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MONITORING AND CONTROL OF ATMOSPHERE IN A CLOSED ENVIRONMENT

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INTRODUCTION

NASA is developing a manned orbiting space station for flight by the 21st century. Currently, the Space Station Freedom (S.S. Freedom), as it has been named, will be manned by an eight-person crew. An Earth-like atmosphere will be provided in 11 pressurized modules where the crew will live and work. The Environmental Control and Life Support System (ECLSS) is being developed to provide these surroundings artificially. The ECLSS is subdivided into six major subsystem groups to accomplish this task. These subsystem groups are composed of temperature and humidity control (THC), atmosphere control and supply (ACS, atmosphere revitalization (AR), water recovery and management (WRM), waste management (WM), and fire detection and suppression (FDS). As a whole, these subsystems supply, revitalize, condition, and monitor the respirable atmosphere; supply, recover, and condition water for hygiene and potable use; and collect, process, and store human waste for return to Earth.

Techniques have been adopted for some of these functions which are similar to those used in ground-based or earlier manned spacecraft applications. And, for the remainder, it has become necessary to develop new techniques. Those applications requiring new technologies for atmosphere monitoring and control in a closed environment will be discussed and their principal function onboard S.S. Freedom will be described.

SYSTEM OVERVIEW

The closed environment inherent to spacecraft is conducive to contaminant buildup, especially over the long periods of time the S.S. Freedom is designed to be operational (~30 years). In such an environment, care must be taken to define all contaminant sources and sinks in detail. These sources range from human to equipment inputs. As part of the S.S. Freedom ECLSS activities, each of these sources is being characterized and analyzed in great depth via testing and analysis.

In striving to meet these challenges, the common denominators of all space system engineers are to minimize weight, power, and volume - three of the most valuable commodities of a spacecraft. Also, of great importance for S.S. Freedom are high reliability, minimization and ease of maintenance, and a low resupply penalty. With these in mind, designers are optimizing the S.S. Freedom ECLSS.

Undoubtedly, the greatest challenge the S.S. Freedom ECLSS designer faces is that of loop closure. For the first time in the history of the United States manned space flight program, both oxygen-and water-loop closure is planned. Oxygen-loop closure will be discussed because it is pertinent to the topic of air purity. Also, of special interest are atmospheric contaminant control and monitoring because of the new technologies necessary to efficiently accomplish these functions onboard S.S. Freedom. Although not addressed, other technologies are being developed which support these specific ECLSS functions. Examples of these other functions are electromechanical devices for new motor-driven valves with integral control devices, smart sensors, new 120-Vdc conversion devices, and others.

OXYGEN LOOP CLOSURE

To minimize resupply demands, recycling is extremely important. Consequently, a string of equipment which can convert carbon dioxide to oxygen has been developed. Evolution of these technologies began in the 1960's and encompassed a number of different techniques. Competitive development of a number of techniques, as shown in table 1, was funded until recently and brought the techniques to a predevelopment maturity for comparative testing. This equipment includes carbon dioxide removal and concentration, carbon dioxide reduction, and oxygen generation.

Low concentration carbon dioxide is extracted form the cabin air and concentrated by the removal subassembly and sent to a carbon dioxide reduction device. In this device, the carbon dioxide is catalytically reacted with hydrogen at high temperature, producing water vapor and a waste product. Water is condensed and ultimately fed in the form of hygiene water to a unit which decomposed it into its elemental parts of oxygen and hydrogen by an electrolytic process. The hydrogen is fed to the carbon dioxide reduction process for reaction with the carbon dioxide while the oxygen is returned to the cabin, thus closing the oxygen loop. Nitrogen purge streams for the carbon dioxide reduction and oxygen generation subassemblies are fed directly to the trace contaminant control subassembly for processing any residual hydrogen during startup and shutdown of these processes.

The water produced by the carbon dioxide reduction subassembly produces potable water for crew consumption. this water eventually is introduced into the air where it is removed as humidity condensate and reclaimed for crew consumption or into the waste management system. The water from the urine introduced into the waste system is reclaimed and processed for crew use during showering, hand washing, and other personal hygiene activities. Also, this water is used as a process feed stream to the oxygen generation subassembly, thus achieving loop closure.

As a consequence of analytical studies combined with evaluation of comparative test results, baseline subassembly selections have recently been made. As indicated in table 1, the preferred approaches are four bed molecular sieve (4BMS) for carbon dioxide removal, the Sabatier reactor (Sa-CRS) for carbon dioxide reduction, and the static feed potassium hydroxide (KOH) electrolyzer (SFWES) for oxygen generation.

