representation of the PMC flight configuration with ECLSS responsibilities is shown in figure 3.

5. OXYGEN/WATER RECOVERY SUBSYSTEM SELECTION

5.1 General

In support of phase C/D ECLSS efforts for the space station and prior to restructure, a test program was initiated to provide data in order that final technology selections could be made between competing regenerative subsystems. This activity was called the comparative test, and it was conducted from late 1989 through early 1990. Latest generation hardware was procured for competing technologies for air revitalization and water recovery. The competing subsystems (original baseline and alternates) are shown in table 1. The baseline subsystems were selected at the end of phase B with the alternate subsystems under continuing development until completion of the comparative test program. The 4BMS was selected as the baseline CO_2 removal subsystem without an alternate.

For each test, the subsystems were run under the same conditions (i.e., inlet feed rates and composition) and performance data were collected. These data, along with anomalies reported and general past experience with the technologies, served as the basis for the comparative analyses and subsystem selections. The selection process involved both quantitative and qualitative assessments, including system impacts associated with each technology as part of the overall ECLSS. Quantitative factors assessed were launch weight and volume, on-orbit power and heat rejection, and resupply weight and volume. Qualitative factors to which the subsystems were evaluated against included safety technical maturity, maintenance, reliability, integration, complexity, and technology problems, among others. The following is a brief summary of the evaluation and selection for each subsystem area.

5.2 CO_2 Reduction

The two competing technologies were the Bosch (baselined), manufactured by Life Systems, Inc., and the Sabatier (alternate), manufactured by Hamilton Standard. The subsystems were run concurrently for a total of 60 test days. Expected station mass balances were developed for each subsystem based on test data from which quantitative system resource impacts were calculated. The size of the Bosch had to be scaled from the comparative test unit's two 60 man-day reactors to a flight subsystem with one 360 man-day reactor capacity. The carbon packing density achieved in the test was the basis for these calculations. The Sabatier did not require any scaling, but system impacts for processing the methane vent through resistojets were assessed. Water resupply was also a logistics penalty for the Sabatier due to incomplete CO_2 reduction.

The Sabatier was selected as the technology for CO_2 reduction. All quantitative resources were much lower than those for the Bosch (e.g., the Bosch expected on-orbit system weight including four subsystems plus spares was calculated a 1,839 kg (4,054 lb) while the Sabatier was 497 kg (1,096 lb)). In fact, the expected Bosch size would not be able to be packaged into the AR rack. The Sabatier is considered to be at a high level of technical maturity, while the Bosch would require some fairly major design revisions to reach flight maturity (a six-times scale-up and the addition of a zero-gravity water separator). There were some additional technical problems with the comparative test Bosch that would need work as well. While the Bosch provides for

Table 1. Competing regenerative ECLSS subsystems.

FUNCTION	COMPETING SUBSYSTEMS	
	ORIGINAL BASELINE	ALTERNATE
Carbon Dioxide Reduction	Bosch Subcontractor: Life Systems, Inc. (LSI)	Sabatier Subcontractor: Hamilton Standard Division (HSD) United Technologies, Inc.
Oxygen Generation	Statis Feed Water Electrolysis Subsystem (SFWES) Subcontractor: LSI	Liquid Feed Solid Polymer Electrolyzer (LFSPE) Subcontractor: HSD
Potable Water Processing	Multifiltration Subcontractor: HSD	Reverse Osmosis Subcontractor: HSD
Hygiene Water Processing	Reverse Osmosis Subcontractor: HSD	Multifiltration Subcontractor: HSD
Urine Processing	Thermoelectric Integrated Membrane Evaporation System (TIMES) Subcontractor: HSD	Vapor Compression Distillation (VCD) Subcontractor: LSI

complete oxygen loop closure, the impacts of incomplete CO_2 reduction (vent gas processing and water resupply) were not considered to be prohibitive for the selection of the Sabatier.

