# "EVALUATION AND COMPARISON OF ALTERNATIVE DESIGNS FOR WATER/SOLID-WASTE PROCESSING SYSTEMS FOR SPACECRAFT"

.INAL REPORT

Prepared by the
Bioenvironmental Systems Study Group
of the
Society of Automotive Engineers, Inc.

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# FOREWORD

The work described in this report was performed on Contract No. NASw-2439 and sponsored by the Life Sciences Directorate, Office of Manned Space Flight of the National Aeronautics and Space Administration. The Bioenvironmental Systems Study Group, a team established and coordinated by the Society of Automotive Engineers, Inc., performed the work and prepared this report. Members of this team included:

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## SUMMARY

This final report presents the results of a study to evaluate the state of technology development for spacecraft water and solid-waste processing systems. The work was accomplished by the Bioenvironmental Systems Study Group, of the Society of Automotive Engineers, on Contract No. NASw-2439. Specific objectives of this investigation included: (1) a detailed comparison and assessment of the most promising candidate designs currently being considered by NASA for the management of solid waste and waste-water materials on spacecraft; (2) a projection of relative attractiveness of each design to NASA for anticipated manned spacecraft applications, using a common basis for comparison and a realistic tradeoff analysis; and (3) the formulation of recommendations which will be useful to NASA in managing and planning continued efforts in this area of technology development. The candidate processes that were evaluated and compared were (1) the Radioisotope Thermal Energy (RITE) evaporation/incinerator process; (2) the Dry Incineration process; and (3) the Wet Oxidation process.

The scope of the technical approach that was used to accomplish the study objectives consisted of: (1) the establishment and analysis of an adequate data base and the analysis of the current status of technology for the alternative processes of interest; (2) the development of a standardized input and output model as a common basis for comparing and evaluating the alternative processes; (3) the development of completed and scaled-up flowsheets for the alternative processes to satisfy the standardized input and output models and performance criteria; (4) the comparison and tradeoff evaluation of the

completed and scale-up (commonly-based) processes; and (5) the development of conclusions and recommendations.

The types of spacecraft waste materials that were included in the base-line ("standardized") computational input to the candidate systems were feces, urine residues, trash and waste-water concentrates. The performance characteristics and system requirements for each candidate process to handle this input and produce the specified acceptable output (i.e., potable water, a storable dry ash, and vapor-phase products that can be handled by a spacecraft atmosphere control system) were estimated and compared to produce the essential conclusions and recommendations of this study. The approach used in the study, the results, and conclusions and recommendations are described in detail in this report.

# 1. INTRODUCTION

## 1.1 Purpose and Scope:

Based upon the results of a task assignment completed and reported to NASA's Bioenvironmental Systems Division (OMSF) in December, 1973, on Contract No. NASw-2439, by the Bioenvironmental Systems Study Group of the Society of Automotive Engineers, Inc., it was determined that NASA's life support systems development program could benefit significantly from a careful analysis of alternative designs for solid-waste management systems, presently being considered by NASA, including a comparison of their relative advantages and disadvantages and a realistic assessment of the potential attractiveness to NASA of each candidate approach. The Study Group recommended to NASA Headquarters that such an assignment could be accomplished competently by the Study Group, but not within the scope or budget of the original terms of Contract No. NASw-2439.

Therefore, an additional task on Contract No. NASw-2439 was authorized to provide the necessary augmentative funding for the study assignment, to be accomplished by the Study Group. The specific objectives of this additional assignment were: (1) a detailed comparison and assessment of the most promising candidate designs currently being considered by NASA for the management of solid waste materials on spacecraft (i.e., dry incineration and wet oxidation processes); (2) a projection of relative attractiveness of each design to NASA for anticipated manned spacecraft applications, using a common basis for comparison and a realistic tradeoff analysis; and (3) the formulation of recommendations which will be useful to NASA in managing and planning continued efforts in this area of technology development.

The scope of the study included: (1) the definition of a common basis for comparing the candidate systems designs; (2) establishing an appropriate tradeoff model; (3) performing the comparison, evaluation and tradeoff analysis (including the characterization of any technology extrapolations that might be required): (4) formulation of recommendations; (5) reporting of results to NASA in a thoroughly definitive report.

## 1.2 Background and Rationale:

For the past several years NASA has been sponsoring research and development efforts to advance the state of technology in the area of solid-waste management for spacecraft applications. Currently there are four principal design approaches for waste management systems or sub-systems. The processes which provide the basis for one or more of these design approaches include (1) dewatering, pyrolysis and incineration; (2) space-vacuum drying of waste with compaction and storage or overboard dumping of residue; (3) wet oxidation followed by water recovery; and (4) the application of a radioisotope heater to thermally supply evaporator and incinerator units. The types of spacecraft wastes for which NASA will require management systems, for certain types of manned missions, include feces, urine residues, trash (e.g., from food packages, etc.), and waste-water concentrates. Generally, it is the desired objective that a system eventually be able to convert these wastes to potable water, a storable dry ash, and vapor-phase products that can be handled by a spacecraft atmosphere control system.

In the fall of 1973, the SAE Bioenvironmental Systems Study Group was assigned a study, on NASA Contract No. NASw-2439, to analyze the state of spacecraft waste-management-systems technology. The Study Group reviewed the work conducted and reported by (1) General Electric (the RITE water-waste management system); (2) Lockheed (the "wet-ox" system); and (3) GARD (the dry-incineration system) for spacecraft waste management systems design and development. The principal objective of this review was the determination of the relative state of technology for each of these three approaches to spacecraft waste management, the pacing technical problems which remain to be solved, and the relative technical readiness of a system consisting of components from one or more of these three approaches to waste management. Although a detailed tradeoff analysis was not within the scope of this original review effort, an attempt was made to adequately define the material balance and flow sheet for each system approach. This definition was expected to provide a basis for a detailed tradeoff analysis in the future, if NASA desires to proceed in that way. In general, the Study Group was chartered to provide NASA Headquarters with information that can assist NASA in its decision-making efforts in this area of technology.

Representatives of the Study Group completed visits at the facilities of G.E., Lockheed and GARD where they met with principal investigators on the respective development programs, discussed progress and status on these programs, and observed apparatus. The results of these visits, combined with the Study Group's review of available reports, were discussed in detail by members of the Study Group team to compare relative status and performance features among the three systems approaches. Recommendations were then formulated by the Study Group and reported as interim findings to NASA. In general, it was determined that even an adequate common basis for comparing the candidate design approaches could not be formulated within the scope and time and budget constraints of that contract task. Too many differences existed in the feed-stream experiences, presumed interfaces with other sub-systems, etc. One design contractor had operated a nearly integrated waste-management system under certain conditions, whereas other contractors had used only a part of a system or entirely different conditions of operation. Furthermore, key pieces of data, necessary to complete a "common-pathway" flowsheet were not available from testing efforts to date. The Study Group suggested additional testing and measurements that should be made; otherwise, a rather tedious analytical procedure must be pursued by the tradeoff analysts in order to formulate an adequate comparison basis and tradeoff model. Additionally, in some cases it was anticipated that it would be necessary to forecast or extrapolate technological developments before the system model could be completed as a basis for the comparison analysis.

NASA's Bioenvironmental Systems Division decided that the contracting for extensive additional testing by the various contractors, using their respective subsystems concepts would be premature until a common or standard basis for comparison has been established. In addition, this NASA group decided that the development of such a standard comparison basis, and the concomitant evaluation of the status of technological development to date on the alternative subsystems concepts should be accomplished independently from the subsystems development activities. This decision, together with the SAE Bioenvironmental Systems Study Group's background and experience in this area of spacecraft life-support systems technology, provided the rationale for the work described in this report.

### 1.3 Background on Prior Subsystems Development Efforts:

Early emphasis by NASA on the development of urine reclamation processes brought several concepts to the prototype subsystem design and testing stage. However, the state of readiness of the early water recovery concepts impacted on the development of the remaining waste-management subsystems; particularly the fecal and solid-waste processing hardware.

The vacuum-drying waste collector and storage subsystem concept demonstrated that the activity of micro-organisms could be controlled adequately for safe storage of the dried waste. Other feces processing concepts that would greatly reduce the amount of residue to be stored were of significant interest, but these necessitated the development of more sophisticated equipment and eventually led to a strong interest at NASA in combination water-and-waste processing subsystems. Development work on these concepts was based initially upon the goals of (1) creating a system that would greatly reduce the amount of residue to be stored or returned to earth, as well as extracting usable materials from these wastes; and (2) improving methods for controlling bacteria in water and waste processing subsystems, including automatic monitoring and control features.

Specific objectives of the development programs that were sponsored by NASA for the three principal water-and-waste processing concepts (wet oxidation, dry incineration, and incineration using radioisotopic heating) are summarized below.

A. Wet Oxidation Process. -- The investigation of the feasibility of applying the wet-oxidation process to spacecraft waste treatment was initiated under Contract NAS1-6295 with the Whirlpool Corporation by the NASA Langley Research Center. The objective of this study was to investigate the recovery of useful water and gases from urine and fecal matter in conjunction with the processing of wastes and the elimination of overboard venting of waste liquids and gases, based upon the wet-oxidation chemical process. The significant data obtained from this initial investigation (i.e., COD reduction; slurry-solids concentration, temperature and pressure effects; etc.) led to a NASA contract with the Lockheed Missiles and Space Company (Sunnyvale, Ca., Contract No. NAS1-9183, for the design and fabrication of a wet-oxidation batch-reactor laboratory apparatus to investigate the effects of temperature, reaction time, oxygen pressure and feed rate, and solids concentration prior to the detailed design of a reactor prototype. A prototype reactor unit, scaled approximately to the waste-handling requirements of a four-man spacecraft mission, was designed and constructed on an extension of this contract and included a test program to verify the system design. Several studies were added from time to time, to provide, for example (1) continuous, rather than batch processing; (2) an evaluation of the most promising water-reclamation subsystem for use with a wet-oxidation reactor; and (3) development of a waste-solids grinder, ash filter, and life-testing of various subsystem components. Results of this work are summarized in Reference 5.6. A simplified schematic diagram of the wet-oxidation test apparatus is shown in Figure 1-1.

B. Radioisotope Thermal Energy (RITE) Process. -- The General Electric Space Division initiated research and development work in 1969 on the RITE concept on Contract No. AT(11-1)-3036 with the U. S. Atomic Energy Commission, with joint sponsorship by NASA Headquarters and the U. S. Air Force (Wright-Patterson Air Force Base). The scope of this work included the design, development, fabrication and testing of an engineering model for an advanced water and waste processing subsystem. The design was based upon concepts studied by General Electric on a previous NASA contract. The engineering model was scaled to meet the approximate requirements for collecting and processing wastes from four men for a 180-day simulated space mission. Process steps included feces, trash and urine collection; water reclamation; storage, heating and dispensing of the water, and disposal of the feces, urine residue and other non-metallic waste materials by incineration. This program eventually consisted of seven phases as listed chronologically and described in Table 1-1. The original approach (shown schematically in Figure 1-2) provided for all wastes to

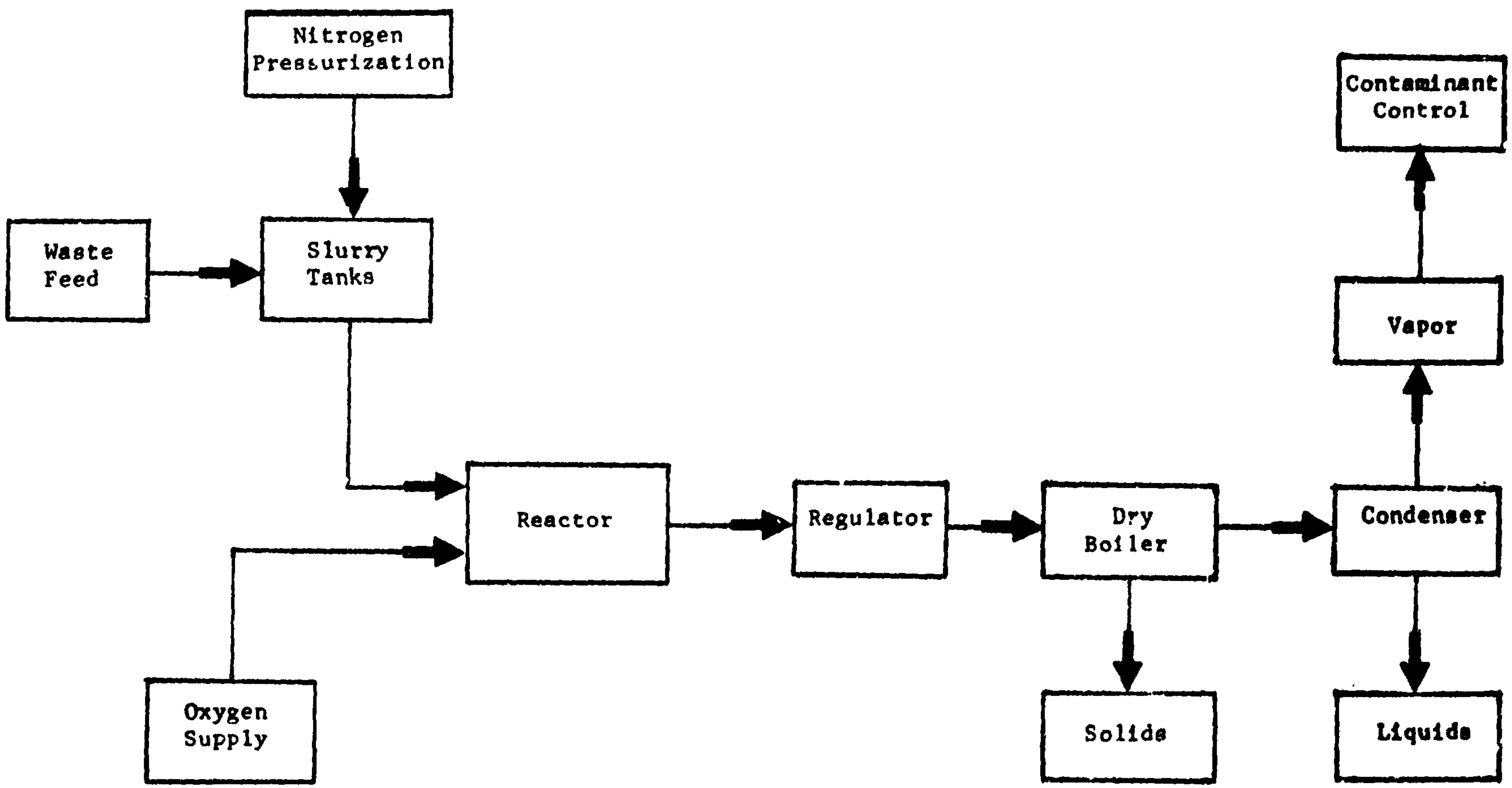



Figure 1-1. Simplified Schematic Diagram of Lockheed Wet-Oxidation Process (Test Model)

Table 1-I. Program Scope and Schedule; G.E. RITE System.

| Phase | Start | Complete | Description |
|---|---|---|---|
| I | June 23, 1969 | January 31, 1970 | Design the waste incinerator/water reclamation unit (including the heat source) for the engineering model with capability for operation with a radioisotope heat source and with an electrical heat source. Develop the critical components and subsystems of the waste incinerator/water reclamation unit to permit design and fabrication of the unit. Prepare a preliminary design (including descriptive drawings), preliminary performance specifications and preliminary operating procedures for the WM-WS engineering model. Prepare test plan for evaluation of the operational, life, safety, and maintenance characteristics of the waste incinerator/water reclamation unit and of the WM-WS engineering model. Prepare a preliminary safety analysis for the radioisotopes heat source. |
| II | February 1, 1970 | July 31, 1970 | Fabricate a waste incinerator/water reclamation unit in accordance with the Phase I design. Test the waste incinerator/water reclamation unit in accordance with the Phase I test plan. |
| III | June 1, 1970 | August 31, 1970 | Analyze Phase II test data, evaluate the design and operation of the waste incinerator/water reclamation unit. Revise the design of the waste incinerator/water reclamation unit to eliminate deficiencies and add improvements indicated by such evaluation. |

Table 1-1. Program Scope and Schedule; G.E. RITE System. (Continued)

| Phase | Start | Complete | Description |
|---|---|---|---|
| IV | September 1, 1970 | June 15, 1972 | Prepare a detailed engineering design (including descriptive drawings), specifications and procedures suitable for fabrication and test of the engineering model, incorporating the revised waste incinerator/water reclamation unit design. Prepare final test procedures, including safety and emergency procedures, for the engineering model. Fabricate any necessary handling tools for the radioisotope heat sources and arrange for use of shipping cask. Prepare a safety analysis report for the radioisotope heat sources. Work with the fueling agency to provide radioisotope heat source final design and fabrication procedures. Perform additional development tests of solid pump concepts and the high temperature process. |
| V | February 1, 1971 | June 15, 1972 | Fabricate the engineering model in accordance with the Phase IV design. |
| VI | June 15, 1972 | July 31, 1972 | Perform a ten day electrically heated operating test of the engineering model in accordance with the Phase IV test plan. Evaluate the 10-day test data. Make necessary modifications to the engineering model and test and operating procedures. Upon completion of the above work, submit and/or distribute drawings, manuals and documentation for license applications. |
| VII | July 31, 1972 | December 31, 1973 | Conduct 180-day test using radioisotope heat source(s). Provide proper facilities to assure safety and security of the test area. Obtain AEC license for this radioisotope test application. |