Carbon Dioxide Removal

The 4BMS, shown schematically in figure 1, uses a zeolite material (Linde 5A) which has been further modified by the supplier to produce a material which is extremely efficient in absorbing carbon dioxide. Unfortunately, this material also has a high affinity for water vapor. Consequently, the influent moist air must be dried. This is accomplished by using a two-media desiccant bed. This bed is made of silica gel and a second zeolite material (Linde 13X) with a high water removal efficiency. The influent air, carbon dioxide, and water vapor mixture is first passed through the desiccant bed where the dew point is reduced to a range of -30^0 F to -90^0 F. The carbon dioxide is then absorbed in the second 5A zeolite bed until the sorbent material becomes saturated. The carbon dioxide molecular sieve material is then desorbed by a combination pressure and temperature swing process which requires first evacuating the bed, then heating it to 400^0 F. The desorbed carbon dioxide is then purged from the bed in a concentrated form. The initial air passing through the bed after desorption is routed back through the desiccant bed to drive the absorbed moisture out of the desiccant bed and back into the cabin. During the desorption period of these two beds, the remaining beds are absorbing so that a continuous carbon dioxide removal capability exists at all times utilizing this four-bed concept.

Carbon Dioxide Reduction

Reduction of the carbon dioxide to water is achieved by a 950 ^{0}F Sabatier reactor process shown schematically by figure 2. The chemical reaction which takes place in this reactor is the following:

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4$$

In this process, concentrated carbon dioxide at greater than 97-percent purity is fed into the reactor with hydrogen produced by the oxygen generator. A packed bed reactor containing a ruthenium on alumina catalyst provides the appropriate conditions for the process to proceed. This reaction forms water vapor and methane stoichiometrically. However, since the reaction is not 100 percent efficient, not all the carbon dioxide is reacted and it exits with the water vapor and methane. A condenser at the reactor outlet condenses the water vapor to the liquid phase and it is pumped away to the potable water subsystem to be processed for crew consumption.

Oxygen Generation

A KOH electrolyte-type generator shown schematically in figure 3 is used to separate water into hydrogen and oxygen. Electricity fed into the unit causes the electrolytic process to occur. At the same time, water enters a static water compartment where it evaporates through a Gortex membrane into the hydrogen cavity of the electrolysis cells. The chemical definition of how the water is separated into its elements by this process is the following:

$$\text{Cathode:}\quad 2e^- + 2H_2O \longrightarrow H_2 + 2OH^-$$

$$\text{Anode:}\quad 2OH^- \longrightarrow H_2O + \tfrac{1}{2}O_2 + 2e^-$$

$$\text{Overall:}\quad H_2O \longrightarrow H_2 + \tfrac{1}{2}O_2 + 2e^-$$

By this process, gaseous hydrogen and oxygen is formed in respective compartments of the multicell unit. It is forced out of the unit by the pressure buildup caused by continuing reaction. The hydrogen produced from this process is fed to the Sa-CRS and the oxygen is supplied to the cabin for crew respiration.

ATMOSPHERIC CONTAMINATION

Inherently, spacecraft must have closed environments. Since gas lost overboard must be produced at an expense of power, weight, and volume for closed loop processing equipment or through costly resupply from the ground, a tight environment is a must to reduce the loss and thus reduce resupply and resource requirements to make up for these losses. As a consequence, all contaminants evolved onboard a spacecraft from crew metabolism, material offgassing, and everyday housekeeping and work activities may build up over time. this buildup must be controlled and monitored to assure that the crew health is not compromised during their exposure to this environment of 180 days or more. This and a combination of other factors make contamination control and monitoring onboard S.S. Freedom a necessity. Of special concern is the large range of payloads and experiments planned over the S.S. Freedom life. This gives rise to the potential for a large variety of potential types as well as quantities of contaminants. Previous manned space flights by the United States have all been of short enough duration and/or in a large enough volume (i.e., Skylab) that metabolic methane buildup was of no concern. Complicating this for the S.S. Freedom is the fact that the new closed loop equipment generates contaminants such as hydrogen, methane, and carbon monoxide internally. All of which, if they leak, are not well removed by previously flown activated charcoal trace contaminant control media. As a consequence, for the first time a high temperature catalytic oxidation reactor or catalytic converter is being developed for the S.S. Freedom to be used in combination with activated carbon adsorption.