5.3 Oxygen Generation

Two water electrolysis technologies were traded in the comparative test. The baselined oxygen generation assembly (OGA) is the static feed water electrolysis subsystem (SFWES) manufactured by Life Systems, Inc., while the competing technology is the liquid feed solid polymer electrolyzer (LFSPE) manufactured by Hamilton Standard. Unfortunately, the LFSPE experienced numerous problems at Hamilton Standard which delayed its delivery to MSFC until April 1990. The late delivery coupled with repeated failures during subsystem startup for the LFSPE checkout test prevented comparative testing of the LFSPE from taking place. The SFWES completed 667 hours of its planned 960-hour test (a hydrogen leak in the cell stack aborted the test early). Quantitative resources were able to be calculated only for the SFWES, and were based on comparative test data with some modifications for expected flight differences. Qualitative assessments were performed for both competing subsystems. The SFWES rated strengths in maturity, test experience, and mechanical design simplicity. A major weakness was a performance degradation that was experienced during the test. The LFSPE technology is considered mature; however, the application for space use is a new concept, particularly with respect to the phase separators. The LSFPE design is inherently complex with individually maintainable ORU's.

The failure of the LFSPE to operate during the comparative test and its poor results in the qualitative assessment demonstrated that a significant development effort may be needed before that subsystem could be considered for flight. Therefore, based on its performance in the comparative test and its superior showing in the trades, the SFWES was recommended to remain the baselined OGA for S.S. *Freedom.*

5.4 Potable Water Processing

The baselined technology for the potable water processor was the MF process, while the competing technology was the reverse osmosis (RO) process. An actual RO potable unit was not procurred due to budget constraints; rather a reverse osmosis hygiene (ROH) processor was used for the potable testing. Because the data showed that the ultrafiltration (UF) module present in the hygiene system did not impact performance, it was simply deleted from the potable trade. Ersatz solutions representing humidity condensate and CO_2 reduction product water were used for the potable feed for the test. Unibed life was determined for each ersatz and used for the comparative assessment. For the analysis, the hardware was resized so that both processors were designed for the same expected flight flow rate, and tanks were added as system impacts. Additional system impacts related to the urine processor were added to the ROP because of the requirement that the urine processor reprocess RO brine.

The quantitative resources for the multifiltration process (MFP) and the reverse osmosis process (ROP) were similar, with the MFP having slightly lower power and resupply weight and volume. The qualitative assessment was more of a driver for the potable selection. The three major issues of reliability, integration, and complexity all favored the MFP because of its single pass operation which leads to a less complex, more reliable design. Though the ROP is not considered unreliable nor complex, the presence of the recycle loop presents inherent integration concerns. Additionally, the recycle loop requires that the ROP have more active components than the MFP, resulting in potential for more unscheduled maintenance for the ROP. Therefore it was recommended that the MFP remain the baseline potable processor.

5.5 Hygiene Water Processing

A reverse of the potable water processor trade, the baseline subsystem was the RO and the alternate MF. The ROH is like the ROP subsystem with the addition of an ultrafiltration module. The MFH subsystem differs from the MFP subsystem in the types of sorbents and resins which the unibeds are packed with. For the comparative test, the ROH was fed a combination of waste hygiene water and combined urine and ROH brine distillate produced from the urine processor. For the MFH, the waste feed stream consisted of waste hygiene water and urine distillate. Brine distillate was not a feed source for the MFH because it does not produce brine. The subsystems were run for multiple unibed saturations. As in the potable trade, adjustments were made to account for the differences in comparative test versus flight capacities. Test data for unibed life was used to calculate expendables using scaled-up components. System impacts were incorporated into the trade by reducing the MFH resources over the baseline system with an ROH which requires the urine processor to handle its brine.

The quantitative resources for the ROH and MFH, as in the potable trade, were similar. the MFH has a power advantage over the ROH, however, (354 W versus 918 W for the ROH) when considering system impacts. The qualitative trade was also very similar for the hygiene processor as for the potable processor. The MFH has major strengths in reliability, integration, and complexity while having no major weaknesses. The opposite is true of the ROH. The ROH has a single string dependence to the urine processor which not only complicates system control, but also creates a situation where the ability to provide hygiene water may be lost due to a failure of the urine processor. The power savings associated with the MFH, along with simplicity in integration and control and better potential reliability, provided the basis for recommending the MFH as the hygiene waste water processor.