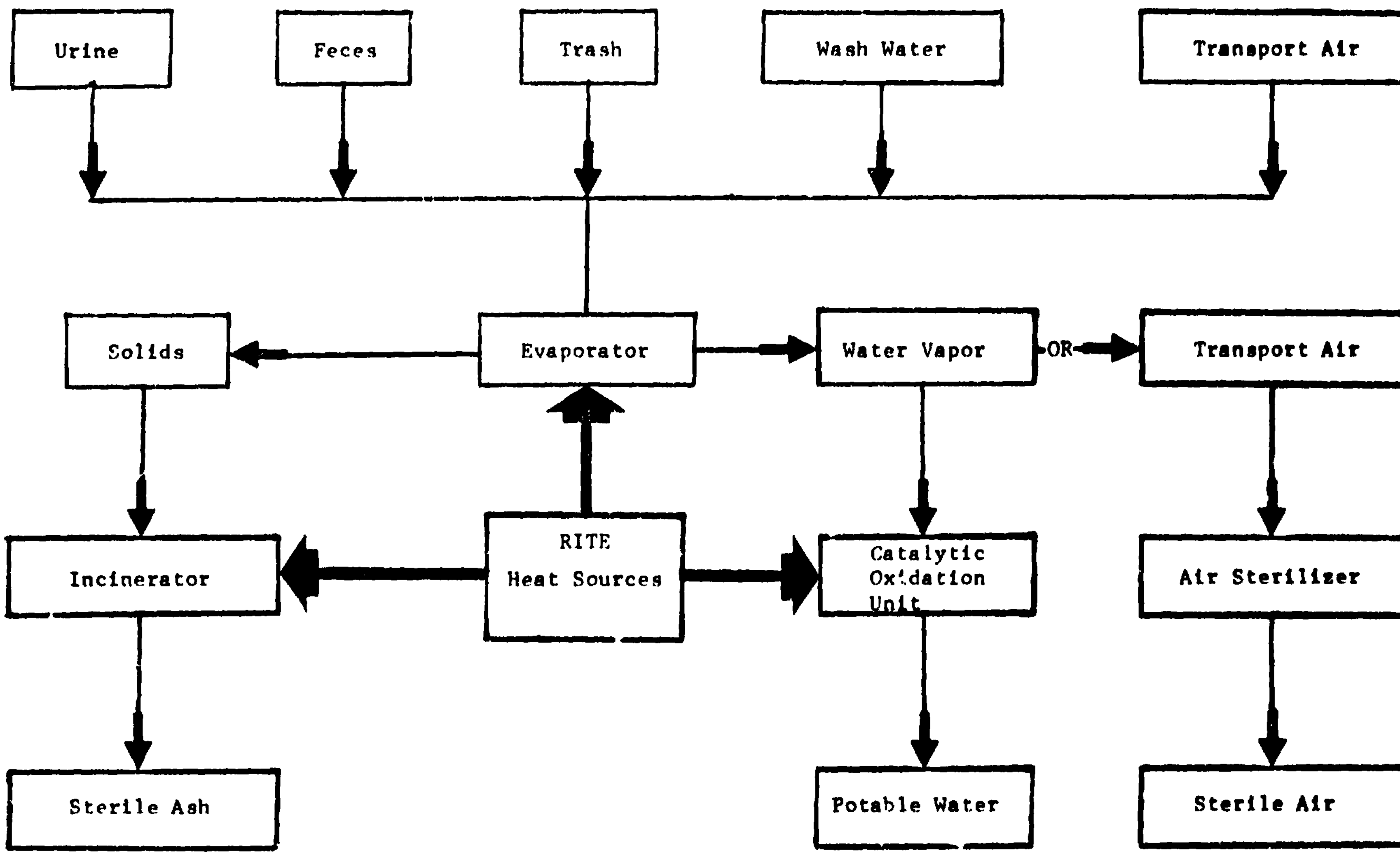



Figure 1-2. Functional Diagram of G.E. RITE Process

be collected in the evaporator where the water was distilled off at low temperature. The remaining solids were removed centrifugally from the evaporator and then dried, thermally decomposed and incinerated, with the resulting gases vented to space vacuum. The remaining ash was stored or jettisoned. Transport air that was used to collect the waste was returned to the spacecraft cabin after being cleaned by catalytic oxidation, etc. More recently, the contractor has investigated requirements for closing the system to meet a zero-dump (to space vacuum) operating condition.

C. Dry Incineration Process. -- The General American Research Division (GARD) of the General American Transportation Corporation designed, fabricated and tested the GARD Model 1493 Waste Incineration System under NASA Contracts NAS2-4438 and NAS2-5442, sponsored by the NASA Ames Research Center. This process concept, shown schematically in Figure 1-3, was based upon automatic dehydration, pyrolysis and incineration of wastes produced by four men on a spacecraft mission. The input model used by this contractor was: 600 grams of fecal matter, 600 grams of urine distillate residue containing 50 percent solids, toilet tissue, and other miscellaneous wastes such as food scraps, plastic storage bags, hair, photo film, and fingernail clippings. The incinerator was initially designed to operate on a batch cycle, with all wastes collected in an incinerator canister. Further development work, under Contract No. NAS2-6386, involved an extension of program objectives to include the design of a zero-g waste transporter; development and integration of the GARD incinerator with commode developments supported by NASA; and the increase of the incinerator system's capacity to accomodate a six-man mission. The program efforts were concluded with the development of an operational specification for a baseline subsystem and the performance of a series of tests to evaluate the performance of the incinerator subsystem model.

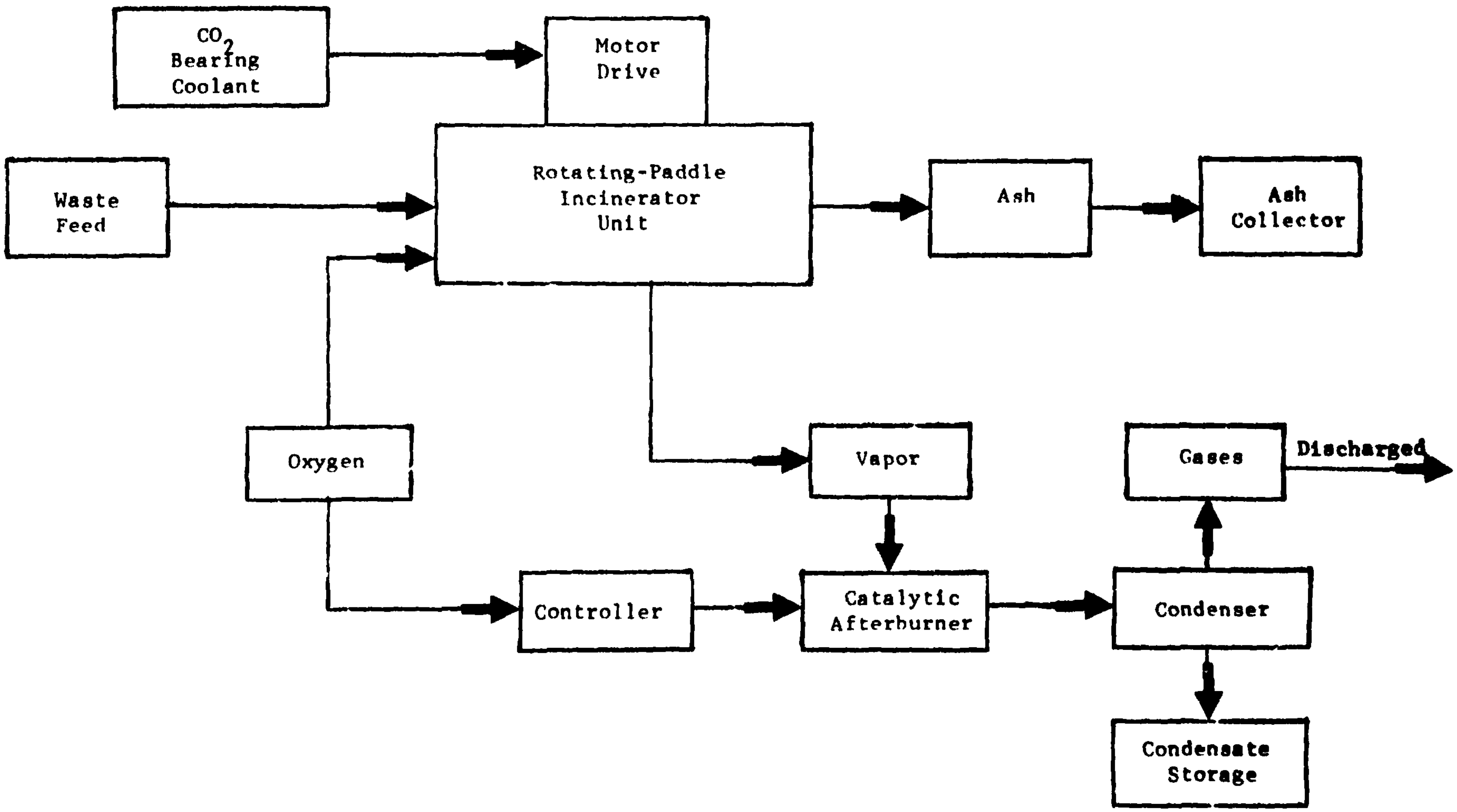



Figure 1-3. Schematic Diagram of GARD Dry-Incineration Process Concept

**1.4 Comparison of Contractors' Objectives:**

**Table 1-II provides a summary of contract objectives for water and waste reclamation programs initiated by the various NASA research centers. Some of the effort originated as early as 1966. The extension by NASA, several years later,** of contract objectives in design and testing resulted from a requirement, established by the Space Station Project Office and the Life Sciences Directorate, that the recovery of useful water and gaseous products be incorporated in the development of these processes.

Except for the G.E. RITE system development, subsystem integration and testing was not a technical objective. However, objectives did include a preliminary design of the system for purposes of evaluating subsystem components, weight, volume, size and system costs.

Early test data that were obtained for the processes were based on a "four-man system" objective which was directed toward the reduction and/or elimination of waste storage requirements and contamination of the space vehicle. Therefore, the extension of the design and testing objectives, specifically for the wet-oxidation and dry-incineration processes, imposed some constraints or limitations on the equipment capability and extent of test data on the oxidation steps by shifting emphasis to the development of other subsystem units.

This background information accounts for the Study Group's earlier observation, discussed in Section 1.2, that common design criteria and bases for data comparison among the three alternative processes do not exist. All of the contractors were not required to work toward the common specifications of a standardized input model, testing to completely characterize all input and output streams, or compatibility of product gases with the air revitalization subsystem of a spacecraft.

Table 1-II. Summary of NASA's Contract Objectives for Water and Waste Reclamation Programs.

| | Development and Testing | | | | | | | | | | | Extension Design and Testing | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Development Process | Laboratory Model | Engineering Model | Solid-waste Disposal | Useful Water | Useful Gases | Potable Water | Subsystem Integration | 4-man Capability | Overboard Dump | Batch-cycle Processing | Continuous Processing | 6-man Capability | No Overboard Dump | Recovery of Useful Water and Gases | Subsystem Components | Subsystem Integration |
| Wet Oxidation | X | | X | X | X | | | X | X | | X | X | X | X | X | X |
| RITE | | X | X | | X | X | X | X | X | | X | X | X | X | | |
| Dry Incineration | X | | X | X | X | | | X | X | X | | X | X | X | X | X |

## 2. METHOD OF APPROACH

**The method of approach that was chosen by the Study Group to accomplish the objectives and scope of study described in Section 1 consisted of five principal elements (or subtasks): (1) establishment of an adequate data base and the analysis of the data base and the current status of technology for the three alternative processing methods of interest; (2) development of a standardized input and output model as a common basis for comparing and evaluating the alternative processes; (3) development of completed and scaled-up flowsheets for the alternative processes to satisfy the standardized input and output models and performance criteria; (4) comparison and tradeoff evaluation of the completed and scaled-up processes; and (5) development of conclusions and recommendations.** The objective, rationale and general activity components associated with each of these subtasks are outlined below. Detailed procedures and results are presented in corresponding subsequent sections of this report.

### 2.1 Establishment and Analysis of the Data Base:

Initially it was necessary for the Study Group to develop an adequate understanding of the actual work performed and results obtained to date by each of the contractors responsible for the development of the three alternative processes, in terms of the various contract objectives discussed in Section 1. This subtask also included the definition of requirements to complete the flowsheets for each process and develop a common basis (i.e., input capabilities and output specifications) for the evaluation of system performance and tradeoff comparisons among the alternative processes. The procedure used to accomplish these objectives included the following steps:

(1) An initial, detailed review of contractors' reports and unpublished data furnished early in this study program by NASA and the contractors, and supportive chemical process literature.

(2) Visits at contractors' facilities to meet with their project-team representatives, discuss project results, clarify questions identified by the Study Group from the review of reports and data, and observe experimental hardware (the list of visits and discussion summary for each are presented in Appendix I).

(3) Study Group work sessions, interspersed among the visits at contractors' facilities, to assess the data-base material, establish the basis for further discussions with contractor and NASA representatives, and formulate the specifications required by the Study Group to accomplish the development of the common basis for comparing the alternative processes.

(4) The analysis of contractor data ("as-tested"), to determined consistency and credibility of the reported data (as well as the demonstration of technical feasibility), by performing detailed material and energy balances for each test system.

Step (4), above, required a very significant effort by the Study Group. This stemmed from the general unavailability of as-tested data, for all three candidate processes, for scaling the test systems to a standardized complete process that would satisfy the performance requirements upon which the Study Group's investigation was based (as discussed in Section 1) and permit a common basis for comparison of the alternative processes. Auxiliary (not tested) process units had to be identified and characterized to adequately complete the process flowsheets for the standardized performance basis for comparison. The material and energy balances also served the very important role of answering questions concerning the demonstrated ability of the test systems to accomplish their design objectives; and, if the systems did not meet these objectives, the reasons that could be determined and recommendations for further testing on design improvements that might lead to better performance. Therefore, the Study Group determined that this material and energy balance development effort would provide a very valuable contribution to the overall understanding of system functions and performance evaluation, in addition to a basis for the scale-up to the standardized case (size, input, output criteria) for each alternative process.

Details of the procedure and results associated with this subtask are presented in Section 3,of this report.

## 2.2 Development of a Standardized Input Model.

Based upon both the preliminary observations by the Study Group before this investigative program was initiated (discussed in Section 1) and the Group's data base analysis on the subtask activity described in Section 2.1, it was determined that the design guidelines used by the three contractors for the development of their respective processes varied significantly. The variances occurred principally in the values the contractors chose for the input models for urine, fecal and trash compositions. In addition, the criteria designated by NASA Headquarters which formed the basis for this investigative program included the requirements for handling wash water, providing for maximum recovery or storage of all products (zero-dump criteria), and concommitantly assuring compatibility of the product streams with other spacecraft life-support subsystems (air revitalization, potable water storage,etc.).

Therefore, it was necessary for the Study Group to develop standardized, common input and output specification models as the basis for comparing the alternative processes (on an essentially one-to-one basis). It was very apparent, from the analysis of the as-tested results compiled during the data-base review step, that auxiliary processing units (not actually used or tested to date by the contractors) of various types would have to be identified and sized by the Study Group to complete the flowsheets for the alternative processes such that each would meet these standardized input and output (i/o) specifications. The grouping of types of auxiliary process units required would, of course, vary among the alternative systems, depending upon the extent to which the current contractor system designs can satisfy the standardized i/o specifications. Hence, the standardized i/o model was developed by the Study Group to provide the basis for completion of the process flowsheets and scale-up of these completed flowsheets to the six-man crew capacity requirements, as necessary. This subtask was conducted essentially in parallel with the data-base subtask described in Section 2.1.

The approach used by the Study Group to accomplish this subtask involved the compilation, review and condensation of appropriate sources of data for spacecraft waste inputs and atmosphere and water quality standards. Best (i.e., most current and/or most credible) data for urine, feces, washwater, trash, and wet-food wastes compositions were selected from source data such as those reported for manned-chamber tests, manned space missions and NASA's advanced mission planning studies. These sources, the detailed procedures used in selecting "standardized" values from these sources, and the standardized values that were selected are summarized in Section 4 of this report. Values for cabin-atmosphere and potable water purity specifications were derived from standards generated for NASA by the National Academy of Sciences.

**2.3 Development of Standardized Flowsheets as a Common Basis for Process Evaluation**:

As was discussed above in Section 2.2, it was necessary for the Study Group to develop complete flowsheets for each alternative process, using the standardized input and output specifications (discussed in Section 2.2 also) as the basis for completing the flowsheet (beyond the as-tested versions) and sizing the various component units of the flowsheet. In general, scale-up of previously-tested components was based upon performance data for the as-tested versions of the units and appropriate scale-up factors developed from accepted engineering practice by the Study Group. Sizes of auxiliary units (added to flowsheets by the Study Group to complete them for the standardized requirements) were estimated by the Study Group from reported design data for similar units. Although actual test data were used for contractor process units to the maximum possible extent, occassionally it was necessary for the Study Group to use available test data only as estimates of probable test results for the as-tested apparatus. This was necessitated in cases where actual testing did not include the processing of material present in the Study Group's standardized input model.

The product of this subtask effort was a set of process flowsheets, for the three processing alternatives which offered reasonable promise of being able to technically satisfy the standardized input/output models. Where auxiliary units had to be added to a given flowsheet, the Study Group attempted to select approaches that had the greatest potential for successful performance in such applications. To the extent possible, auxiliary units were also selected to impose the least penalties on the process to which they were added.

Details of the development of these "standardized flowsheets" also are presented in Section 4 of this report.

## 2.4 Comparison of Process Alternatives and Tradeoff Analysis:

The principal objective of this subtask was the analysis of the data compiled or developed on the subtasks described in the above subsections to effectively compare and evaluate the three alternative processing methods and establish a basis for recommendations concerning further developmental efforts on these methods. A tradeoff evaluation was of particular interest to NASA Headquarters, with a specific emphasis on the standardized input/output models as the basis (but with consideration also of effects of certain variances in these models as a characterization of sensitivity of the evaluation model).

Subtask objectives were accomplished by the procedure outlined below:

(1) The tradeoff model was established based upon an analysis of the scope of the required evaluation, the identification of key parameters to be considered and conversion factors for penalty assessments (in terms of equivalent system weight), and a review and assessment of conventional tradeoff models used for the comparison of spacecraft life-support systems alternatives.

(2) Each of the alternative processes was analyzed, component by component, to establish best-estimate values for weight, volume, power and thermal penalties, all in terms of an equivalent-weight parameter using the conversion factors that were established on this subtask.

(3) An evaluation "scoring" form was developed as a tool for applying the tradeoff model to the comparison of relative advantages and disadvantages associated with each of the alternative processes.

(4) The Study Group prepared a concensus rating for the alternative processes using the scoring form, penalty values (from the earlier step on this subtask), and judgment derived from the data-base, as-

tested experience information and the standardized flowsheet subtasks as the basis for scoring. Initially, this scoring was accomplished for a baseline mission model.

(5) Results of the tradeoff (sccring) evaluation were analyzed for significance and sensitivity. Sensitivity was estimated from a comparison of baseline results with results obtained for alternative mission cases.

Details of the tradeoff analysis for the baseline case, and a summary of the results that were obtained,are presented in Section 5 of this report. Results of the consideration of alternative (other than baseline) cases are presented in Section 6.

2.5 Development of Conclusions and Recommendations:

From the results of the previous subtasks, comprehensive recommendations were formulated to guide NASA in planning and managing continued technology development for spacecraft water and waste management systems. These recommendations focused on (1) design factors which will require better clarification through more incisive study of process performance characteristics; (2) design alternatives that offer promise of improved performance to satisfy requirements of the standard input/output model; and (3) criteria for the selection of complete water/waste management systems to best satisfy some typical mission-application requirements. These conclusions and recommendations are presented in Section 7.