The need to monitor unexpected contaminants, long-term buildup of known contaminants, and contamination leakage gives rise to the need for an onboard real-time trace contaminant monitor. The need to monitor multiple atmospheric constituents points toward the desire to fly both a major constituent analyzer as well as a separate carbon monoxide monitor. The concern with long-term buildup of airborne particulates, where a clean room environment of less than or equal to 100,000 particles/ft^3 for particles between 0.5 and 100 μm is desired in the station atmosphere, while hazardous aerosols may be generated by potential payloads such as gallium arsenide (GaAs) and mercury cadmium telluride (HgCdTe) crystal growth experiments, has stimulated both particulate and aerosol monitoring requirements on S.S. Freedom.

Airborne Trace Contaminant Control

The trace contaminant control subassembly (TCCS) combines activated carbon adsorption with high temperature catalytic oxidation to achieve the most efficient long-duration airborne contamination control. This subassembly is shown schematically in figure 4. An activated charcoal impregnated with phosphoric acid is used to remove ammonia and high molar volume organic contaminants. Other contaminants which are not easily removed by the charcoal are removed in a 600^0 F to 700^0 F catalytic reactor. This reactor removes primarily methane, hydrogen, and low molar volume compounds while converting carbon monoxide to carbon dioxide. The reactor utilizes a palladium on alumina catalyst in a packed bed to achieve its function. Methane oxidation efficiencies as high as 95 percent per pass have been experienced using predevelopment and prototype testing. The reactor effluent is scrubbed by a lithium hydroxide (LiOH) packed bed to remove any acidic reaction products from the air stream before it is exhausted to the spacecraft cabin.

Atmospheric Composition Monitoring

Atmospheric composition is monitored for trace contaminants, major consitutents, carbon monoxide, and particulates on a continuous basis at multiple locations in the S.S. Freedom. Four separate instruments provide these functions since it is difficult for any one instrument to monitor the entire spacecraft atmospheric composition. Table 2 summarizes the S.S. Freedom atmospheric monitoring capabilities. Each instrument is described briefly.

Trace Contaminant Monitor

The trace contaminant monitor (TCM) instrument utilizes a gas chromatography/mass spectrometry principle to analyze both species and quality for mass to charge (m/e) ratio of 24 to 250. The TCM gas chromatograph uses two stages of sample preconcentration to detect low contaminant concentrations. The analysis is conducted in a cyclic, three-stage process. The sample is concentrated on a large sorbent trap and then further concentrated on a smaller sorbent trap. A small carrier volume is then used to transfer the sample to the carbonous fused silica gas chromatographic columns and then to a scanning double focusing magnetic sector mass spectrometer which scans a mass range from m/e 24 to 250. The unit is capable of detecting at a resolution of 50 percent of the spacecraft maximum allowable concentration (SMAC) for each species monitored. Approximately 200 compounds are monitored through use of a software mass spectra fit library search. Any compounds which are not contained in the library are labeled as stranger compounds and may be analyzed offline if desired. The typical cycle time for this unit is 1 hour, and its software allows direct automated outputs of speciation and quantity. The samples are drawn through long, thin tubing from several locations within the S.S. Freedom cabin for analysis.

Major Constituent Analyzer

The major constituent analyzer (MCA) is a mass spectrometer which utilizes a single focusing magnetic sector with a Faraday cup detector. It has a capability of monitoring in the mass to charge range of 1 to 48. this unit specifically focuses on oxygen, nitrogen, carbon dioxide, methane, hydrogen, and water vapor. The instrument's response time is less than 100 milliseconds (ms) for all gases except water which has a response time of 500 to 800 ms. Vacuum is maintained to the instrument by an ion pump which operates by surface absorption and chemical reaction of gases with the active metals of titanium and tantalum. It has a sampling rate of one sample per minute and draws samples from lines similar to those of the TCM.

Carbon Monoxide Monitor

The carbon monoxide analyzer (COA) is a nondispersive infrared instrument using a dual isotope fluorescence technique. This instrument is used since carbon monoxide is not easily detected with mass spectrometry because it has approximately the same molecular weight as nitrogen. An air sample is introduced into the COA similarly to the TCM and MCA. In the instrument, an infrared source excites a fluorescent cell which in turn produces radiation in the range for the most abundant isotope of carbon monoxide (carbon-12). The radiation passes through a chopper filter which contains the abundant and rare isotopes of carbon monoxide (carbon-12 and carbon-13) which results in the sample gas being exposed to alternating bursts of radiation which is absorbed by either the carbon-12 isotope or the carbon-13 isotope. Since carbon-13 is not very abundant, the radiation associated with it is not absorbed significantly by the sample and is used as a reference. The transmission and adsorption of the fluorescent radiation associated with the two isotopes is detected by a thermoelectrically cooled lead selenide (PbSe) detector. Since the degree of absorption is proportional to the carbon monoxide partial pressure, the detector signal is compared to calibration data to determine the partial pressure.