5.6 Urine Processing

The two subsystems comparatively tested were the thermoelectric integrated membrane evaporation subsystem (TIMES) (baselined) and the vapor compression distillation subsystem (VCDS) (alternate). For the comparative test, both subsystems were operated with pretreated urine and flush water for 29 batches, followed by 2 batches of a 50/50 mixture of pretreated urine and RO brine. Actual comparative test data were used for resource calculations as the two units were sized for flight capacity.

The total system resources for the two technologies were very similar, except for a lower power requirement for the VCDS (177 W versus 334 W for the TIMES). Product water quality of the two subsystems was also comparable. The processing rate of the two subsystems, however, was found to be quite different. The VCDS met the specification of 1.6 kg/h (3.5 lb/h) with no problems. In contrast, the TIMES barely met the 1.6 kg/h (3.5 lb/h) requirement during the entire test, and subsequent testing with an earlier TIMES unit has showed degradation to as low as 0.45 kg/h (1 lb/h) when processing RO brine and urine alternately. The TIMES also lacks in its ability to process clean water. While this is not a specific requirement, it could lead to potential integration problems in the event of an upstream flush or other unexpected event. The VCDS was recommended as the urine processing subsystem based on lower power requirements, better processing rate, and higher level of hardware maturity.

Of the five areas traded, three alternate technologies were selected: Sabatier for CO_2 reduction over Bosch, MF for hygiene water processing over RO, and VCD for urine processing over the TIMES. All of the selections made by MSFC coincided with independent Boeing selections. In every case, the technologies selected represented the least risk for meeting flight readiness for S.S. *Freedom*.

6. ITCS

This section describes the restructured, PMC ITCS. Reference 1 approximately describes the pre-restructure ITCS. This reference included a body-mounted radiator (BMR) system as part of the ITCS. The BMR system was deleted prior to the restructure activities.

The ITCS is divided into active thermal control (ATCS) and passive thermal control subsystems (PTCS). The active subsystem collects waste heat within the pressurized elements and transports the collected heat to externally located heat rejection components. The passive subsystem consists of insulations, isolators, heaters, and external surface coatings to provide thermal radiation protection and heat balance between the internal pressurized volume and the external space environment.

6.1 Active Subsystem

The PMC active subsystem consists of several independent water coolant fluid loops as shown in figure 11. The thermal transport loops (TTL) acquire waste heat from subsystem and customer (i.e., experiment) equipment and transport the waste heat to central thermal bus interface heat exchangers (CTB HX's). The CTB HX's are mounted on the exterior of the pressurized elements and are the interface between the pressurized elements' internal active TCS and the external active TCS. Each TTL is tailored to that module's individual requirements, although each loop has similar characteristics. The U.S. modules utilize a dual-loop architecture in each module to allow segregation of low- and moderate-temperature heat rejection. The following paragraphs describe the individual loops that form the internal active TCS for the U.S. elements. The international module internal active TCS systems are described in references 2 and 3.

6.1.1 U.S. Laboratory and Habitation Module Loops

The internal active TCS loops are pumped, single-phase water loops which collect waste heat from subsystem and customer equipment located within the LAB and HAB modules. As shown in figure 11, each module's active TCS is independent of the other; i.e., no TCS fluid interfaces exist between the U.S. LAB and HAB modules and any other module. Within each module, a dual-loop architecture is utilized as depicted schematically in figure 12. Each module contains a low-temperature (LT) and a moderate-temperature (MT) fluid loop. The LT (nominally 4.4 °C (40 °F) inlet temperature) loop services equipment requiring the LT heat rejection such as the ECLSS THC cabin air condensing heat exchanger, ARS heat exchangers, the refrigerator/freezers (in the HAB, MPLM, and PLM modules), certain payload experiments and laboratory support equipment. The MT (nominally 18.3 °C (65 °F) inlet temperature) loop supports subsystem electronics equipment mounted on coldplates. The MT loop also services the ECLSS avionics air heat exchanger as well as payload experiments. Each MT or LT loop transports and rejects its collected waste heat to CTB HX's located on the aft external endcones of each module. The dual-loop architecture allows segregation of the heat loads to the corresponding LT and MT external TCS loops. This architecture simplifies the station-level heat load management and optimizes the sizing of the external ATCS radiator systems.