## 3. ANALYSIS OF AS-TESTED SYSTEMS

As discussed in the preceding section, the objective of one of the first tasks of this study was to ascertain what systems and feeds had been tested and what experimental data were available. These data were to be used to develop a material and energy balances for each as-tested system. The material and energy balances were needed to evaluate the adequacy and consistency of the experimental results, to evaluate the credibility of technical feasibility, and to establish a basis for scale-up of the as-tested systems to the standardized input model.

For each system, the Study Group found insufficient experimental data available for adequate closure of material and energy balances. In general, the scope of the contractors' program did not include material and energy balanced closure as an objective; and, consequently, the experimental procedures did not include thorough analysis of inputs and outputs; nor did they necessarily include accurate measurement of all input and output flow rates. In many cases, output compositions were determined only for a small number of grab-samples from exit streams which varied with time due to the batch nature of the experiments.

Due to the inadequacy of the experimental data the Study Group had to make numerous assumptions and approximations to force closure of the material and energy balances of the as-tested cases.

None of the contractors measured elemental compositions of urine, feces, trash, or washwater feed. Thus, the Study Group had no alternative but to estimate elemental breakdowns; the values used for these input estimates are those adopted by the Study Group for the standardized input model and are given in Section 4.1.

In one case, the Lockheed Wet-ox system, the as-tested feed was significantly different from the contractor's design objective. In particular, the reactor was designed to process a feed of urine, feces, trash, and washwater. The only experimental tests in which output compositions were available (i.e., the as-tested case) used urine and feces as inputs. The Study Group decided to estimate material and energy balances for a hypothetical case in which the feed would correspond to that stated in the contractor design objective (the CDO case). It was assumed that the experimental system would adequately handle this entire feed. This hypothetical CDO case was used as a basis for scale-up to the standardized wet-ox model, as discussed in Section.

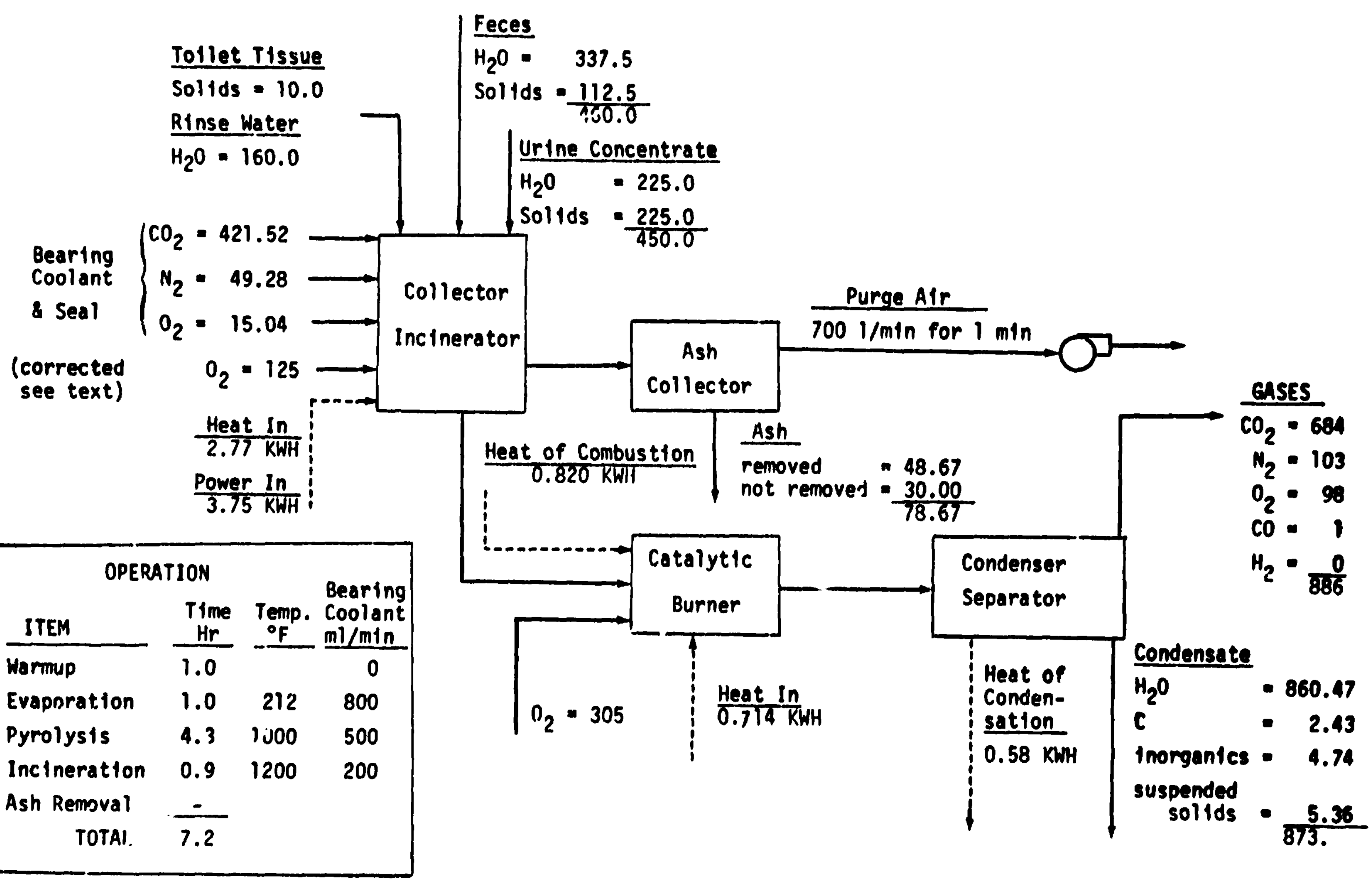
3.1 GARD Mass and Energy Balance as Tested:

The GARD process is basically an incinerator that was originally designed to handle principally metabolic wastes. The only test data available are for the incineration of a slurry of feces, toilet tissue, and urine concentrates. A mass and energy balance of the process is shown in Figure 3-1 and Table 3-I. The output figures were supplied by GARD and were obtained by averaging the measured quantities from tests 3, 4 and 5 reported in Reference 4.9 (at the end of Section 4).

The total input weights of urine, feces, toilet paper and rinse water were measured by GARD during these tests, but no compositional data were obtained. The compositions of urine and feces were taken as those developed for the standardized input model (see Section 4.1).

GARD calculated that an average of 520 g. of $CO_2$ was supplied to the bearing and seal during the three tests. In the calculation, a total volume of gas was measured and the stream was assumed to be 100% $CO_2$. Based on

(all units in grams except as noted)




OPERATION

| ITEM | Time Hr | Temp. °F | Bearing Coolant ml/min |
|---|---|---|---|
| Warmup | 1.0 | | 0 |
| Evaporation | 1.0 | 212 | 800 |
| Pyrolysis | 4.3 | 1000 | 500 |
| Incineration | 0.9 | 1200 | 200 |
| Ash Removal | - | | |
| TOTAL | 7.2 | | |

Figure 3-1. GARD Mass and Energy Balance as Tested.

TABLE 3-I. GARD Mass Balance as Tested (corrected, see text)

| INPUT | Total | C | N | O | H | S | inorganic ash |
|---|---|---|---|---|---|---|---|
| URINE SOLIDS | 225.0 | 41.18 | 49.32 | 38.74 | 9.14 | 0.81 | 85.95 |
| FECES SOLIDS | 112.5 | 76.20 | 4.50 | 13.20 | 13.20 | 0.32 | 5.10 |
| TOILET TISSUE | 10.0 | 4.44 | | 4.90 | 0.62 | | |
| $H_2O$ | 722.5 | | | 642.22 | 80.28 | | |
| $O_2$ | 430 | | | 430.00 | | | |
| $CO_2$ + AIR | | | | | | | |
| $CO_2$ | 421.52 | 114.96 | | 306.56 | | | |
| $N_2$ | 49.28 | | 49.28 | | | | |
| $O_2$ | 15.04 | | | 15.04 | | | |
| TOTAL | 1985.84 | 236.78 | 103.1 | 1450.66 | 103.24 | 1.13 | 91.05 |
| OUTPUT | | | | | | | |
| gas: $CO_2$ | 684 | 186.54 | | 497.45 | | | |
| gas: $N_2$ | 103 | | 103.00 | | | | |
| gas: $O_2$ | 98 | | | 98.00 | | | |
| gas: CO | 1 | 0.43 | | 0.57 | | | |
| gas: $H_2$ | 0 | | | | | | |
| Condensate: $H_2O$ | 860.46 | | | 764.85 | 95.61 | | |
| Condensate: Total Carbon | 2.43 | 2.43 | | | | | |
| Condensate: Inorganic Salt | 4.74 | | | | | | 4.74 |
| Condensate: Suspended Solids | 5.36 | | | | | | 5.36 |
| ASH REMOVED | 48.67 | | | | | | 48.67 |
| ASH IN SYSTEM* | 30. | | | | | | 30. |
| TOTAL | 1837.66 | 189.4 | 103.00 | 1360.87 | 95.61 | NO DATA | 88.77 |
| (input - output)Δ | +148.18 | +47.38 | -0- | +89.83 | +17.63 | | +2.88 |
| (input - output)% | +7.5 | +20.0 | -0- | +6.2 | +17.0 | | +2.5 |

* GARD estimate, personal communication

this assumption, the mass balance showed the nitrogen output to be approximately 100% more than the nitrogen input. GARD felt that this was too large a discrepancy to be accounted for by the normal variations encountered in the composition of urine and feces. Their best explanation is that there must have been an air leak into the $CO_2$ supply system. Assuming this to be true, and that the measured volume of bearing supply gas is accurate, but the composition was $CO_2$ and air, not pure $CO_2$, the gas stream composition was calculated to obtain a nitrogen balance as follows:

| | | $CO_2$ | $N_2$ | $O_2$ | TOTAL |
|---|---|---|---|---|---|
| Original assumption (g-mole) | $\frac{520}{44}$ = | 11.81 | 0 | 0 | 11.81 |
| Nitrogen required to balance input & output (g-mole) | $\frac{49.28}{28}$ = | | 1.76 | | |
| Oxygen contained in air with nitrogen (g-mole) | $\frac{1.76}{3.76}$ = | | | 0.47 | |
| New assumption (g-mole) | | 9.58 | 1.76 | 0.47 | 11.81 |
| New assumption (g) | | 421.52 | 49.28 | 15.04 | |

This assumption was used to compute the mass balance shown in Figure 3-1 and Table 3-I. In this mass balance there is an output deficit of up to 20% in each category, which is reasonable considering that the composition of the urine and feces inputs was assumed rather than measured. There are several obvious explanations for output deficits including the following:

1) The urine and feces contained less solids than assumed;
2) The measured amount of bearing gas was erroneously high;
3) The final ash contained some carbon;
4) More ash remained unrecovered from the system than the amount reported.

The stoichiometric amount of oxygen required to combust all of the carbon and hydrogen in the input was computed as follows:

| ASSUMPTIONS | H or C in Solids, g | $O_2$ Required, g |
|---|---|---|
| $C + O_2 \rightarrow CO_2$ | 121.82 | 324.85 |
| $2H + ½O_2 \rightarrow H_2O$ | 22.96 | 183.68 |
| O in solid feed | | - 56.84 |
| | TOTAL | 451.67 |

The oxygen supplied for combustion was 430 + 15.04 = 445 grams. The apparent amount of oxygen actually used in combustion (including oxygen in solids) can be determined from the output figures of the mass balance as follows:

| COMBUSTION PRODUCTS | | $O_2$ in combustion products, g |
|---|---|---|
| $CO_2$ = 684 - 421.52 = 262.48 | $\times \frac{32}{44}$ = | 190.89 |
| CO = 1 | $\times \frac{16}{28}$ = | .57 |
| $H_2O$ = 860.46 - 722.5 = 137.96 | $\times \frac{16}{18}$ = | 122.63 |
| | TOTAL | 314.09 |

This is less than the amount of $O_2$ required to combust the input products by 138 grams or 30 percent. This suggests that there were uncombustible or partially oxidized organic output products that escaped measurement during the test. It is concluded from the analysis above that the GARD system was actually oxidizing approximately 20 to 30 percent fewer solids than the input assumptions show in the mass balance. This deficiency must be taken into account when scaling up from the "as tested" mass balance to the "standard" mass balance.

To improve the accuracy of the mass balance and to ascertain more accurately the actual capacity of the GARD incinerator, the ash should be analyzed for carbon content, the water condensate should be analyzed for organics, and the off gas should be analyzed for partial oxidation products. It should be noted that until a satisfactory closure of the oxygen balance is obtained, the efficiency of the catalytic oxidizer cannot be ascertained within a satisfactory degree of confidence.

The heat and power requirements for the GARD as-tested system, as determined from GARD personnel, are as follows: catalytic burner, 714 w-hr; incinerator, 2770 w-hr; blowers and paddle, 3750 w-hr; and heat of combustion, 820 w-hr.

3.2 G.E. Mass and Energy as Tested:

The data base used for the analysis was obtained from references 4.8 4.10 and 4.11. Most of the results came from the 10- and 180-day tests conducted by G.E. (Ref. 4.8). Since detailed listings of inputs were not available, it was assumed that the as-tested inputs were, on the average, consistent with the design inputs given in Section 4.1. These input requirements were followed as closely as possible by G.E. (Ref. 4.11).

Feces: 1.2 lb/day

Urine: 14.0 lb/day

Trash: 1.2 lb/day

Wash water: 24.0 lb/day

ECS condensate: 20.0 lb/day

A schematic of the system is shown in Figure 3-2. In addition to the inputs listed above, oxygen was fed to the catalytic oxidizer (stream 6) and incinerator (stream 7), and nitrogen was used to purge the incinerator

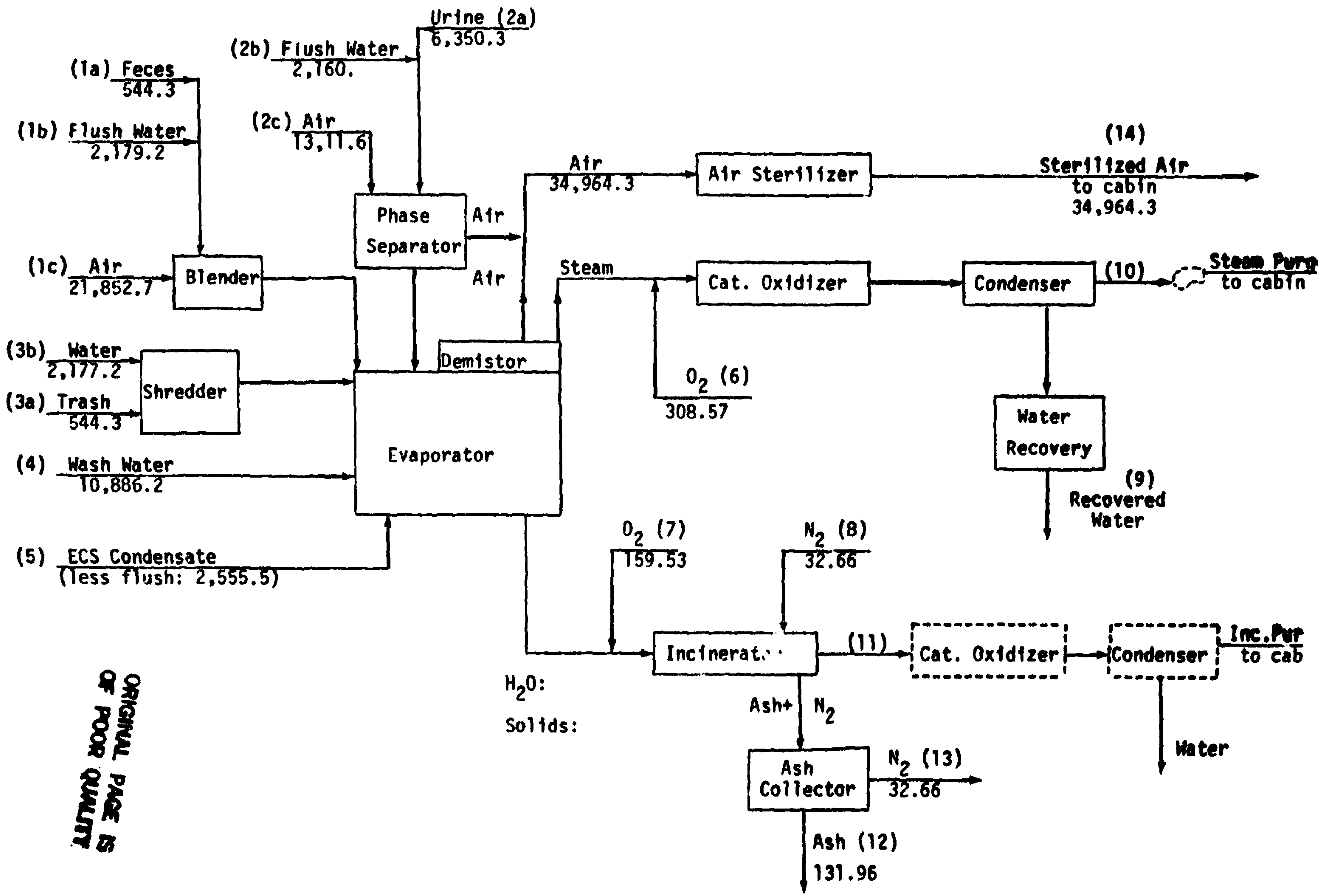



Figure 3-2. Schematic of G.E. RITE WMWS.

(stream 8). The subsystem components shown by dashed boxes in Figure 3-2 were not used by G.E.; these components were identified during our analysis as additions necessary to achieve zero-dump requirements.

The outputs shown in Figure 3-2 are streams 9 through 14. As the original design basis did not call for zero dump, the experimental program did not involve monitoring of all exit streams. The impurities in the recovered water (stream 9) were monitored periodically; a few grab-samples of the catalytic oxidizer vent gas (stream 10) and the incinerator off-gas (stream 11) were available. No attempt was made to determine quantitatively the ash collected (stream 12), although a few tests were performed to determine the ash content of dry solids feed.

To determine the consistency of the experimental results, the Study Group attempted to determine the extent to which the experimental results could be used to close the mass balance. The following procedure was used:

1. Inputs. The average daily inputs were broken down into water, organics (C,H,O,N,S), inorganics (salts and ash), air, oxygen, and nitrogen. (See Tables 3-II and 3-III). The sum of the liquid and solid inputs was taken as the evaporator feed.