Particulate Counter Monitor

The particle counter monitor (PCM) is a compact commercial model based on light scattering. This device uses an AlGaAs laser diode to produce a light beam at a 780-nm (nanometer) wavelength which is scattered by particles in the air sample and detected by a photodetector. The light beam passes through several lenses and an aperture to produce a thin plane in the particle sensing zone. A light trap captures the main light beam after it passes the instrument's sensing zone. As each particle passes through the sensing zone and scatters light, the photodetector converts the scattered light energy to electrical pulses which have an amplitude corresponding to the particle size. The air is sampled through a dedicated line to continuously measure the total particle constituency from 0.5 to 100 μm.

Table 1. O_2 closure competitive techniques

• CO_2 Removal	• 4 Bed Molecular Sieve* • Solid Amine Water Desorbed (SAWD) • Electrochemical Depolarized Cell (EDO)
• CO_2 Reduction	• Sabatier/Advanced Carbon Reactor • Bosch Carbon Reactor • Sabatier*
• O_2 Generation	• Static Feed Water Electrolysis Subsystem (SFWES)* • Anode Feed Solid Polymer Electrolyzer (AFSPE)

* Baselined for SSF

Table 2. Atmospheric composition monitor (ACM) functional summary.

SUBASSEMBLY	INSTRUMENT	SPECIES MONITORED	RANGE/ ACCURACY	SAMPLE LOCATIONS	SAMPLE INTERVAL
Major Constituent Analyzer (MCA)	MS	N_2, O_2, H_2O, H_2, CH_2, CO_2	±5% of range	6	1 min/line
Trace Contaminant Monitor (TCM)	GC/MS	trace contaminants	0-50% of SMAC	6	30 min/line
Carbon Monoxide Analyzer (COA)	NDIR	CO	±1% of range	6	1 min/line
Particle Counter Monitor (PCM)	Light Scattering	particulates	0.5-100μm	1	continuous

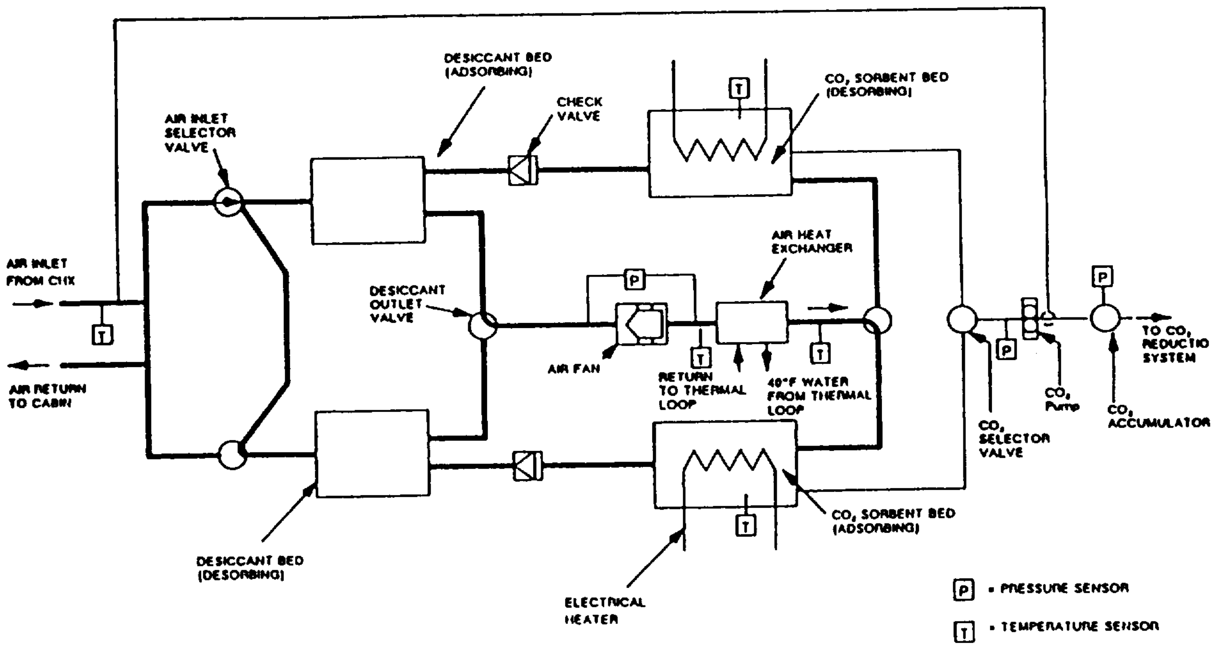

Figure 1. S.S. Freedom 4BMS CO_2 removal subassembly schematic.