The LT and MT loops are plumbed in a parallel, reverse-return manner. The LAB-A MT loop flow circuit approach allows service at any module rack or endcone location. This arrangement increases flexibility in location of equipment in the module and allows reconfiguration of experiments into

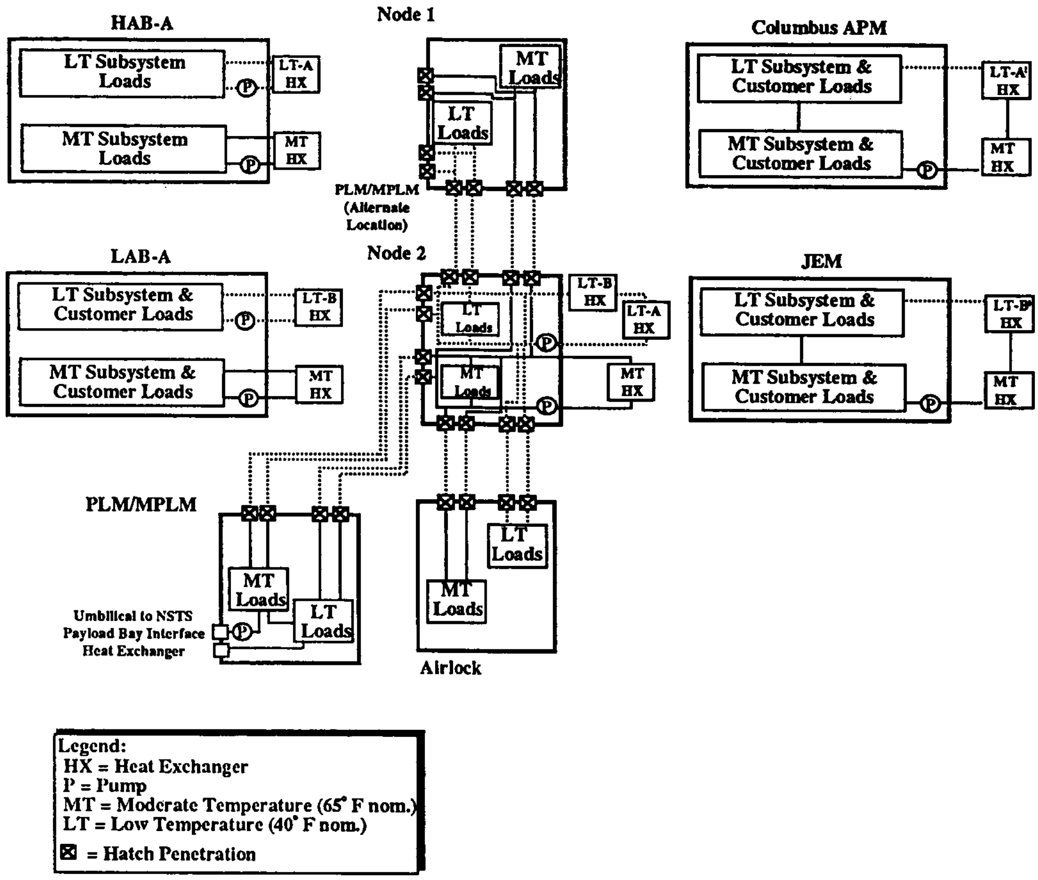

Figure 11. PMC S.S. *Freedom* internal active TCS overview.