2. Evaporator Outputs. The evaporator splits the liquid and solid feeds into a vapor fraction (mostly steam) which is the catalytic oxidizer feed, and a dense slurry fraction, which is the incinerator feed.

   a. Vapor Fraction. In theory, the composition of the vapor fraction leaving the evaporator can be determined from the analyses of the condenser off-gas (stream 10) and the recovered water (stream 9). As described in a subsequent section, this

TABLE 3-II. G.E. INPUTS (As-Tested*)
(grams/day)

| Stream No. | Item | Total Inputs | Air (flush) | $H_2O$ | Total Solids | C | N | O | H | S | Ash |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2a,b,c | Urine | 21,621.9 | 13,111.6 | 8,282.3 | 228.0 | 41.68 | 49.95 | 39.22 | 9.26 | 0.83 | 87.06 |
| 1a,b,c | Feces | 24,576.2 | 21,852.7 | 2,587.4 | 136.1 | 92.17 | 5.44 | 15.96 | 15.96 | 0.37 | 6.16 |
| 3a,b | Trash | 2,721.5 | -0- | 2,177.2 | 544.3 | 466.52 | -0- | -0- | 77.78 | -0- | -0- |
| 5 | ECS Cond.** | 2,555.5 | -0- | 2,555.5 | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| 4 | Wash water | 10,886.2 | -0- | 10,831.8 | 54.4 | 34.47 | -0- | 19.96 | neg. | -0- | -0- |
| 6 | $O_2$ (Cat. Ox.) | 341.58 | -0- | -0- | -0- | -0- | -0- | ** (341.58) | -0- | -0- | -0- |
| 7 | $O_2$ (Incin.)* | 2,588.30 | -0- | -0- | -0- | -0- | -0- | *** (2,588.30) | -0- | -0- | -0- |
| 8 | $N_2$ (Ash Dump) | 32.66 | -0- | -0- | -0- | -0- | *** (32.66) | -0- | -0- | -0- | -0- |
| | TOTAL | 65,323.84 | 34,964.3 | 26,434.2 | 962.8 | 634.84 | 55.39 (32.66) | 75.14 (2,929.88) | 103.00 | 1.20 | 93.22 |

*$O_2$ input adjusted to zero dump requirement. Assumes 1.2 x theoretical $O_2$ required for complete oxidation of organics fed to incinerator.

**Total ECS Condensate feed = 9,071.9 g, of which 6516.4 g is used for flush water.

***Excluded from total solids summation.

TABLE 3-III. SUMMARY OF G.E. INPUTS (As-Tested*)
(grams/day)

| Input | Total | C | N | O | H | S | Ash |
|---|---|---|---|---|---|---|---|
| $H_2O$ | 26,434.2 | - | - | 23,497.07 | 2,937.13 | - | - |
| Solids | 962.8 | 634.84 | 55.39 | 75.14 | 103.00 | 1.20 | 93.22 |
| $O_2$* | 2,929.88 | - | - | 2,929.88 | - | - | - |
| $N_2$ | 32.66 | - | 32.66 | - | - | - | - |
| Air | 34,964.3 | - | 27,194.46 | 7,769.84 | | | |
| TOTAL | 65,323.84 | 634.84 | 27,282.51 | 34,271.94 | 3,040.13 | 1.20 | 93.22 |

*$O_2$ input adjusted to zero dump requirement. Assumes 1.2 x theoretical $O_2$ required for complete oxidation of organics fed to incinerator.

procedure could not be used because it predicts unrealistic organic concentrations in the evaporator vapor output. Furthermore, the condenser off-gas analyses are inconsistent with the recovered water analyses. These two streams should reach a liquid-vapor phase equilibrium in the condenser. If the condenser off-gas analyses were assumed to be correct, the impurity levels in the recovered water should be much higher than those reported. Thus, the condenser off-gas analyses were suspect and were deemed too unreliable to be used to back-calculate evaporator vapor output. Lacking better data, the only alternative was to estimate evaporator vapor output based on assumptions of the volatilities of the components fed to the evaporator. It was assumed that all of the urea plus 50% of the remaining non-ash solids of urine plus 50% of the non-ash solids of feces would be sufficiently volatile (as fed or through decomposition in the evaporator) to be carried over with the steam.

b. Slurry Fraction. Having estimated composition of the vapor fraction, the organic and inorganic components of the slurry fed to the incinerator were found by difference (i.e., evaporator feed less vapor output). The water content of the slurry was estimated from two independent observations made by G.E.: (1) the water losses from the incinerator were estimated to be about 1% of the total water input per incineration, with an average of 5 incineration cycles per day (Ref. 4.8); and (2) the incinerator feed was measured in one test and found to be about 50 wt-% water (Ref. 4.11). These two independent estimates differed by about a factor of 2. Consequently, an average of the two estimates was used.

3. <u>Incinerator Outputs</u> The incineration is actually a three-step batch process: the water is driven off, a portion of the organics are pyrolyzed, and then the remaining combustibles are oxidized with oxygen feed (stream 7). Since the G.E. system was not designed for zero dump, the extent to which organics were pyrolyzed or oxidized was immaterial in G.E.'s test program. In fact, we estimated the oxygen required to completely oxidize the organics fed to the incinerator and found that the actual oxygen fed was less than 10% of the theoretical requirement. In modifying the system to meet zero-dump requirements, it was assumed that oxygen would be fed in 20% excess above theoretical and that the off-gas would be processed in a catalytic oxidizer to ensure complete combustion.

Based on our analysis of the ash content of the total inputs to the system, we obtained an estimate of the ash output of the incinerator output. This value was approximately 10% of the total solids input. There is a significant discrepancy between this value and results reported by G.E.: "reduction in solid waste weight is greater than 95%" and "the ash is approximately 1% of the initial solid waste input weight" (Ref. 4.8).

A summary of the results of the system outputs is given in Table 3-IV.

Using the results of the mass balance as a basis, energy balances were made for each major piece of equipment. Independent estimates of heating requirements for the G.E. RITE system have been reported previously by McDonnell Douglas (Ref. 4.10).

## TABLE 3-IV. SUMMARY OF G.E. OUTPUTS
(grams/day)

| Stream No. | Item | Total | C | N | O | H | S | Ash |
|---|---|---|---|---|---|---|---|---|
| 14 | Air sterilizer | 34,964.3 | - | 27,194.46 | 7,769.84 | - | - | - |
| 12 | Ash | 93.22 | - | - | - | - | - | 93.22 |
| 13 | $N_2$ from ash collected | 32.66 | - | 32.66 | - | - | - | - |
| 10 | Condenser off-gas | 924.93 | 75.17 | 46.98 | 741.65 | 60.53 | 0.60 | - |
| 9 | Recivered water | 24,973.55 | - | - | 22,198.71 | 2,774.84 | - | - |
| 11 | Incinerator off-gas* | 4,335.19 | 559.66 | 8.45 | 3,561.74 | 204.74 | 0.60 | |
| | TOTAL | 65,323.85 | 634.83 | 27,282.55 | 34,271.94 | 3,040.11 | 1.20 | 93.22 |

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*$O_2$ input adjusted to zero-dump requirement. Assumes 1.2 x theoretical $O_2$ required for complete oxidation of organics fed to incinerator.

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The results are summarized in Table 3-V. In general, the two estimates were in good agreement. Where differences were significant, the Study Group elected to use what it considered to be the more accurate estimate (column 3).

Heat losses were determined by difference from heat inputs and heat requirements.

For the low-temperature heating loop, the input heat is used for the evaporator and the water storage tanks. Since the water storage tanks were not considered part of the waste management system, the heat input and losses charged to the G.E. RITE system were taken as a fraction of the total, the fraction corresponding to the ratio of evaporator heat to total heat requirements.

3.3 Lockheed Mass and Energy Balance, as Tested:

The wet-oxidation process for disposal of waste materials in space cabins differs from the other candidate processes in that "wet-ox" operates in a continuous mode, in aqueous environment, and at high pressure and temperature (2200 psia, 550°F). However, the fundamental thermodynamic cycle of water vaporization, combustion of organic matter, and gas clean-up is similar.

The contractor (Lockheed Missiles & Space Co.) chose a "standard" design based on a four-man crew, and assumed the human waste would consist of equal parts of urine and feces, at the rate of 3.2 lb urine per man-day with 5% solids and 0.35 lb feces per man-day with 25% solids, both with a 25% design margin. This was estimated to produce a feed flow rate of 5.5 cc/min with 6.5% solids (Ref. 4.12). These are reasonably consistent, but not identical. Therefore the fecal-urine design basis was used for the analysis of the "as-tested" case, i.e.,

## TABLE 3-V. SUMMARY OF ENERGY REQUIREMENTS (As-Tested)
(All numbers in kwhr)

| High Temperature (HT) Loop | BSSG Estimates | MCDAC(2) | Best estimates (used herein) |
|---|---|---|---|
| Air Sterilizer | 2.20 | 1.06 | 2.2 |
| Catalytic Oxidizer | 1.36 | 1.56 | 1.5 |
| Incinerator | 1.50 | 1.73 | 1.6 |
| Total HT Requirements | 5.06 | 4.35 | 5.3 |
| Total HT Inputs (420 w) | 10.1 | 10.1 | 10.1 |
| HT Loop Loses (by difference) | 5.04 | 5.75 | 4.8 |
| **Low Temperature (LT) Loop** | | | |
| Evaporator | 17.63 | 17.44 | 17.5 |
| Water Tanks | | 6.33 | |
| % of requirements used for evaporator = $\frac{17.44 \times 100}{17.44+6.33}$ = 73.4 | | | |
| Total L1 Input (1550 w) | | 37.20 | 27.3* |
| LT Loop Losses (by difference) | | 13.43 | 9.9** |

* 73.4% of 37.20 kwhr charged to evaporator

**73.4% of 13.43 kwhr charged to evaporator

Urine (3.2)(4)(1.25) = 16.0 lb/day

Feces (0.35)(4)(1.25) = 1.75 lb/day

The trash model (Ref. 4.1 and Table 4-V) was developed later, but has not been tested.

The as-tested inputs are shown in Table 3-VI, with the inputs broken down by elements on the basis of the Study Group's standardized composition models (see Section 4.1).

The gas input rate was designed to be 1.2 g $O_2$ per g solids (which is approximately the stoichiometric amount of $O_2$), but the as-tested $O_2$ rate was not directly measured; therefore, the as-tested $O_2$ input rate was reconstructed from the carbon balance, based on $CO_2$ and CO in the outlet gas and corrected for measured COD in the liquid effluent.

In the only long-term continuous test performed, lasting 100 hours, one gas sample was taken and analyzed at 72 hours, and liquid samples were taken and analyzed at 58 and 66 hours. The gas-phase composition is given in Table 3-VII, and the liquid-phase measurements in Table 3-VIII.

The oxygen supplied was estimated from the carbon balance by assuming that all C supplied was found in the following outputs: $CO_2$ and CO in the gas phase, and COD in the liquid phase (as fecal cellulosic material). Then with the data of Table 3-VI, the $O_2$ for combination with C and H, less the O in the organic feed gives the theoretical $O_2$. The actual $O_2$ supplied is estimated as the sum of $O_2$ found in exit $CO_2$, CO, free $O_2$, and the calculated $H_2O$ formed.

Table 3-VII reveals a large excess of oxygen, indicating that about three times the theoretical oxygen requirement was supplied (1175 sec/min supplied vs. 391.5 sec/min theoretical).

TABLE 3-VI

Input Quantities for Lockheed Wet Oxidation System, As-Tested
(Basis: 1 day)

| | Total | $H_2O$ | Total Solids | C | N | O | H | S | F | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| Urine | 7,257.6 | 6,974.5 | 283.1 | 51.8 | 62.0 | 48.7 | 11.5 | 1.0 | - | 108.2 |
| Feces | 793.8 | 585.1 | 208.7 | 141.4 | 8.3 | 24.6 | 24.6 | 0.57 | - | 9.4 |
| $O_2$ | (Unknown - est. 200% excess) | | | | | | | | | |
| | 8,051.4 | 7,559.6 | 491.8 | 193.2 | 70.3 | 73.3 | 36.1 | 1.6 | - | 117.6 |

## TABLE 3-VII

**Gas Analysis Taken from Test of the Continuous Wet Oxidation Process conducted by the Lockheed Missiles and Space Corporation. (Sample taken at 72 hours).**

| | |
|---|---|
| Carbon Dioxide | 16.7 % |
| Oxygen | 60.0 % |
| Nitrogen | 20.4 % |
| Carbon Monoxide | 0.18 % |
| Ammonia | 20 ppm |
| Oxides of Nitrogen | None |
| Oxides of Sulfur | None |
| Hydrogen Sulphide | None |
| Total Hydrocarbons | 0.115 % |
| Methane | 19 ppm |

TABLE 3-VIII

Reactor Effluent Water Characteristics from Test of the Continuous Wet Oxidation Process conducted by the Lockheed Missiles and Space Corporation

| Sample | 58 hours | 66 hours |
|---|---|---|
| o Effluent Water | | |
| Chemical Oxygen Demand ($mgO_2$/gm water) | 3.9 | 1.0 |
| Total Suspended Solids (% by weight) | 0.63 | 0.25 |
| o Filtered Effluent | | |
| Total Water Soluble Solids (% by weight) | 1.2 | 1.3 |
| pH | 8.4 | 8.4 |
| Total Alkalinity (mg/cc) | 14 | 10 |
| Conductivity | Infinite | Infinite |
| Total Nitrogen (mg $N_2$/gm water) | 9.3 | 8.0 |
| Ammonia Nitrogen (mg $N_2$/gm water) | 8.1 | 7.0 |
| Organic Nitrogen (mg $N_2$/gm water) | 1.2 | 1.0 |
| Dissolved Ions (% by weight) | | |
| Ammonia | 1.2 | 1.0 |
| Chloride | 0.39 | 0.38 |
| Sulphate | 0.05 | 0.05 |
| Phosphate | 0.02 | 0.02 |
| o Percent Reduction in COD | 93 | 98 |

The nitrogen measured in the outlet gas (Table 3-VII) is believed to come from the slurry feed tanks, which were pressurized under nitrogen atmosphere. Since the solubility of nitrogen in water at this pressure can account for only about 1% $N_2$ in the outlet gas, the nitrogen probably entered the reactor by physical entrainment, or else was introduced when one of the slurry feed tanks emptied. In the as-tested system, there was probably only a negligible contribution of $N_2$ from oxidation of ammonia N.

During the 100-hr continuous test performed by the contractor, 380 watt of power supplied the reactor to maintain the temperature at 550°F. Using the Study Group's estimate of the as-tested inputs (as given in Table 3-VI) and the measured off-gas composition (as given in Table 3-VII), an energy balance was reconstructed in the following manner. The heat losses from the reactor were estimated using a First Law balance around the open system of the reactor:

$$dU = dQ_{net} - dW + \sum_{in} H_{in} dN_{in} - \sum_{out} H_{out} dN_{out} \qquad (1)$$

where $U$ = internal energy of the reactor

$dU$ = 0 at steady state

$Q_{net}$ = net heat required to sustain the reactor at 550°F

$dW$ = PdV - work done by the reactor = 0

$H$ = specific enthalpy

$N$ = moles

On a basis of one day, the integrated form of Eq (1) is:

$$\begin{aligned} Q_{net} &= \sum_{out} H_{out} N_{out} - \sum_{in} H_{in} N_{in} \\ &= (H_{out} - H_{in})_W N_W \\ &+ (HN)_{CP_{out}} - (HN)_{CR_{in}} \\ &+ (H_{out} - H_{in})_I N_I \end{aligned} \qquad (2)$$

where subscript W = water

CP = combustion products

CR = combustion reactants

I = inerts (less water)

Noting that

$$(HN)_{CP_{out}} - (HN)_{CR_{in}} = [(HN)_{CP_{out}} - (HN)_{CP_{in}}] + [(HN)_{CP_{in}} - (HN)_{CR_{in}}]$$

$$= (HN)_{CP_{out}} - (HN)_{CP_{in}} + \Delta H_{combustion}$$

$$= (NCp)_{CP}(T_{out} - T_{in}) \qquad (3)$$

Eq (2) becomes

$$Q_{net} = (H_{out}-H_{in})_W N_W + [(NCp)_{CP} + (NCp)_I]\,(T_{out}-T_{in}) + \Delta H_{combustion} \qquad (4)$$

Evaluating the first term of Eq (4) from the Steam Tables,

$$(H_{out}-H_{in})_W N_W = (H_{550°F,sat} - H_{77°F,sat})N_W$$

$$= \frac{(550 - 45)}{1.8}\ \frac{cal}{g} \times 7560\ \frac{g}{day}$$

$$= (280)(7560)\ cal/day$$

$$= 2.12 \times 10^6\ cal/day$$

To estimate the second term of Eq (4) the carbon balance is used with Table 3-VII to estimate the moles of products and inerts leaving the reactor:

$$N_{CP+I} = \frac{1}{.167 \; \frac{\text{mol } CO_2}{\text{mol out}}} \times \frac{193.2}{12} \; \frac{\text{atm C in}}{\text{day}} = 96.4 \; \frac{\text{mol out}}{\text{day}}$$

Using an average Cp of 8 cal/g-mol°C, the second term is:

$$[(NCp)_{CP} + (NCp)_I](T_{out}-T_{in}) = (N_{CP+I}) \bar{C}p \; (T_{out}-T_{in})$$

$$= (96.4) \frac{\text{g-mol}}{\text{day}} \times 8 \frac{\text{cal}}{\text{g-mol}°C} \times (\frac{550-77}{1.8})°C$$

$$= 0.20 \times 10^6 \text{ cal/day}$$

The third term of Eq (4) is estimated using a value of 2,030 cal/g-solids as the heat of combustion, which is typical of the lower heating value of a municipal solid waste.

$$\Delta H_{combustion} = -2,030 \frac{\text{cal}}{\text{g-solids}} \times 491.8 \frac{\text{g-solids}}{\text{day}}$$

$$= -1.00 \times 10^6 \frac{\text{cal}}{\text{day}}$$

Thus,

$$Q_{net} = (2.12 + .20 - 1.00) \times 10^6 \text{ cal/day}$$

$$Q_{net} = 1.32 \times 10^6 \text{ cal/day} = 62.9 \text{ watt}$$

Since the input heat was measured as 380 watt, the reactor losses are:

$$Q_{loss} = Q_{input} - Q_{net} = (380 - 62.9) \text{ watt}$$

$$Q_{loss} = 317 \text{ watt}$$

The heat rejected to the environment is the sum of the reactor losses plus the heat rejected in cooling the products back to ambient:

$$Q_{rejected} = Q_{loss(reactor)} + Q_{cooling(products)}$$

where $Q_{cooling(products)} = (H_{550^{\circ}} - H_{77^{\circ}})_W N_W$

$$+ (N_{CP+I}\overline{C}p)(T_{out} - T_{ambient})$$

$$Q_{cooling(products)} = [2.12 \times 10^6 + .20 \times 10^6]$$

$$= 2.32 \times 10^6 \text{ cal/day}$$

$$\approx 112 \text{ watt}$$

Therefore,

$$Q_{rejected} = 317 + 112 = 429 \text{ watt}$$

The "as-tested" system, described above, was designed to process significantly larger quantities of waste than that used in the contractor's 100-hr test. In particular, the system was designed to process the inputs listed in Table 3-IX, which is the contractor's design objective (CDO). Since the material and energy balances of the "as-tested" system were to be used as a basis for scale-up to the standardized input model, the Study Group concluded that the Lockheed system would be unduly penalized if scale-up were to be based on the "as-tested" inputs. Therefore, the Study Group decided to give Lockheed the benefit of the uncertainty by assuming that the Lockheed system, as built, would adequately handle the CDO input model as given in Table 3-IX. Simultaneously, the Study Group recommends that

TABLE 3-IX

Input Quantities for Lockheed Wet Oxidation System, CDO-Basis

(Basis: 1 day)

| | Total | $H_2O$ | Total Solids | C | N | O | H | S | F | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| Urine | 7,257.6 | 6,974.2 | 283.1 | 51.8 | 62.0 | 48.7 | 11.5 | 1.0 | - | 108.2 |
| Feces | 793.8 | 585.1 | 208.7 | 141.4 | 8.3 | 24.6 | 24.6 | 0.6 | - | 9.4 |
| Trash | 1,632.0 | - | 1,632.0 | 977.4 | - | 475.8 | 144.6 | - | 34.2 | - |
| Wet Food | 362.0 | 241.3 | 120.7 | 54.0 | 5.0 | 36.0 | 6.8 | - | - | 19.0 |
| Flush Water | 7,560.0 | 7,560.0 | - | - | - | - | - | - | - | - |
| Oxygen | | | | | | 5,020.4 | | | | |
| | 17,605.4 | 15,360.5 | 2,244.5 | 1,224.6 | 75.3 | 5,605.5 | 187.5 | 1.6 | 34.2 | 136.6 |

the Lockheed system be tested with the CDO input model to verify this assumption. Furthermore, in subsequent testing of the Lockheed system, it is recommended that the analytical effort be expanded substantially. Specifically, frequent sampling and more detailed analyses of all inputs, off-gases, and product water should be instituted. More attention should be paid to closing the elemental material balances (e.g., the ash should be analyzed for carbon content).