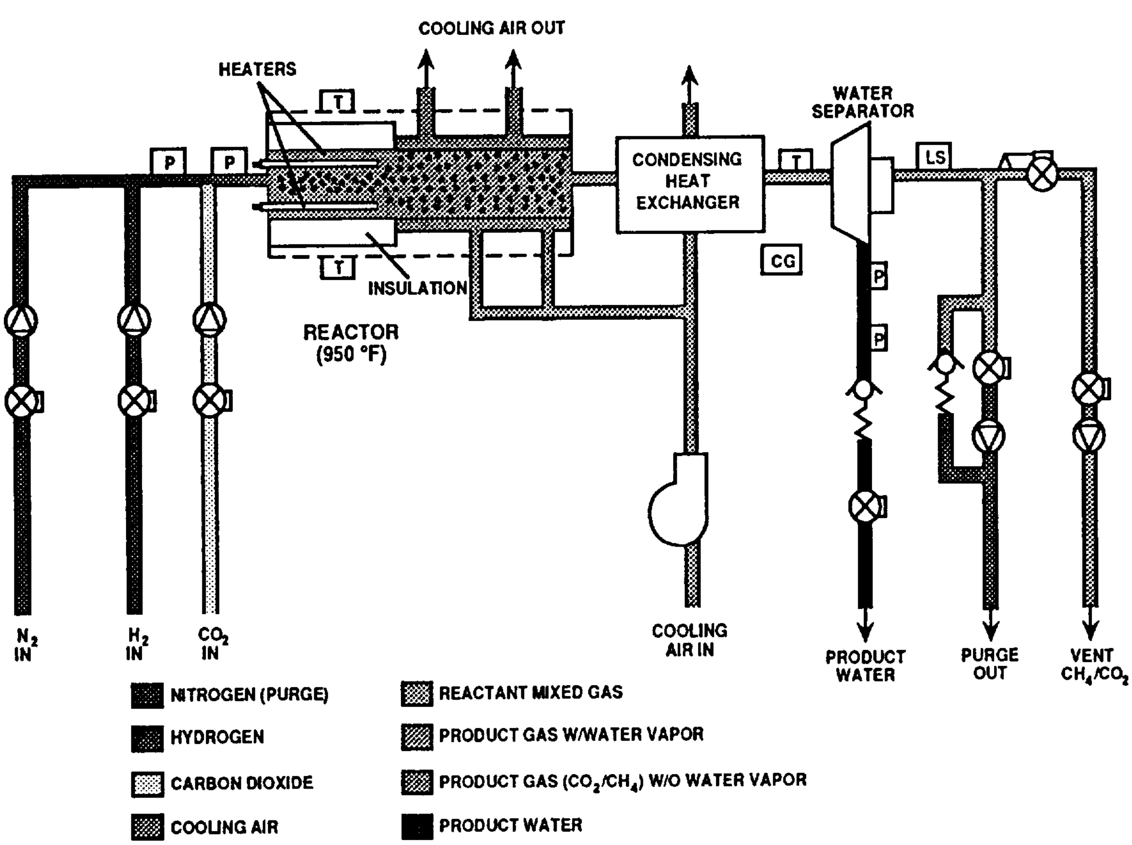

Figure 2. S.S. Freedom sabatier CO_2 reduction subsystem schematic.