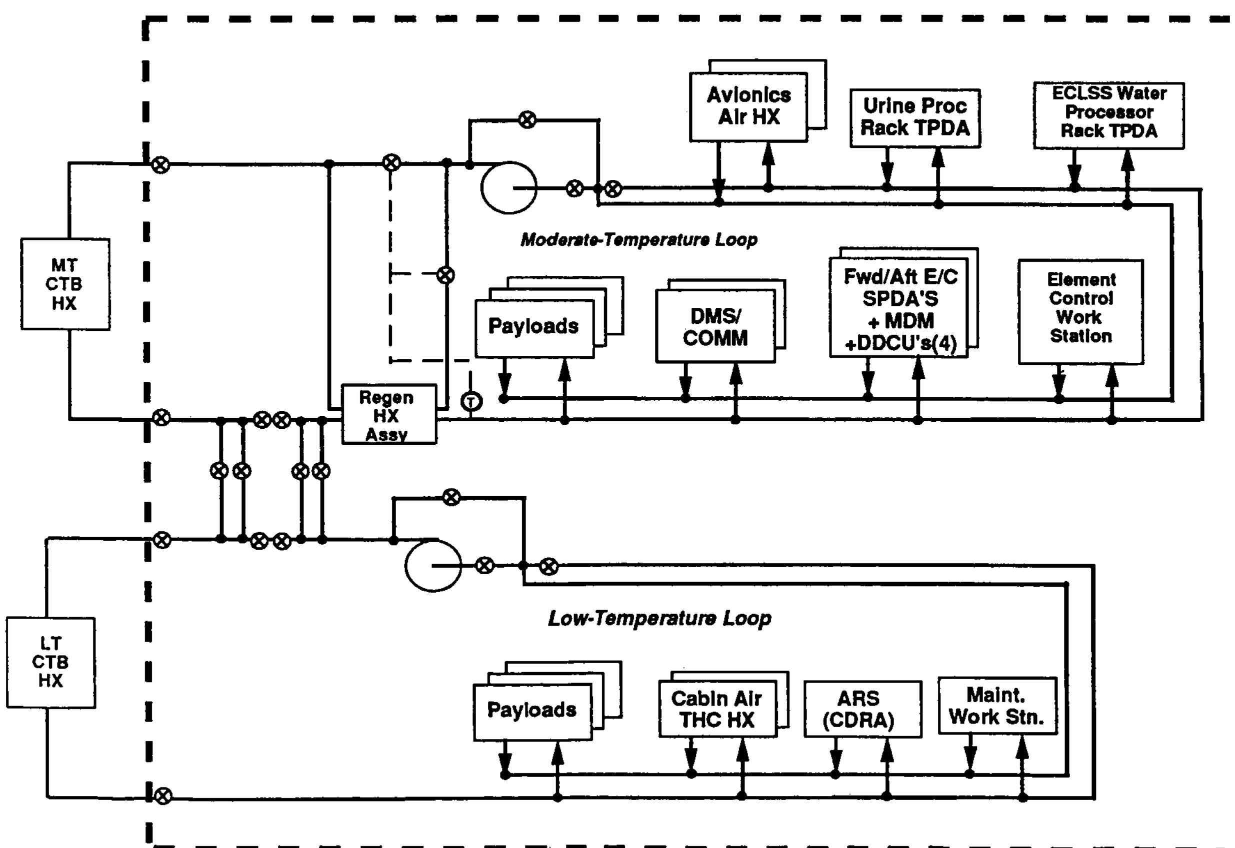

Figure 12. LAB-A active TCS schematic.

different payload rack locations. The reverse-return feature insures near equal system flow length through each rack fluid circuit and allows simplified flow balancing with simultaneous changing heat loads on multiple racks. This arrangement also allows "sweeping" of the entire fluid circuit to avoid/minimize any "dead spots" or trapped flow in the system.

Each rack has its own rack flow control assembly (RFCA) which consists of a modulation valve and flow and temperature sensors. The RFCA controls the flow to the rack to maintain either coolant flow rate or rack outlet temperature. For payload racks, the RFCA is located in the module standoff area. A system flow control assembly (SFCA) contains a delta pressure-regulated bypass valve across the system supply and return lines to maintain the entire system level pressure control and allow coolant pump operation at a near constant speed. As overall module heat loads change, the coolant pump speed and SFCA delta pressure setpoint can be adjusted to minimize coolant pump electrical consumption. The combination of the LT and MT loops has a transport capability of 29 and 15 kW in LAB-A and HAB-A, respectively. Each pump has a maximum flow capability of 1,361 kg/h (3,000 lb/h) and a heat rise of about 455 kPa (66 psid).