The hypothetical CDO system is shown in Figure 3-3. The as-tested system included only a slurry supply system, the reactor, and a dry boiler. Other elements that are required to form a complete continuous system for space-cabin application are included in Fig. 3-3 as blocks enclosed in dashed lines.

Some elements have been separately tested. These include the trash grinder, slurry holding tanks (and pumps), and the vapor compression still. These elements are assumed to be sufficiently developed for inclusion in a functional continuous wet oxidation system.

However, the elements shown as "condenser" and "catalytic oxidation" have not been sufficiently developed to permit their application to the system, and they are hypothetical elements of the system.

The reactor discharges a hot, high-pressure mixture which should be used to provide preheat to the input stream. However, a heat exchanger for this purpose has not been developed. Such an exchanger would logically serve for blowdown and condensation of the reactor effluent, and therefore it is called the "condenser" in the hypothetical Contractor Design Objective (CDO) system postulated by the Study Group (in order to establish material and energy balance for the wet-ox process).

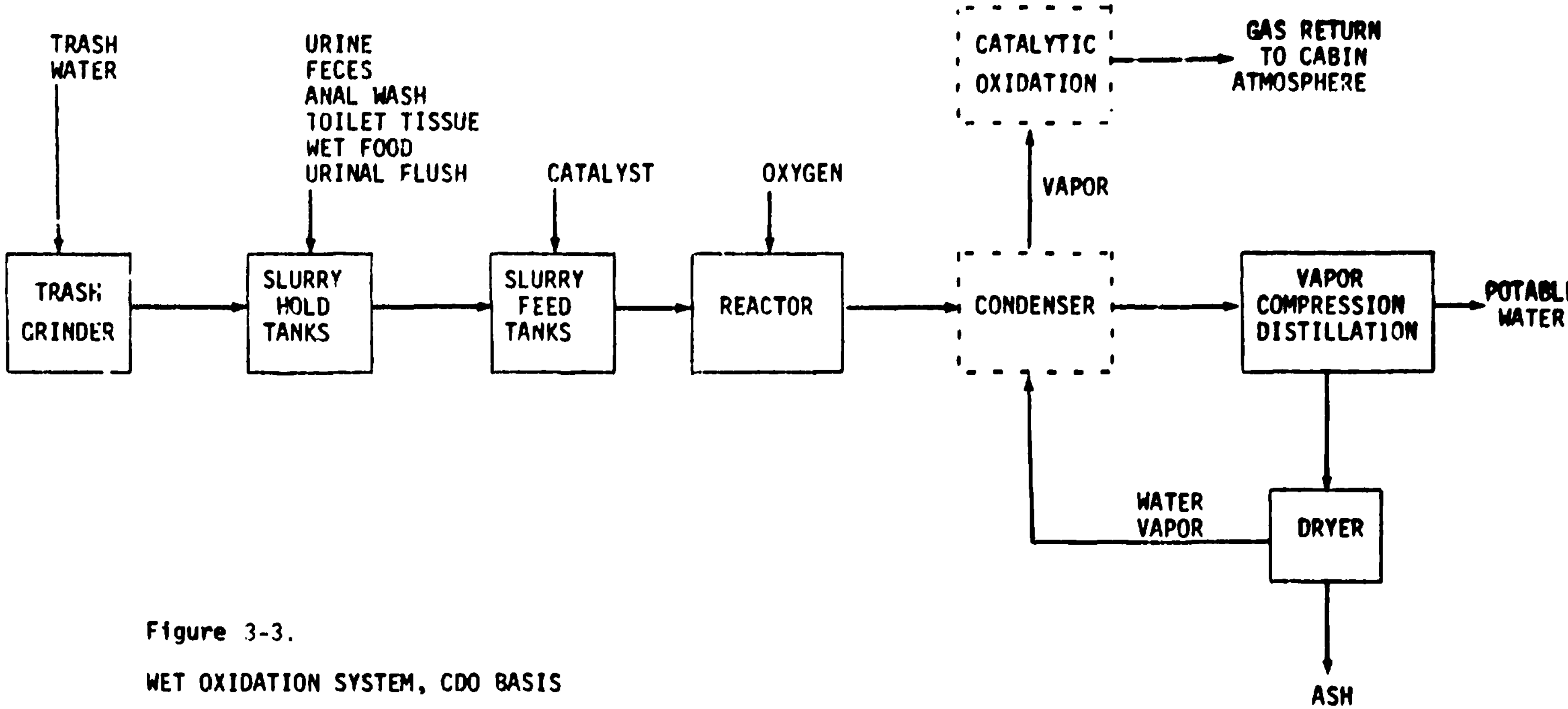


Figure 3-3.

WET OXIDATION SYSTEM, CDO BASIS

J THE ACTUAL 100-HR TEST, THE EFFLUENT FROM THE REACTOR WAS FLASHED TO THE ATMOSPHERE, AND THE LIQUID RESIDUE WAS SENT TO THE DRY BOILER.

THE VAPOR COMPRESSION DISTILLATION SYSTEM HAS NEVER BEEN COUPLED DIRECTLY TO THE WET OXIDATION SYSTEM.

The contractor envisioned that trash, food wastes, and flush water would be supplied to the wet oxidation system in actual use, in addition to human wastes. The trash model is shown in Table 3-IX. The wet food amounts to 362 lb per day, and flush water is 2 gallons (7560 cc) per day.

When these inputs are included, the CDO system is obtained as shown in Table 3-IX. The oxygen required for combustion of this mixture is calculated on the basis of a 20% excess of $O_2$ above the theoretical requirement, including the oxidation of $NH_3$ to $N_2$.

When this mixture is subjected to oxidation, the theoretical exit gas analysis (measured at 70°F) is

| | |
|---|---|
| $CO_2$ | 75.9% |
| $O_2$ | 19.5 |
| $H_2O$ | 2.6 |
| $N_2$ | 2.0 |
| | 100.0% |

Other gases are assumed to make an insignificant contribution. Sulfur is assumed to be oxidized to sulfate ion.

The increase in inputs in the CDO case, with respect to the as-tested case, results in a reduction of the residence time to 32 minutes (based on combined liquid and gas throughput, and assuming that the phases are perfectly mixed, taking no credit for gas solubility). This is believed to be approximately the minimum necessary for satisfactory elimination of organic material in a wet oxidation process.

An estimate of the heating requirements for the hypothetical CDO system was made by following the same procedure used in the "as-tested" case, above. The results are as follows:

$$Q_{net} = 280 \times 15{,}360.5 + 356.85 \times 8 \times (550-77)/1.8$$

$$- 2{,}030 \times 2{,}244.5 \text{ cal/day}$$

$$= (4.30 + .75 - 4.56) \times 10^6 \text{ cal/day}$$

or $Q_{net} = 0.49 \times 10^6 \text{ cal/day} = 490 \text{ kcal/day}$

Assuming the input can be reduced to 200 watt by minimizing heat losses from the reaction,

$$Q_{input} = 200 \text{ watt} \quad 4{,}128 \text{ kcal/day}$$

$$Q_{loss} = 4{,}128 - 490 = 3{,}640 \text{ kcal/day}$$

$$Q_{cooling(products)} = (4.30 + .75) \times 10^6 = 5.05 \times 10^6 \text{cal/day}$$

or $Q_{cooling(products)} = 5{,}050 \text{ kcal/day}$

$$Q_{rejected} = 3{,}640 + 5{,}050 = 8{,}690 \text{ kcal/day}$$

The analysis reported above makes clear that more data are required in order to permit confident estimates of the performance of the wet oxidation system under space flight conditions.

In particular, the lack of adequate regulation of oxygen input is an omission that needs attention. The metering of a gas at constant rate, at a high pressure, subject to fluctuations in back pressure, is obviously a difficult procedure that may require equipment of special design. Nevertheless, accurate metering is essential to assure that (a) sufficient oxygen is provided and (b) that the system is not flooded with gas to the detriment of oxidizing contact time in the reactor.

It is clear from analysis of the CDO system that the addition of trash, wet food, and flush water to the "as-tested" system drastically changes the demands upon the reactor. For example, the total input is approximately doubled, and the carbon input is raised more than six-fold. The effect of these alterations in the "as-tested" system cannot be predicted, and can only be resolved by further tests.

# 4. EXTRAPOLATION TO A STANDARDIZED MODEL

## 4.1 Basis for the Standardized Input Model:

A number of different water and waste input models have been used by various NASA contractors over the years. The models are periodically revised as new data become available from manned chamber tests, manned space missions, and advanced mission planning activities. A summary of the models most pertinent to this study are shown in Table 4-I. The last column of Table 4-I is the model that was selected for this study. A compositional breakdown for this model is given in Table 4-II. The rationale for the selection of this particular model is discussed in the following paragraphs. In general, the values selected represented the best existing data and the latest NASA thinking at the time they were chosen.

URINE: The total amount of urine was based on the Lockheed model (see Reference 4.1) which reflected the latest JSC thinking at the time of this study. The solids content of urine was based on 90-Day Test data (see Reference 4.2) which is the best data available. The composition of urine solids (C,N,O,H,S,ash) was obtained from Reference 4.3 which was based on original experimental work as well as literature surveys. The compositional breakdown for urine is shown in Table 4-III.

FECES: The total amount of feces was based on the Lockheed model (see Reference 4.1) which reflected the latest JSC thinking at the time of this study. The solids content of feces was based on 90-Day Test data (see Reference 4.2). The composition of fecal solids was based on GARD estimates that were developed from References 4.4 and 4.5.

WASH WATER: The amount of wash water and wash water solids was obtained from Reference 4.6. This study used 90-Day Test data as well as a theoretical analysis to predict the values shown. A model of the compositional breakdown is shown in Table 4-IV.

Table 4-I. Summary of Water and Waste Models Pertinent to this Study (Basis: 6-man Crew)

| | GARD | | LOCKHEED | | SSP | | 90-Day Test Data | | BSSC | |
|---|---|---|---|---|---|---|---|---|---|---|
| | lb/day | g/day | lb/day | g/day | lb/day | g/day | lb/day | g/day | lb/day | g/day |
| Water in Urine | | | ? | ? | 19.86 | 9008 | 18.78 | 8519 | 20.85 | 9459 |
| Solids in Urine | 0.9921 | 450 | ? | ? | 0.78 | 354 | 0.8466 | 384 | 0.8446 | 384 |
| Urine | 0.9921 | 450 | 21.7 | 9843 | 20.64 | 9362 | 19.627 | 8903 | 21.7 | 9843 |
| Water in Feces | 1.488 | 657 | ? | ? | 1.20 | 544 | 0.876 | 397 | 1.253 | 568 |
| Solids in Feces | 0.496 | 225 | ? | ? | 0.42 | 190 | 0.447 | 203 | 0.447 | 203 |
| Feces | 1.984 | 900 | 1.7 | 771 | 1.62 | 734 | 1.323 | 600 | 1.7 | 771 |
| Water in Wash Water | | | | | | | | | 221.8 | 100597 |
| Solids in Wash Water | | | | | | | | | 0.2258 | 102 |
| Wash Water | | | | | | | | | 222 | 100699 |
| Metabolic Water in Humidity Condensate | | | | | 24.12 | 10941 | 17.58 | 7974 | Assume Processed | |
| Non-Metabolic Water in Humidity Condensate | | | | | 10.78 | 4890 | 30 | 13608 | by Multi-Filtration | |
| Solids in Humidity Condensate | | | | | | | nil | nil | | |
| Humidity Condensate | | | | | 34.90 | 15831 | 47.58 | 21582 | | |
| Water in Solid Wastes | | | -0- | -0- | ? | ? | 0.29 | 132 | -0- | -0- |
| Solid Wastes (dry) | 0.1 | 45 | 3.6 | 1633 | ? | ? | 3.28 | 1488 | 3.6 | 1633 |
| Solid Wastes | 0.1 | 45 | 3.6 | 1633 | 2.053+ | 931 | 3.57 | 1620 | 3.6 | 1633 |
| Trash Grinder Water | | | 18.40 | 8346 | | | | | 18.4 | 8346 |
| Urinal Flush Water (male) | | | 33.4 | 15150 | 12.00 | 5443 | | | | |
| Urinal Flush Water (male-female) | | | | | 24.00 | 10886 | | | 24.0 | 10886 |
| Anal Wash Water | | | | | | | | | 6.81 | 3089 |
| Food Wastes (dry) | | | ? | ? | | | | | 0.27 | 121 |
| Water in Food Wastes | | | ? | ? | | | | | 0.53 | 242 |
| Wet Food Wastes | | | 0.80 | 363 | | | | | 0.80 | 363 |

Table 4-II. Water and Waste Input Model -- 6-man Crew

| Item | Total Input | $H_2O$ | Total Solid | C | N | O | H | S | P | Inorganic Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | grams per day | | | | | | |
| Urine | 9843.1 | 9459.1 | 384.0 | 70.22 | 84.12 | 66.08 | 15.59 | 1.38 | | 146.61 |
| Urinal Flush | 10886.4 | 10886.4 | | | | | | | | |
| Feces | 771.1 | 568.4 | 202.7 | 137 29 | 8.11 | 23.78 | 23.78 | .56 | | 9.18 |
| Toilet Tissue | 30.0 | | 30.0 | 13.32 | | 14.82 | 1.86 | | | |
| Anal Wash | 3089.0 | 3089.0 | | | | | | | | |
| Wash Water | 100699.2 | 100596.8 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | | | 27.65 |
| Wet Food | 362.9 | 241.9 | 121.0 | 54.1 | 5.0 | 36.1 | 6.8 | | | 19.0 |
| Trash | 1633.0 | | 1633.0 | 978.4 | | 475.8 | 144.6 | | 34.2 | |
| Trash Grinder Water | 8346.2 | 8346.2 | | | | | | | | |
| TOTALS: | 135660.9 | 133187.8 | 2473.1 | 1293.88 | 100.71 | 641.36 | 198.57 | 1.94 | 34.2 | 202.44 |

Table 4-III. Composition of Urine Solids (Reference 4.3)

| Urine Solids | Total | C | N | O | H | S | Inorganic Ash |
|---|---|---|---|---|---|---|---|
| | | | - grams per man-day - | | | | |
| Inorganic Salts | 24.45 | -0- | -0- | -0- | -0- | -0- | 24.45 |
| Urea | 23.14 | 4.63 | 10.80 | 6.17 | 1.54 | -0- | -0- |
| Organic Compounds | 9.27 | 4.26 | 2.09 | 2.13 | 0.60 | 0.23 | -0- |
| Organic Ammonium Salts | 7.13 | 2.82 | 1.14 | 2.72 | 0.46 | -0- | -0- |
| TOTAL SOLIDS | 64.00 | 11.71 | 14.03 | 11.02 | 2.60 | 0.23 | 24.45 |

Table 4-IV. Composition of Wash Water Solids (Reference 4.6)

| Wash Water Solids | Total | C | N | O | H | Inorganic Ash |
|---|---|---|---|---|---|---|
| | | | - grams per man-day - | | | |
| Soluble Constituents: | | | | | | |
| Lactic Acid, $CH_3 \cdot CHOH \cdot CO_2H$ | 1.54 | 0.62 | -0- | 0.82 | 0.10 | -0- |
| Urea, $(NH_2)_2CO$ | 0.90 | 0.18 | 0.42 | 0.24 | 0.06 | -0- |
| Glucose, $C_6H_7O_6(COCH_3)_5$ | 0.13 | 0.06 | -0- | 0.06 | 0.01 | -0- |
| Other organics (assume urea) | 0.34 | 0.07 | 0.16 | 0.09 | 0.02 | -0- |
| Soap, $C_{12}H_{25}-C_6H_4-SO_3Na$ | 5.17 | 3.20 | -0- | -0- | 0.43 | 1.54 |
| Inorganics ($Na^+$, $K^+$, $Cl^-$) | 3.07 | -0- | -0- | -0- | -0- | 3.07 |
| Insoluble Constituents: | | | | | | |
| Assume cellulose, $C_6H_{10}O_5$ | 5.92 | 2.63 | -0- | 2.92 | 0.37 | -0- |
| TOTAL SOLIDS: | 17.07 | 6.76 | 0.58 | 4.13 | 0.99 | 4.61 |

**HUMIDITY CONDENSATE**: It was assumed that all humidity condensate would be processed by a multifiltration system and recycled as drinking water. Therefore the waste management system would have no input from the humidity condensate loop.

**SOLID WASTES**: The solid waste figures were taken from the Lockheed model (see Reference 4.1 and Table 4-V). This model represented NASA's latest thinking at the time of this study.