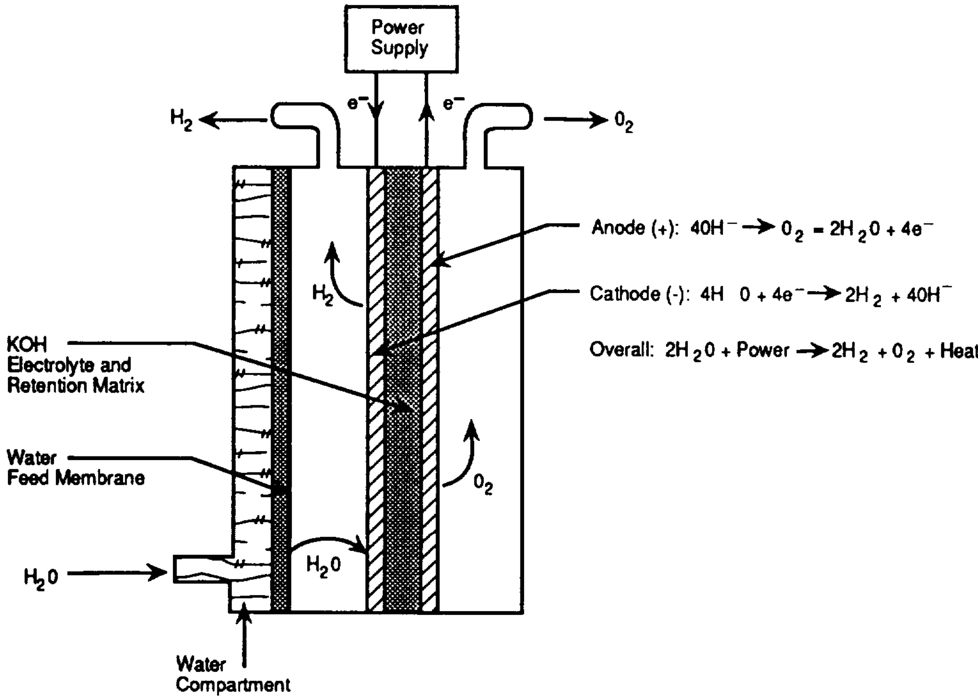

Figure 3. S.S. Freedom oxygen generator cross-sectional schematic.

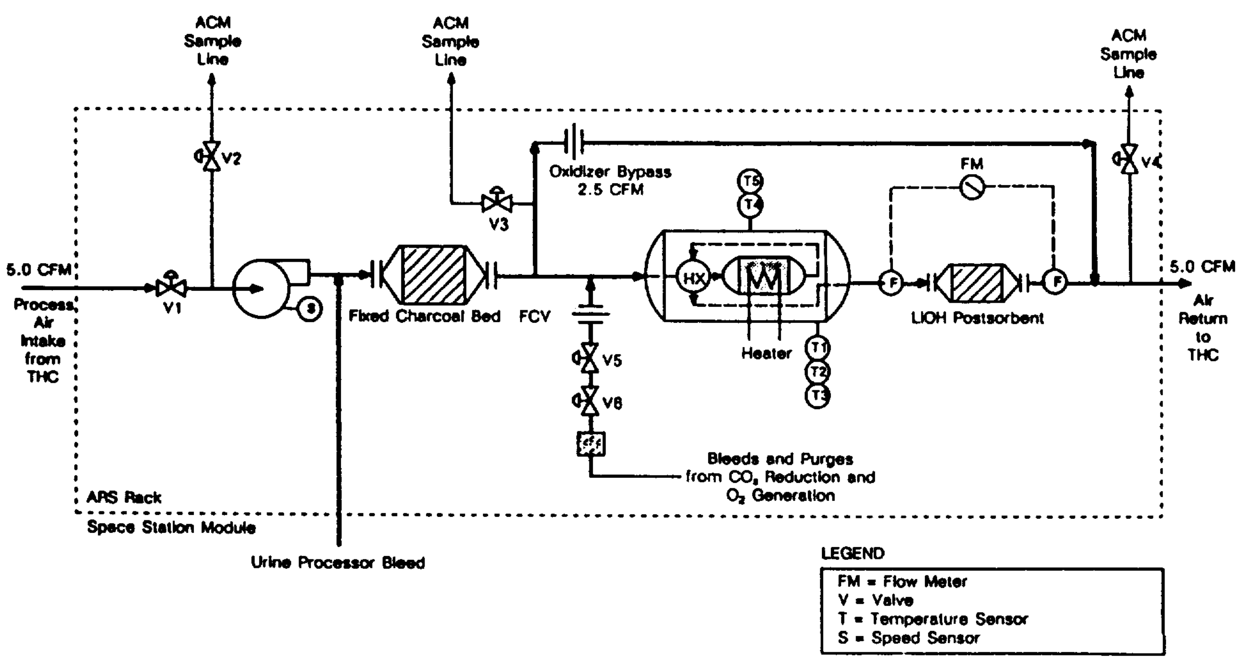

Figure 4. S.S. Freedom TCCS schematic.

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