The LT and MT external active TCS loops operate over a range of 0.6 to 3.9 °C (33 to 39 °F) and 12.8 to 16.7 °C (55 to 62 °F), respectively. This results in the LT and MT water TTL's potentially operating over a range of water inlet temperatures 0.6 to 5.6 °C (33 to 42 °F) and 12.8 to 18.3 °C (55 to 65 °F), respectively, depending on the individual module and station-level heat load profile. Operation of the MT loop below the maximum dew point of 15.6 °C (60 °F) could potentially result in condensation forming on MT loop plumbing, equipment, and especially in the avionics air heat exchanger. In order to avoid this situation, a regenerative heat exchanger/valve arrangement is utilized to preheat/control the rack inlet water supply from the exiting heated water return. This arrangement will maintain the MT rack inlet temperature in the 16.1 to 18.3 °C (61 to 65 °F) range.

Normally, the LT and MT loops operate independently of each other. However, during early assembly and contingency operations, the LT and MT loops can be cross-connected to allow either of the LT or MT pumping stations to service the entire module. This arrangement maintains the single-fault tolerance capability for life-critical service within each module. Because of the independence of each module and multiple modules, dual-fault tolerance for life-critical functions is maintained at a station level. Heat exchangers, coldplates, and plumbing are considered to be high-reliability equipment and, therefore, are not required to be redundant.

The active TCS loops are monitored/controlled via software located on data management system (DMS) components. The status of the system is monitored via instrumentation such as flow sensors, pressure transducers, and temperature sensors. Commands to TCS components such as valves and pumps are also controlled via DMS. Communications to/from TCS pump packages are made via a 1553B data bus.

6.1.2 Node Loops

The node loops use a similar dual-loop architecture. Components and software common with the U.S. LAB and HAB module ITCS are utilized. The node LT and MT pumping stations are located only in node 2 (fig. 11). Node 1, the airlock, PLM/MPLM are supported from node 2. Connections to these supported elements are made via internal fluid connections in the hatch area between the elements. A parallel, reverse-return plumbing system is used to connect the loads in the node racks and the supported elements. Because node heat loads are expected to be constant, RFCA's are not required in node racks. A manual valve is utilized to initially balance the flow and maintain the rack outlet temperature within required limits. The collected waste heat is rejected to CTB HX's located on the external surface of node 2. Because of early assembly heat rejection requirements, node 2 has two LT CTB HX's.

6.1.3 PLM/MPLM Loops

The PLM/MPLM ITCS loop is represented schematically in figure 13. This loop also features LT and MT capability and collects waste heat from PLM/MPLM subsystems, principally ECLSS refrigerator and freezer units. During on-orbit operations, the PLM/MPLM heat loads are rejected via hatch-area fluid interfaces to the node 1 and node 2 ITCS loops. During ground, prelaunch, ascent, descent, and postlanding operations when the PLM or MPLM is located in the NSTS orbiter payload bay, the logistics module waste heat is rejected to the orbiter TCS. The PLM/MPLM ITCS loop has its own pumping and valving system which allows fluid circulation and heat rejection to the orbiter payload bay interface heat exchanger. Connections between the PLM or MPLM and the orbiter are made via an umbilical located external to the PLM or MPLM. During on-orbit operations, the PLM/MPLM pumping station is inactive.

6.1.4 Airlock Loop

The airlock ITCS loop has separate LT and MT services which collect airlock subsystem waste heat and reject to the node 2 ITCS LT and MT loops. Connections to the airlock SPCU thermal conditioning coolant loop are made via an interface heat exchanger.

6.2 Passive Thermal Control System

The passive TCS system is represented schematically in figure 14. Each pressurized module is insulated from the space environment via a combination of coatings, isolators, and multilayer insulation (MLI). Anodized aluminum coatings are used on the module meteoroid/debris shields to maintain touch temperatures within limits acceptable for EVA manned operation. A combination of these coatings, titanium debris shield supports, and surrounding MLI minimize the heat transfer between the modules and the space environment. The MLI consists of an outer layer of Beta cloth for handling protection and an inner layer of Kapton for flammability protection. Nineteen inner layers of Mylar and Dacron spacers are utilized as shown in figure 14. Each inner layer is double-aluminized to provide efficient thermal radiation shielding and protection from atomic oxygen effects. Each blanket layer is grounded to the pressure shell via redundant electrical leads. The Mylar and Kapton layers are ultrasonically welded together. The Beta cloth layer is sown on along the edge.