URINAL FLUSH WATER: The amount of urinal flush water was based on the SSP male/female commode design (see Reference 4.7).

ANAL WASH WATER: The amount of anal wash water was taken from the General Electric Wet John (see Reference 4.8).

WET FOOD WASTES: The amount of Wet Food Wastes was taken from the Lockheed model (see Reference 4.1). Wet food solids were assumed to have a formula $C_2H_3O$ with 15.8% ash.

SUMMARY: An elemental breakdown of the waste solids (solid wastes on a dry basis) that was used in this study is presented in Table 4-VI. For convenience, a normalized version of the same breakdown is presented in Table 4-VII.

**Table 4-V. Composition of Trash Model**

| | | grams per day - six-man crew | | | |
|---|---|---|---|---|---|
| | Total input | C | H | O | F |
| Mylar | 136.0 | 75.9 | 9.5 | 50.6 | - |
| Teflon | 45.0 | 10.8 | - | - | 34.2 |
| Polyethylene | 408.0 | 340.0 | 68.0 | - | - |
| Polystyrene | 182.0 | 168.0 | 14.0 | - | - |
| Cellulosics<br>Gauze 45.0<br>Cotton 362.0<br>Paper 454 0 | 861.0 | 382.7 | 53.1 | 425.2 | - |
| TOTALS: | 1632.0 | 977.4 | 144.6 | 475.8 | 34.2 |

Table 4-VI. Summary of Elemental Composition of Waste Solids "Standardized Model"

| | Total Solids | C | N | O | H | S | F | Inorganic Ash |
|---|---|---|---|---|---|---|---|---|
| | | | grams per day - six-man crew | | | | | |
| Urine | 384.0 | 70.22 | 84.12 | 66.08 | 15.59 | 1.38 | -0- | 146.61 |
| Feces | 202.7 | 137.29 | 8.11 | 23.78 | 23.78 | 0.56 | -0- | 9.18 |
| Wash Water | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | -0- | -0- | 27.65 |
| Food | 121.0 | 54.1 | 5.0 | 36.1 | 6.8 | -0- | -0- | 19.0 |
| Trash | 1633.0 | 978.4 | -0- | 475.8 | 144.6 | -0- | 34.2 | -0- |
| Toilet Tissue | 30.0 | 13.32 | -0- | 14.82 | 1.86 | -0- | -0- | -0- |
| TOTAL: | 2473.1 | 1293.88 | 100.71 | 641.[illegible] | 198.57 | 1.94 | 34.2 | 202.44 |

Table 4-VII. Normalized Elemental Breakdown of Waste Solids for "Standardized Model"

| | | grams per day - six-man crew | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Total Solids | C | N | O | H | S | F | Inorganic Ash |
| Urine | 1.0 | 0.1830 | 0.2192 | 0.1722 | 0.0406 | 0.0036 | -0- | 0.3820 |
| Feces | 1.0 | 0.6773 | 0.0400 | 0.1173 | 0.1173 | 0.0028 | -0- | 0.0453 |
| Wash Water | 1.0 | 0.3960 | 0.0400 | 0.2419 | 0.0580 | -0- | -0- | 0.2701 |
| Food | 1 0 | 0.4471 | 0.0413 | 0.2983 | 0.0562 | -0- | -0- | 0.1570 |
| Trash | 1.0 | 0.5989 | -0- | 0.2915 | 0.0886 | -0- | 0.0210 | -0- |
| Toilet Tissue | 1.0 | 0.4440 | -0- | 0.4940 | 0.0620 | -0- | -0- | -0- |

4.2 **Rationale for Standardized Flow Sheets**:

**GE: The GE system comes the closest of any of the systems to being able to directly process all of the waste streams and was designed for this purpose.. However, for the purpose of this study a reverse osmosis unit was added in the standardized flowsheet to preprocess wash water. Wash water concentrate was fed to the GE system because this results in lower overall penalty for the rather large amount of wash water involved. Although the amount of total wash water in the standardized model is an order of magnitude more than that in the original GE specification, the amount of wash water concentrate is less than that in the original GE specification.**

LOCKHEED: A reverse osmosis unit was added to the Lockheed Wet-Ox System to preprocess wash water for the same reasons it was added to the GE system. In addition, a vapor compression distillation unit was added to remove potable water from the Wet-Ox effluent. Vapor compression distillation is considered to be the lowest penalty process for this purpose. Wet-Ox removes organic material but not the inorganic constitutents, therefore further processing is required. In addition to the added RO and VC units, a dryer was also added to recover water from the VC concentrate effluent and produce a dry ash. This was necessary in order to make the Lockheed Wet-Ox system equivalent to the GE and GARD systems.

GARD: A reverse osmosis unit was added to the GARD incineration system to process wash water for the same reasons it was added to Lockheed and GE. In addition, a vapor compression distillation unit was added ahead of the GARD incinerator unit to further concentrate effluent from the RO unit and to process urine and trash grinder water This arrangement was chosen because it results in the lowest overall penalty for the GARD system. For the same reason a Liquid-solid separator was added to the trash grinder so that trash grinder water could be concentrated in the VC prior to being introduced to the GARD incinerator.

**4.3 GARD Standardized Mass Balance:**

The GARD standardized flow-sheet is shown in Figure 4-1. The rationale for the flow-sheet was presented in Section 4.2. The basic input values were obtained from the Standardized Water and Waste Model shown in Table 4-II. A summary mass balance on each of the components in the flow-sheet is given in Table 4-VIII. Calculation of the total oxygen required in the incinerator and catalytic burner is presented in Table 4-IX. From Figure 4-1 it can be seen that the total output water from the GARD incinerator unit amounts to 7805.8 grams. Of this, 120 grams exit as water vapor with the gases and 7685.8 grams are condensed. It is assumed that this condensed water is pure enough to be used as wash water makeup or trash grinder water so that it does not have to be reprocessed.

The amount of gas required for bearing coolant flow is not shown in Figure 4-1. Carbon Dioxide was used by GARD, but nitrogen would be a better choice for a space mission. It is estimated that the amount of nitrogen required would be less than that required for make-up of cabin leakage. Therefore, since $N_2$ could be bled through the GARD bearing and seal with a very low penalty, this was not considered to have a significant role in the flow-sheet or mass balance.

In addition to the flows shown in Figure 4-1, there are 22082.7 grams of air required for the urinal and 32546.2 grams of air for the commode. These flows are common to GARD, Lockheed and GE.

Scale-up Criteria:

A comparison of the inputs of the "as tested" GARD incinerator unit to the "standardized" unit is shown in Table 4-X. The "as tested" values for solids input (278 g/day) are 20 percent smaller than the mass-balance input

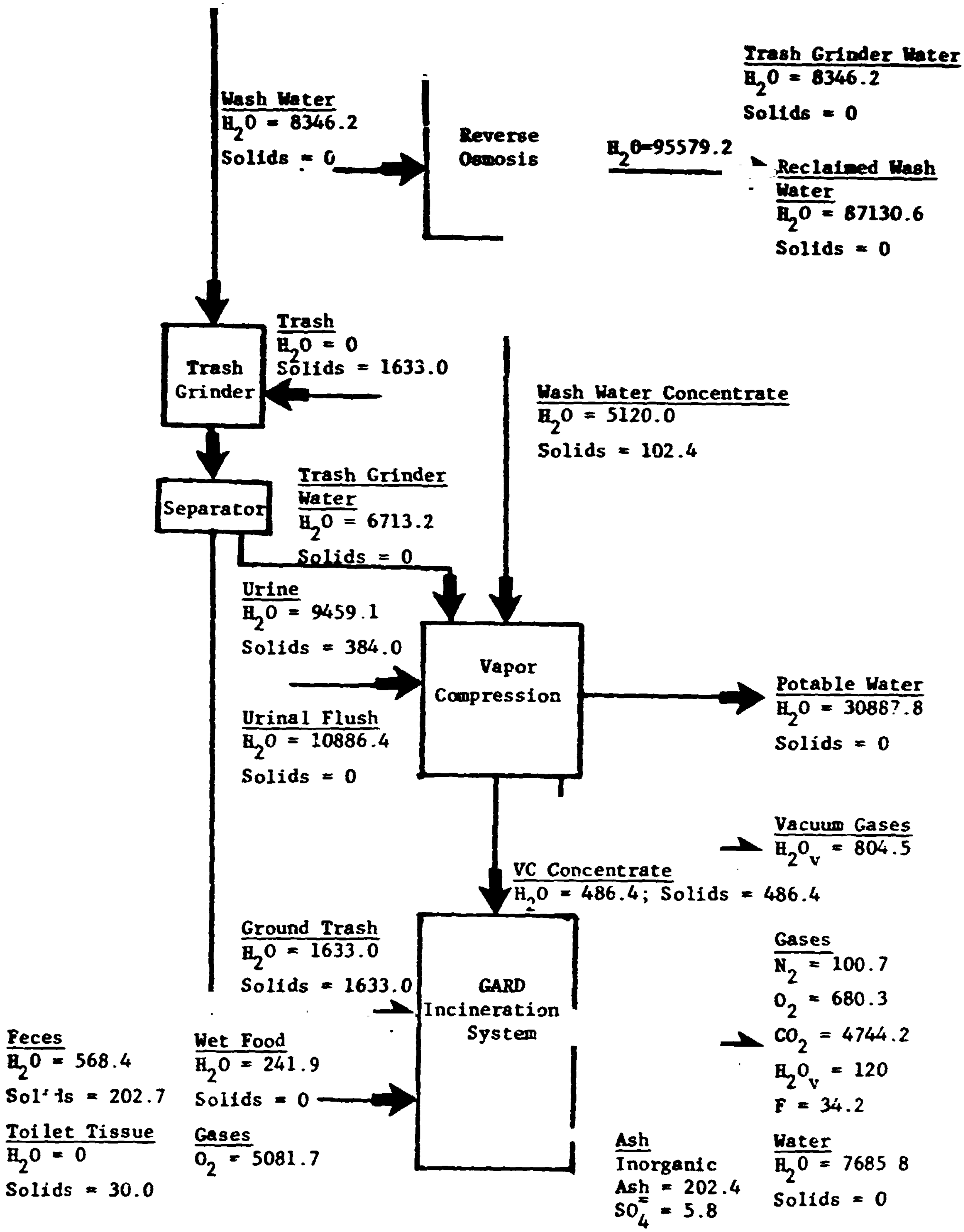


Figure 4-1. GARD Standardized Flow Sheet (6-Man Crew - Grams per Day).

Table 4-VIII. OARD Mass Balance: Standardized and As-Tested Flow Sheets.
(6-man Crew - Grams per Day)

| | TOTAL | $H_2O$ | SOLIDS | C | N | O | H | S | F | ASH |
|---|---|---|---|---|---|---|---|---|---|---|
| **RO INPUT** | | | | | | | | | | |
| Wash water | 100699.2 | 100596.8 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | -0- | -0- | 27.65 |
| **RO OUTPUT** | | | | | | | | | | |
| Water to trash grinder | 8346.2 | 8346.2 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Reclaimed wash water | 87130.6 | 87130.6 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Wash water concentrate to VC unit | 5222.4 | 5120.0 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | -0- | -0- | 27.65 |
| Standardized: | 100699.2 | 100596.8 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | -0- | -0- | 27.65 |
| As-Tested: | NOT TESTED | | | | | | | | | |
| **TRASH GRINDER INPUT** | | | | | | | | | | |
| Water from RO unit | 8346.2 | 8346.2 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Trash | 1633.0 | -0- | 1633.0 | 978.4 | -0- | 475.8 | 144.6 | -0- | 34.2 | -0- |
| Standardized: | 9979.2 | 8346.2 | 1633.0 | 978.4 | -0- | 475.8 | 144.6 | -0- | 34.2 | -0- |
| As-Tested: | NOT TESTED | | | | | | | | | |
| **TRASH GRINDER OUTPUT** | | | | | | | | | | |
| Ground trash to incinerator | 3266.0 | 1633.0 | 1633.0 | 978.4 | -0- | 475.8 | 144.6 | -0- | 34.2 | -0- |
| Water to VC unit | 6713.2 | 6713.2 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Standardized: | 9979.2 | 8346.2 | 1633.0 | 978.4 | -0- | 475.8 | 144.6 | -0- | 34.2 | -0- |
| As-Tested: | NOT TESTED | | | | | | | | | |
| **VAPOR COMPRESSION UNIT INPUT** | | | | | | | | | | |
| Wash water concentrate | 5222.4 | 5120.0 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | -0- | -0- | 27.65 |
| Trash grinder water | 6713.2 | 6713.2 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Urine | 9843.1 | 9459.1 | 384.0 | 70.22 | 84.12 | 66.08 | 15.59 | 1.38 | -0- | 146.61 |
| Urinal flush water | 10886.4 | 10886.4 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Standardized: | 32665.1 | 32178.7 | 486.4 | 110.77 | 87.60 | 90.86 | 21.53 | 1.38 | -0- | 174.26 |
| As-Tested: | NOT TESTED | | | | | | | | | |
| **VAPOR COMPRESSION UNIT OUTPUT** | | | | | | | | | | |
| Potable water | 30887.8 | 30887.8 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Vacuum gases | 804.5 | 804.5 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Concentrate | 972.8 | 486.4 | 486.4 | 110.77 | 87.60 | 90.86 | 21.53 | 1.38 | -0- | 174.26 |
| Standardized: | 32665.1 | 32178.7 | 486.4 | 110.77 | 87.60 | 90.86 | 21.53 | 1.38 | -0- | 174.26 |
| As-Tested: | NOT TESTED | | | | | | | | | |

(continued)

Table 4-VIII. GARD Mass Balance: Standardized and As-Tested Flow Sheets. (continued)
(6-man Crew - Grams per Day)

| | | TOTAL | $H_2O$ | SOLIDS | C | N | O | H | S | F | ASH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **GARD Incinerator Input** | | | | | | | | | | | |
| VC concentrate | - Standardized: | 972.8 | 486.4 | 486.4 | 110.77 | 87.60 | 90.86 | 21.53 | 1.38 | -0- | 174.26 |
| | As-Tested: | 450.0 | 2[illegible]0 | 225.0 | 41.14 | 49.29 | 38.72 | 9.14 | .81 | -0- | 85.90 |
| Ground Trash | - Standardized: | 3266.0 | 1633.0 | 1633.0 | 978.4 | -0- | 475.8 | 144.6 | -0- | 34.2 | -0- |
| | As-Tested: | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Feces | - Standardized: | 771.1 | 568.4 | 202.7 | 137.29 | 8.11 | 23.78 | 23.78 | .56 | -0- | 9.18 |
| | As-Tested: | 610.0 | 497.5 | 112.5 | 76.20 | 4.50 | 13.20 | 13.20 | .30 | -0- | 5.10 |
| Toilet Tissue | - Standardized: | 30.0 | -0- | 30.0 | 13.32 | -0- | 14.82 | 1.86 | -0- | -0- | -0- |
| | As-Tested: | 10.0 | -0- | 30.0 | 4.44 | -0- | 4.94 | .62 | -0- | -0- | -0- |
| Anal Wash | - Standardized: | 3089.0 | 3089.0 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| | As-Tested: | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Wet Food | - Standardized: | 362.9 | 241.9 | 121.0 | 54.1 | 5.0 | 36.1 | 6.8 | -0- | -0- | 19.0 |
| | As-Tested: | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| Sub-Total | - Standardized: | 8491.8 | 6018.7 | 2473.1 | 1293.88 | 100.71 | 641.36 | 198.57 | 1.94 | 34.2 | 202.44 |
| | As-Tested: | 1070.0 | 722.5 | 347.5 | 121.78 | 53.79 | 56.86 | 22.96 | 1.11 | -0- | 91.00 |
| | Ratio: | 7.94 | 8.3[illegible] | 7.12 | 10.62 | 1.87 | 11.28 | 8.65 | 1.75 | ∞ | 2.22 |
| Oxygen | - Standardized: | 5281.7* | -0- | -0- | -0- | -0- | 5281.7 | -0- | -0- | -0- | -0- |
| | As-Tested: | 445 | -0- | -0- | -0- | -0- | 445 | -0- | -0- | -0- | -0- |
| | Ratio: | 11.87 | -0- | -0- | -0- | -0- | 11.87 | -0- | -0- | -0- | -0- |
| TOTAL | - Standardized: | 13773.5 | 6018.7 | 2473.1 | 1293.88 | 100.71 | 5923.06 | 198.57 | 1.94 | 34.2 | 202.44 |
| | - As-Tested: | 1515.0 | 722.5 | 347.5 | 121.78 | 53.79 | 501.86 | 22.96 | 1.11 | -0- | 91.00 |
| **GARD Incinerator Output** | | | | | | | | | | | |
| | $CO_2$ | 4744.2 | -0- | -0- | 1293.9 | -0- | 3450.3 | -0- | -0- | -0- | -0- |
| | $H_2O$ (oxidation product) | 1787.1 | -0- | -0- | -0- | -0- | 1588.5 | 198.6 | -0- | -0- | -0- |
| | $N_2$ | 100.71 | -0- | -0- | -0- | 100.71 | -0- | -0- | -0- | -0- | -0- |
| | $SO_4^{=}$ | 5.8 | -0- | 5.8 | -0- | -0- | 3.87 | -0- | 1.93 | -0- | -0- |
| | F | 34.2 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | 34.2 | -0- |
| | Ash | 202.44 | -0- | 202.44 | -0- | -0- | -0- | -0- | -0- | -0- | 202.44 |
| | $H_2O$ (evaporated) | 6018.7 | 6018.7 | -0- | -0- | -0- | -0- | -0- | -0- | -0- | -0- |
| | $O_2$ excess | 880.3 | -0- | -0- | -0- | -0- | 880.3 | -0- | -0- | -0- | -0- |
| | | 13773.5 | 6018.7 | 208.2 | 1293.9 | 100.71 | 5922.97 | 198.6 | 1.93 | 34.2 | 202.44 |

* Includes 20% excess $O_2$ (i.e., 4401.4 + 880.3 = 5281.7). See Table 4-IX for calculation of $O_2$ required.

Table 4-IX. Calculation of $O_2$ Required for the GARD Incinerator

| Assumptions Pertaining to Oxidation of Solids | Solids C, N, O, S or F | | $O_2$ Required | | Output Product |
|---|---|---|---|---|---|
| $C + O_2 \rightarrow CO_2$ | 1293.88 C | $\times \frac{32}{12} =$ | 3450.3 | $\times \frac{44}{32} =$ | 4744.2 $CO_2$ |
| $2H + \frac{1}{2} O_2 \rightarrow H_2O$ | 198.57 H | $\times \frac{16}{2} =$ | 1588.6 | $\times \frac{18}{16} =$ | 1787.1 $H_2O$ |
| $2N \rightarrow N_2$ | 100.71 N | | 0 | | 100.71 $N_2$ |
| $S + 2O_2 \rightarrow SO_4^{=}$ | 1.94 S | $\times \frac{64}{32} =$ | 3.9 | $\times \frac{96}{64} =$ | 5.8 $SO_4^{=}$ |
| $F \rightarrow F$ | 34.2 F | | 0 | | 34.2 F |
| $2O + C \rightarrow CO_2$ | 641.36 O | | -641.36 | | - |
| Inorganic Ash | 202.44 Ash | | 0 | | 202.44 Ash |
| TOTAL: | 2473.1 | | 4401.44 | | 6874.45 |

**Table 4-X. Summary Comparison of Water and Waste Inputs, and Scale-up Ratios, for "Standardized" and "As-tested" GARD System Models.**

| Input Category | "Standardized" Model (grams/day) | "As-tested" Model (grams/day) | Scale-up Ratio |
|---|---|---|---|
| $O_2$ | 4,398 | 445 | 9.9 |
| $CO_2$ | ? | 520 | |
| Purge Air | ? | 840 | |
| Urinal Air | 22,083 | ? | |
| Water | 6,018 | 723 | 8.3 |
| Solids: | | | |
| C | 1,293 | 97.4 | 13.3 |
| N | 101 | 43.0 | 2.3 |
| O | 641 | 45.5 | 14.1 |
| H | 199 | 18.4 | 10.8 |
| S | 2 | .9 | 2.2 |
| F | 34 | -0- | |
| Ash | 202 | 72.8 | 2.8 |
| TOTAL SOLIDS: | 2,472 | 278.0 | 8.9 |
| TOTAL SOLIDS + WATER : | 8,490 | 1,001 | 8.5 |

figures (347.5 g/day) shown in Table 4-VIII. The reasons for this reduction have been discussed earlier in this report.

The scale-up factors that were selected by the Study Group for the GARD system were based mainly on the ratios shown in Table 4-X. The rationale for the selection of these factors was as follows:

Weight Scale-up Factor = 4 x the "as tested" model weight

Rationale: "As tested" model was tested ½ full; standardized input is roughly 8 x the "as tested" input

Scale-up = ½ x 8 = 4

Paddle Power Scale-up Factor = 8 x "as tested" model power

Rationale: Standardized input is roughly 8 x "as tested" input

Heat Input Scale-up Factor = 8.5 x "as tested" model

Rationale: Assume in same proportion as total solids + water which is 8.5

Heat of Combustion Scale-up Factor = 12.5 x "as tested" model

Rationale: Weighted average of carbon ratio (13 3) and hydrogen ratio (10.8)

A summary of the scaled-up values for heat and power is presented in Table 4-XI.

Table 4-XI. Summary of Heat Rejection Requirement Scale-up Values for GARD Standardized System.

| Heat Rejection Requirement Source | As-tested Reqmt. (w-hr) | Scale-up Factor | Standardized Reqmt. (w-hr) | Standardized Time of Operation (hr) | Standardized Power (watts) |
|---|---|---|---|---|---|
| A. Electric Power Inputs | | | | | |
| Catalytic Burner | 714 | 8.5 | 6,069 | 8.0 | 759 |
| Incinerator | 2,770 | 8.5 | 23,545 | 6.3 | 3,737 |
| Blowers, paddles | 3,750 | 8 | 30,000 | 8.0 | 3,750 |
| | | | Total Electric Power Input to be Rejected | | 8,246 |
| B. Heat of Combustion | 820 | 12.5 | 10,250 | 6.3 | 1,627 |
| | | | Total Heat to be Rejected | | 9,873 |

## 4.4 GE Standardized Model:

A schematic of the process incorporating the GE RITE system is shown in Figure 4-2. The rationale for the auxiliary components is presented in Section 4.2 The basic input values are those of the standardized water and waste model, as shown in Table 4-II. A summary mass balance on each of the components in the flowsheet is given in Table 4-XII; where appropriate, the as-tested values are also given, together with the scale-up ratios of standardized to as-tested values.

In addition to the streams shown in Figure 4-2, there are 22082.7 g of air required for the urinal and 32546.2 g of air for the commode. These flows are common to GARD, GE, and Lockheed. as discussed in Section 4.3.

Scale-up Criteria:

The scale-up factors for the GE system were based on the standardized to as-tested ratios, as given in Table 4-XII. The rationale for the selection of these factors is as follows.

Weight and Power Scale-up Factor = 2 x the "as-tested" model values;

Rationale: Total water input scale-up = 1.43

Total solids input scale-up = 2.57

Using a weighted average of these give a

Scale-up of $\frac{1}{2}(1.43 + 2.57) = 2.0$.

Heat Input Scale-up Factor (HTHL and LTHL)* = 1.5 x "as-tested" model

Rationale: Assume to be in proportion to water input;

Total water input scale-up = 1.43

Heat of Combustion Scale-up Factor = 10250 W-hr;

Rationale: Total heat liberated is the same for all three systems in the standardized case. See GARD estimate (Section 4.3).

*HTHL: High-temperature heat loop;
LTHL: Low-temperature heat loop.

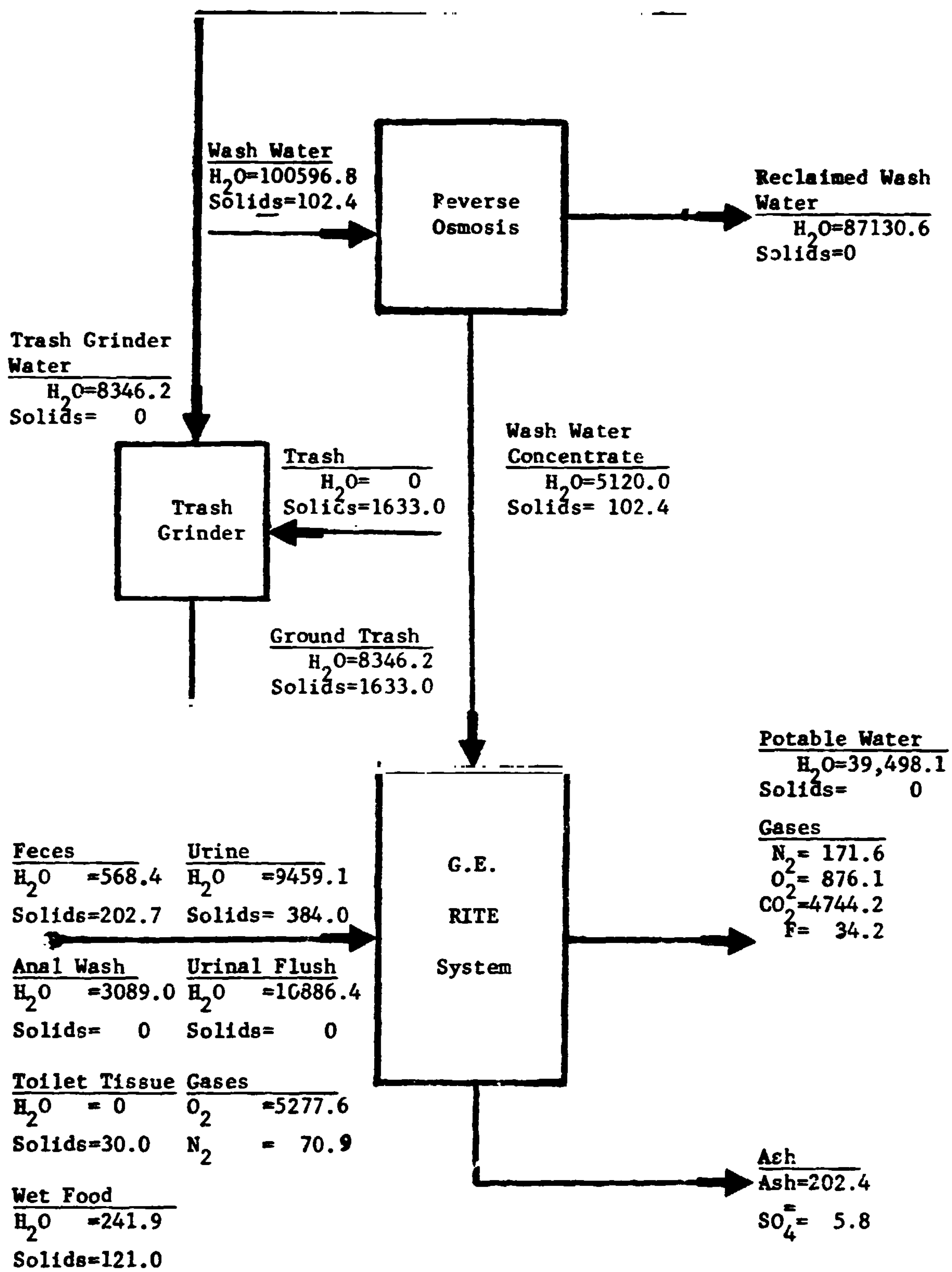


Figure 4-2. G.E. RITE Standardized Flow Sheet
(6-Man Crew - Grams per Day)

Table 4-XII. G. E. Rite Mass Balance: Standardized and As-tested Flow Sheets.

(6 Man Crew - Grams per Day)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | P | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **R. O. Input** | | | | | | | | | | |
| Wash water+ | 100699.2 | 100596.8 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | 0 | 0 | 27.65 |
| **R. O. Output** | | | | | | | | | | |
| Water to trash grinder+ | 8346.2 | 8346.2 | 0 | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| Reclaimed wash water+ | 87130.6 | 87130.6 | 0 | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| Conc. to evaporator+ | 5222.4 | 5120.0 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | ----- | ----- | ----- |
| | 100699.2 | 100596.8 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | 0 | 0 | 27.65 |
| **Trash Grinder Input** | | | | | | | | | | |
| Water from R. O.+ | 8346.2 | 8346.2 | 0 | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| Trash | 1633.0 | 0 | 1633.0 | 978.4 | ----- | 475.8 | 144.6 | ----- | 34.2 | ----- |
| | 9979.2 | 8346.2 | 1633.0 | 978.4 | 0 | 475.8 | 144.6 | 0 | 34.2 | 0 |
| **Trash Grinder Output**: See Evaporator Input | | | | | | | | | | |
| **Evaporator Inputs** | | | | | | | | | | |
| **R. O. Conc. (ECS and Wash)** | | | | | | | | | | |
| Standardized | 5222.4 | 5120.0 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | ----- | ----- | 27.65 |
| As tested | 13441.7 | 13387.3 | 54.4 | 34.47 | ----- | 19.96 | ----- | ----- | ----- | ----- |
| **Ground Trash** | | | | | | | | | | |
| Standardized | 9979.2 | 8346.2 | 1633.0 | 978.4 | ----- | 475.8 | 144.6 | ----- | 34.2 | ----- |
| As tested | 2721.5 | 2177.2 | 544.3 | 466.52 | ----- | ----- | 77.78 | ----- | ----- | ----- |

- continued -

Table 4-XII (Continued)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | F | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **Evaporator Inputs (cont'd)** | | | | | | | | | | |
| **Wet Food** | | | | | | | | | | |
| Standardized | 362.9 | 241.9 | 121.0 | 54.10 | 5.00 | 36.10 | 6.80 | ----- | ----- | 19.00 |
| As-tested | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| **Feces & Anal Wash** | | | | | | | | | | |
| Standardized | 3860.1 | 3637.4 | 202.7 | 137.29 | 8.11 | 23.78 | 23.78 | 0.56 | ----- | 9.18 |
| As-tested | 2723.5 | 2587.4 | 136.1 | 92.17 | 5.44 | 15.96 | 15.96 | 0.37 | ----- | 6.16 |
| **Toilet Tissue** | | | | | | | | | | |
| Standardized | 30.00 | ----- | 30.00 | 13.32 | ----- | 14.82 | 1.86 | ----- | ----- | ----- |
| As-tested | ----- | ----- | ----- | ----- | ----- | ------ | ----- | ----- | ----- | ----- |
| **Urine & Urinal Flush** | | | | | | | | | | |
| Standardized | 20729.5 | 20345.5 | 384.0 | 70.22 | 84.12 | 66.08 | 15.59 | 1.38 | ----- | 146.61 |
| As-tested | 8510.3 | 8282.3 | 228.0 | 41.68 | 49.95 | 39.22 | 9.26 | 0.83 | ----- | 87.06 |
| **Total** | | | | | | | | | | |
| Standardized | 40184.1 | 37711.0 | 2473.1 | 1293.88 | 100.71 | 641.36 | 198.57 | 1.94 | 34.2 | 202.44 |
| As-tested | 27397.0 | 26434.2 | 962.8 | 634.84 | 55.39 | 75.14 | 103.00 | 1.20 | 0.0 | 93.22 |
| Ratio | 1.47 | 1.43 | 2.57 | 2.04 | 1.82 | 8.54 | 1.93 | 1.62 | | 2.17 |

**Evaporator Outputs**: See Incinerator and Steam Catalytic Oxidizer Inputs

- continued -

Table 4-XII (Continued)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | P | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **Steam Catalytic Oxidizer Inputs** | | | | | | | | | | |
| **Evaporator** | | | | | | | | | | |
| Standardized | 35061.8 | 34776.8 | 284.99 | 117.66 | 78.57 | 63.46 | 24.33 | 0.97 | ----- | ----- |
| As-tested | 25556.9 | 25380.2 | 176.68 | 75.17 | 46.98 | 38.60 | 15.35 | 0.60 | ----- | ----- |
| **Oxygen** | | | | | | | | | | |
| Standardized | 533.95 | ----- | ----- | ----- | ----- | 533.95 | ----- | ----- | ----- | ----- |
| As-tested | 341.58 | ----- | ----- | ----- | ----- | 341.58 | ----- | ----- | ----- | ----- |
| **Total** | | | | | | | | | | |
| Standardized | 35595.8 | 34776.8 | 284.99 | 117.66 | 78.57 | 597.41 | 24.33 | 0.97 | ----- | ----- |
| As-tested | 25898.5 | 25380.2 | 176.68 | 75.17 | 46.98 | 380.18 | 15.35 | 0.60 | ----- | ----- |
| Ratio | 1.37 | 1.37 | 1.61 | 1.57 | 1.67 | 1.57 | 1.59 | 1.62 | ----- | ----- |
| **Steam Catalytic Oxidizer Outputs**+ | | | | | | | | | | |
| $CO_2$ | 431.42 | ----- | ----- | 117.66 | ----- | 313.76 | ----- | ----- | ----- | ----- |
| $H_2O$ (oxidation product) | 218.97 | 218.97 | ----- | ----- | ----- | 194.64 | 24.33 | ----- | ----- | ----- |
| $N_2$ | 78.57 | ----- | ----- | ----- | 78.57 | ----- | ----- | ----- | ----- | ----- |
| $SO_3$ | 2.43 | ----- | ----- | ----- | ----- | 1.46 | ----- | 0.97 | ----- | ----- |
| $O_2$ (excess) | 87.55 | ----- | ----- | ----- | ----- | 87.55 | ----- | ----- | ----- | ----- |
| $H_2O$ (evaporated) | 34776.8 | 34776.8 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| | 35595.8 | 34995.71 | 0 | 117.66 | 78.57 | 597.41 | 24.33 | 0.97 | 0 | 0 |

- continued -

Table 4-XII (Continued)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | [illegible] | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **Incinerator Inputs** | | | | | | | | | | |
| **Evaporator** | | | | | | | | | | |
| Standardized | 5122.5 | 2934.2 | 2188.33 | 1176.27 | 22.23 | 577.94 | 174.28 | 0.97 | 34.2 | 202.44 |
| As-tested | 1840.1 | 1054.0 | 786.08 | 559.66 | 8.45 | 36.55 | 87.63 | 0.60 | ----- | 93.22 |
| **Oxygen** | | | | | | | | | | |
| Standardized | 4743.62 | ----- | ----- | ----- | ----- | 4743.62 | ------ | ------ | ------ | ----- |
| As-tested* | 2588.3 | ----- | ----- | ----- | ----- | 2588.3 | ------ | ------ | ------ | ----- |
| **Nitrogen** | | | | | | | | | | |
| Standardized | 70.93 | ----- | ----- | ----- | 70.93 | ----- | ----- | ----- | ----- | ----- |
| As-tested | 32.66 | ----- | ----- | ----- | 32.66 | ----- | ----- | ----- | ----- | ----- |
| **Total** | | | | | | | | | | |
| Standardized | 9937.0 | 2934.2 | 2188.33 | 1176.27 | 93.16 | 5321.56 | 174.28 | 0.97 | 34.2 | 202.44 |
| As-tested | 4461.1 | 1054.0 | 786.08 | 559.66 | 41.11 | 2624.85 | 87.63 | 0.63 | ----- | 93.22 |
| Ratio | 2.23 | 2.78 | 2.78 | 2.10 | 2.27 | 2.03 | 1.99 | 1.54 | ∞ | 2.17 |

- continued -

Table 4-XII (Continued)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | F | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| Incinerator Outputs[+] | | | | | | | | | | |
| $CO_2$ | 4312.99 | ----- | ----- | 1176.27 | ----- | 3136.72 | ----- | ----- | ----- | ----- |
| $H_2O$ (oxidation product) | 1568.52 | 1568.52 | ----- | ----- | ----- | 1394.24 | 174.28 | ----- | ----- | ----- |
| $N_2$ | 93.16 | ----- | ----- | ----- | 93.16 | ----- | ----- | ----- | ----- | ----- |
| $SO_4$ | 2.91 | ----- | 2.91 | ----- | ----- | 1.94 | ----- | 0.97 | ----- | ----- |
| F | 34.2 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | 34.2 | ----- |
| Ash | 202.44 | ----- | 202.44 | ----- | ----- | ----- | ----- | ----- | ----- | 202.44 |
| $O_2$ (excess) | 788.66 | ----- | ----- | ----- | ----- | 788.66 | ----- | ----- | ----- | ----- |
| $H_2O$ (evaporated) | 2934.2 | 2934.2 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| | 9937.0 | 4502.72 | 205.35 | 1176.27 | 93.16 | 5321.56 | 174.28 | 0.97 | 34.2 | 202.44 |

- End -



[+] Standardized values only

[*] Theoretical oxygen for complete combustion

Table 4-XIII. Summary of Heat Rejection Requirement Scale-up Values for G.E. RITE Standardized System.

| Heat Rejection Requirement Source | As-tested Reqmt. (watt) | Scale-up Factor | Standardized Reqmt. (watt) |
|---|---|---|---|
| Power (electrical) | 162.2 | 2.0 | 324 |
| High-temp. Heat Loop (RI)* | 420 | 1.5 | 630 |
| Low-temp. Heat Loop (RI)* | 1,550 | 1.5 | 2,325 |
| Heat of Combustion | | | 427 |
| | | Total Heat to be Rejected: | 3,706 |

* - R.I.: Radioisotope Heater.