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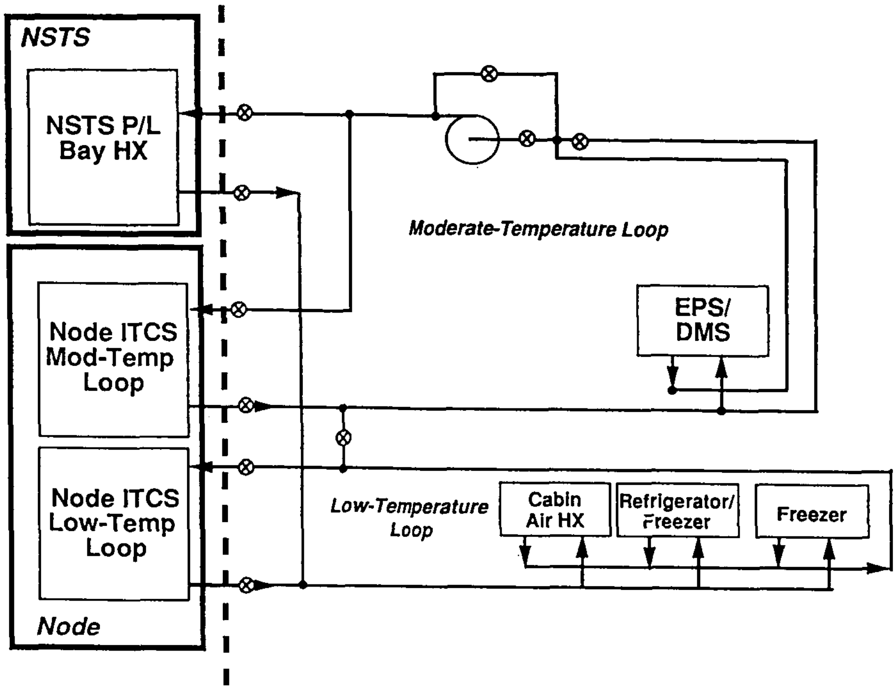

Figure 13. PLM/MPLM active TCS schematic.

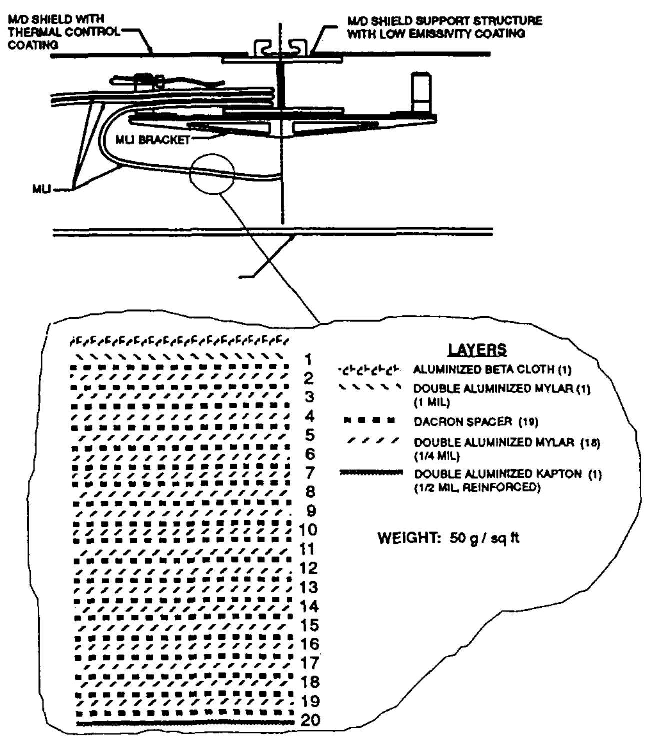

Figure 14. Passive TCS.