**4.5 Lockheed Standardized Model:**

**The standardized wet oxidation system that incorporates the Lockheed wet oxidation method for degradation of wastes is illustrated in Figure 4-3. The rationale for addition of components auxiliary to the wet oxidation reactor is given in preceding sections. Inputs to the system are summarized in Table 4-II which applies to all three of the systems under analysis.**

**A summary mass balance on each of the components of the basic flowsheet is given in Table 4-XIV. The as-tested values are included where appropriate, along with scale-up ratios.**

**Scale-up Criteria:**

**The basis for the scale-up ratios selected are outlined below. It should be pointed out that a duty cycle of 16 hours of operation per day was selected by the Study Group as a best-estimate value for realistic conditions of use. This was based upon the addition of fifty percent increased capacity to the Lockheed as-tested equipment and appropriate scaling of the throughput time, allowing for charging the system and "blowdown" periods, to accommodate the "standardized" input requirements.**

**Weight and Power (Fluid Handling Elements). A ratio of 2.5 is used as a convenient approximation to the ratio of water inputs (2.445) for the two cases, i.e.,**

$$\frac{\text{Water input, standardized}}{\text{Water input, pseudo-as-tested}} = 2.445 \quad .$$

**This does not apply to the weight and power of the reactor (see below). The water input is chosen because all operations within the wet oxidation system except the reaction process are involved purely in fluid handling.**

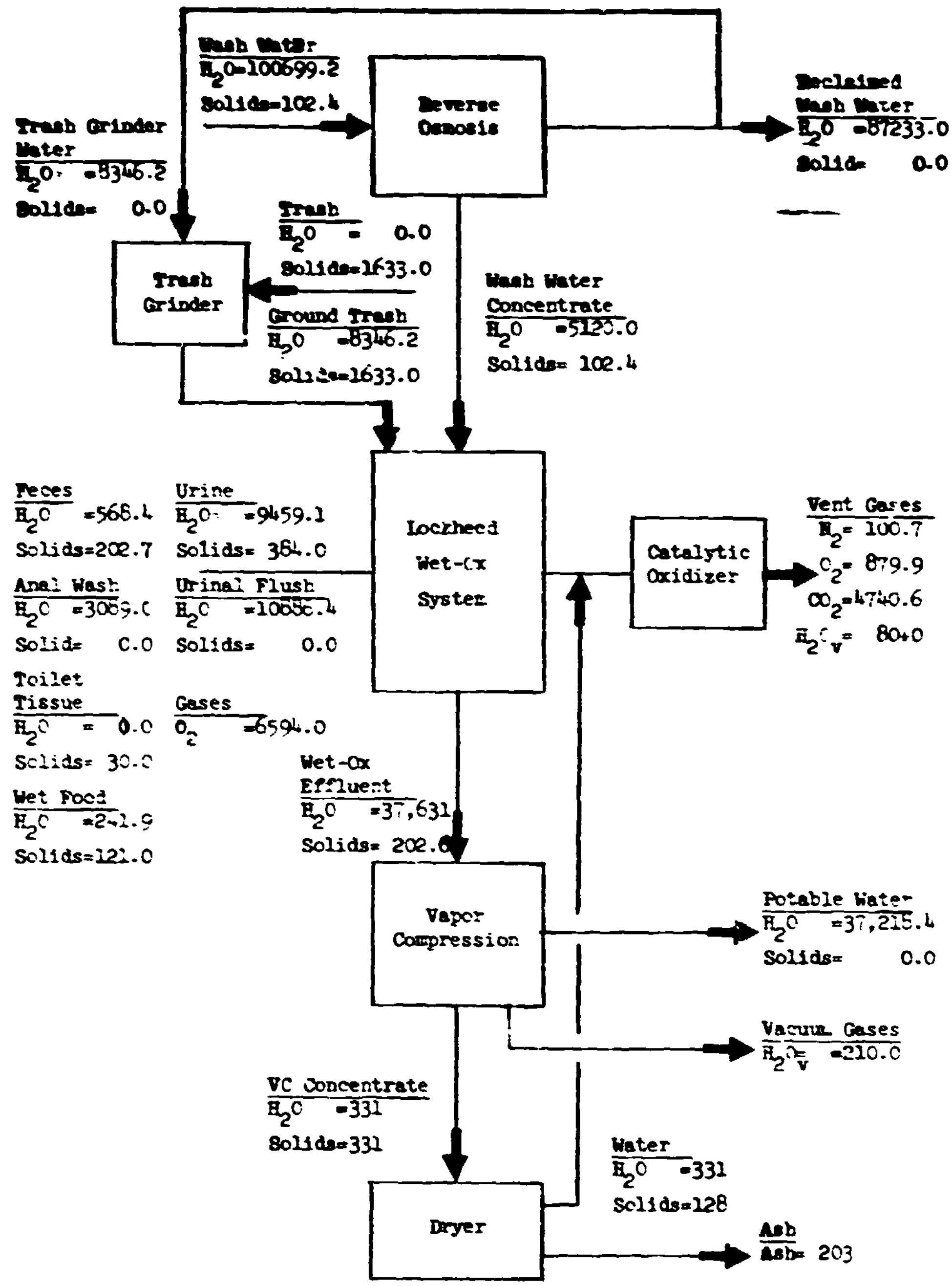


Figure 4-3. Lockheed Standardized Flow Sheet (6-Man Crew - Grams per Day)

Table 4-XIV. Lockheed Mass Balance: Standardized and CDO Cases.

( Basis: 6 men, 1 day )

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | P | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **R. O. Input** | | | | | | | | | | |
| Wash water | 100699.2 | 100596.8 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | 0 | 0 | 27.65 |
| **R. O. Output** | | | | | | | | | | |
| Water to trash grinder | 8346.2 | 8346.2 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| Reclaimed wash water | 87130.6 | 87130.6 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| Conc. to reactor | 5222.4 | 5120.0 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | ----- | ----- | 27.65 |
| | | 100699.2 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | 0 | 0 | 27.65 |
| **Trash Grinder Input** | | | | | | | | | | |
| Water from R. O. | 8346.2 | 8346.2 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| Trash | 1633.0 | 0 | 1633.0 | 978.4 | ----- | 475.8 | 144.6 | ----- | 34.2 | ----- |
| | 9979.2 | 8346.2 | 1633.0 | 978.4 | 0 | 475.8 | 144.6 | 0 | 34.2 | 0 |
| **Trash Grinder Output**: See Reactor Inputs | | | | | | | | | | |
| **Reactor Inputs** | | | | | | | | | | |
| R. O. Concentrate ( ECS and Wash ) | | | | | | | | | | |
| Standardized | 5222.4 | 5120.01 | 102.4 | 40.55 | 3.48 | 24.78 | 5.94 | ----- | ----- | 27.65 |
| CDO | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |

- continued -

Table 4-XIV (Continued)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | P | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| Reactor Inputs (cont'd) | | | | | | | | | | |
| Ground Trash | | | | | | | | | | |
| Standardized | 9979.2 | 83[illegible]6.2 | 1633.0 | 978.4 | ----- | 475.8 | 144.6 | ----- | 34.2 | ----- |
| CDO | 1632.0 | 0 | 1632.0 | 977.4 | ----- | 475.8 | 144.6 | ----- | 34.2 | ----- |
| Wet Food | | | | | | | | | | |
| Standardized | 362.9 | 241.9 | 121.0 | 54.10 | 5.00 | 36.10 | 6.80 | ----- | ----- | 19.00 |
| CDO | 362.0 | 241.3 | 120.7 | 54.0 | 5.0 | 36.0 | 6.8 | ----- | ----- | 19.0 |
| Feces & Anal Wash | | | | | | | | | | |
| Standardized | 3860.[illegible] | 3657.4 | 202.7 | 137.29 | 8.11 | 23.78 | 23.78 | 0.56 | ----- | 9.18 |
| CDO | 793.8 | 585.1 | 208.7 | 141.4 | 8.3 | 24.6 | 24.6 | 0.6 | ----- | 9.4 |
| Toilet Tissue | | | | | | | | | | |
| Standardized | 30.00 | ----- | 30.00 | 13.32 | ----- | 14.82 | 1.86 | ----- | ----- | ----- |
| CDO | ------ | ----- | ------ | ------ | ----- | ----- | ----- | ----- | ----- | ----- |
| Urine & Urinal Flush | | | | | | | | | | |
| Standardized | 20729.5 | 20345.5 | 384.0 | 70.22 | 84.12 | 66.08 | 15.59 | 1.38 | ----- | [illegible] |
| CDO | 7257.6 | 6974.2 | 283.1 | 51.8 | 62.0 | 48.7 | 11.5 | 1.0 | ----- | 108.[illegible] |
| Oxygen | | | | | | | | | | |
| Standardized | [illegible]279.6 | ----- | ----- | ----- | ----- | 5279.6 | ----- | ----- | ----- | ----- |
| CDO | 5020.4 | ----- | ----- | ----- | ----- | 5020.4 | ----- | ----- | ----- | ----- |

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Table 4-XIV (continued)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | P | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **Reactor Inputs (cont'd)** | | | | | | | | | | |
| **Total Reactor Inputs (Liquids)** | | | | | | | | | | |
| Standardized | 40184.1 | 37711.0 | 2473.1 | 1292.9 | 100.7 | 5921.0 | 198.7 | 1.93 | 34.2 | 202.6 |
| CDO | 17605.4 | 15360.5 | 2244.5 | 1224.6 | 75.3 | 5605.5 | 187.5 | 1.6 | 34.2 | 136.6 |
| Ratio | 2.82 | 2.46 | 1.10 | 1.06 | 1.34 | 1.06 | 1.06 | 1.21 | 1.0 | 1.48 |
| **Condenser Inputs** (Standardized case) | | | | | | | | | | |
| $H_2O$ | 39499.3 | 39499.3 | ----- | ----- | ----- | 35110.5 | 4388.8 | ----- | ----- | ----- |
| $CO_2$ | 4740.6 | ----- | ----- | 1292.9 | ----- | 3447.7 | ----- | ----- | ----- | ----- |
| $N_2$ | 100.7 | ----- | ----- | ----- | 100.7 | ----- | ----- | ----- | ----- | ----- |
| $SO_4$ (ion) | 5.79 | ----- | ----- | ----- | ----- | 3.86 | ----- | 1.93 | ----- | ----- |
| $O_2$ (excess) | 819.9 | ----- | ----- | ----- | ----- | 879.9 | ----- | ----- | ----- | ----- |
| Ash | 202.6 | ----- | 202.6 | ----- | ----- | ----- | ----- | ----- | ----- | 202.6 |

**Condenser Output**: See (1) Vapor Compression Distillation Input and (2) Vent Gases

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | P | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **Vapor Compression Distillation Input** | | | | | | | | | | |
| Standard | 37833.6 | 37631.0 | 202.6 | ----- | ----- | 33449.8 | 4181.2 | ----- | ----- | 202.6 |
| CDO | 17178.4 | 17041.8 | 136.6 | ----- | ----- | 15148.3 | 1893.5 | ----- | ----- | 136.6 |

- continued -

Table 4-XIV (Continued)

| Item | Total | $H_2O$ | Solids | C | N | O | H | S | P | Ash |
|---|---|---|---|---|---|---|---|---|---|---|
| **Vent Gases** (Standardized case) | | | | | | | | | | |
| $H_2O$ | 80.0 | 80.0 | ----- | ----- | ----- | 8.9 | 71.1 | ----- | ----- | ----- |
| $CO_2$ | 4740.6 | ----- | ----- | 1292.9 | ---- | 3447.7 | ----- | ----- | ----- | ----- |
| $N_2$ | 100.7 | ----- | ----- | ----- | 100.7 | ----- | ----- | ----- | ----- | ----- |
| $O_2$ | 879.9 | ----- | ----- | ----- | ----- | 879.9 | ----- | ----- | ----- | ----- |
| **Vapor Compression Distillation Output** (Standardized) | | | | | | | | | | |
| Potable water | 37218.4 | 37218.4 | ----- | ----- | ----- | 33083.0 | 4135.4 | ----- | ----- | ----- |
| Gases | 210.0 | 210.0 | ----- | ----- | ----- | 186.7 | 23.3 | ----- | ----- | ----- |
| VC Conc. | 405.2 | 202.6 | 202.6 | ----- | ----- | ----- | ----- | ----- | ----- | 202.6 |

Weight and Power (Reactor). The reactor weight is scaled up on the basis of residence time for the gas-liquid mixture. Although the rate of water entering the reactor varies by a factor of 2.445 (see above), the gas rate is approximately proportional to the carbon ratio (1.056). Both rates must be considered, and they are as follows in the two cases:

| | Gas Rate | Liquid Rate | Total |
|---|---|---|---|
| Standardized | 32.6 cc/min | 26.2 cc/min | 59.0 |
| Pseudo-as-tested | 24.5 cc/min | 10.7 cc/min | 35.2 |

Therefore, the weight scale-up ratio is the ratio of the respective total throughputs, i.e.

$$\text{Scale-up ratio} = \frac{59.0}{35.2} = 1.68 \quad .$$

This assumes that reactor weight increases in proportion to reactor volume. A scale-up ratio of 1.7 was adopted.

Heat Input and Heat Rejection Requirements. These requirements were estimated directly for the standardized wet-ox system from a First Law analysis (see Section 3.3 for a discussion of the procedure). The results are as follows:

$$Q_{net} = 280 \times 37{,}711.0 + 128 \times 8 \times (550 - 77)/a.8$$

$$- 3{,}564 \times 2{,}473.1 \text{ cal/day}$$

$$= (10.56 + .27 - 8.81) \times 10^6 \text{ cal/day}$$

$$= 2.02 \times 10^6 \text{ cal/day} = 2{,}020 \text{ K cal/day}$$

On a 16 hr/day basis,

$$Q_{net} = 147.1 \text{ watt}$$

The heat loss from the reactor was scaled-up from the CDO model with the assumption that the loss is directly proportional to the two-thirds power of reactor volume. Thus,

$$Q_{loss} = (1.686)^{2/3} \times (200) = 282 \text{ watt}$$

$$Q_{input} = Q_{net} + Q_{loss} = 147 + 282 = 429 \text{ watt}$$

$$Q_{cooling\ (products)} = (10.56 + .27) \times 10^6 \text{ cal/day}$$

$$= 10.83 \times 10^6 \text{ cal/day}$$

$$= 10{,}830 \text{ K cal/day}$$

On a 16 hr/day basis,

$$Q_{cooling\ (products)} = 786 \text{ watt}$$

Therefore,

$$Q_{rejected} = 282 + 786 \text{ watt} = 1{,}067 \text{ watt} \quad .$$

A summary of the scale-up values for power and heat is presented in Table 4-XV.

Table 4-XV. Summary of Heat Rejection Requirement Scale-up Values for Lockheed Standardized System.

| Heat Rejection Requirement Status | As-tested (watt) | Scale-up Factor | Standardized Reqmt. (watt) | Amount to be Rejected (Standardized Case) |
|---|---|---|---|---|
| Fluid-handling elements (e.g., reactor drive) | 269 | 2.5 | 672.5 | 672.5 |
| Reactor heater input | 380 | --- | 429. | --- |
| Reactor heat loss | 352 | --- | 282. | 282.0 |
| Product cooling requirement | 112. | --- | 786. | 786.0 |

Total Heat to be Rejected (Standardized Case): 1,740.5 watts

References for Section 4.


| Ref. No. | Citation |
|---|---|
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| 4.10 | Coggi, J.V., A.V. Loscutoff and R.S. Baker, "G-189A Analytical Simulation of the Integrated Waste Management-Water System Using Radioisotopes for Thermal Energy", NASA Contract No. NAS 8-28982, MDC G4901; November 1973. |
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| Ref. No. | Citation |
| --- | --- |
| 4.12 | Jagow, R. B., "Design and Development of a Prototype Wet Oxidation System for the Reclamation of Water and the Disposition of Waste Residues Onboard Space Vehicles," NASA ...-112151; Lockheed Missiles and Space Co., Inc., for Contract NAS 1-9183; May 1972. |

## 5. BASELINE TRADE-OFF ANALYSIS

In Section 2.4 of this report the general procedure by which the Study Group accomplishes the trade-off comparison of the alternative "standardized" processes was outlined. By way of a review, this procedure included: (1) establishing the trade-off model; (2) assessment of weight, volume, power and thermal penalties for each of the alternative processes; (3) development of an evaluation scoring form as a tool for the application of the trade-off model; (4) rating of the alternative processes, using the scoring forms and point-selection criteria; and (5) analysis of the scoring-evaluation results. The technical details and results of the trade-off comparison are presented in this section.

### 5.1 Establishment of the Trade-off Model:

As was discussed in Section 2.4, the procedure by which the Study Group formulated an appropriate trade-off model for the comparative analysis initially involved an analysis of the scope of the required evaluation. This included the identification of key parameters to be considered for the type of spacecraft life-support system represented by the three alternative processes of interest. It was also necessary to identify appropriate conversion factors for penalty assessments. Finally, conventional trade-off models, used in industrial practice for the comparison of life-support systems alternatives and similar applications, were reviewed and assessed to identify the most appropriate model format. The model selected by the Study Group had the form:

$$S_{TOTAL} = (M_{CS})(M_{CP})\sum_{i=1}^{6} s_i \quad ,$$





C-2

where,

$S_{TOTAL}$ = the total rating score for a given candidate process;

$M_{CS}$ = Critical Safety Coefficient for the candidate process;

$M_{CP}$ = Critical Performance Coefficient for the candidate process;

$s_i$ = six comparison-category terms, scored separately for the candidate process and then summed.

This model form which consists of a combination of weighted summation (additive) terms and coefficient (multiplicative) terms, is very similar not only to those typically used by systems analysts in the aerospace industry, but also to several popular models and in the chemical process industries for comparative evaluation of new commercial-venture alternatives. The successful application of these trade-off models as management decision-structuring tools, for purposes similar to those of interest in this study, has been well documented.

The Study Group selected six categories for the terms $s_i$ in the above trade-off model. These included:

- General safety characteristics
- Operating complexity of the system
- Simplicity of interfacing
- Adaptability to flight conditions
- Versatility
- Penalties (weight, volume, power, thermal)

Weighting factors for each of these categories, in terms of maximum point values, were assigned based upon conventional spacecraft systems-analysis practice; and criteria were established for the assignment of points (up to the maximum value) in each category. These are summarized in Table 5-1. The

Table 5-I. Weighting Factors and Point Assignment Criteria for Comparison Categories, $s_i$, in Trade-off Model.

| Comparison Category | Weighting Factor (maximum point value) | Point-assignment Criteria |
|---|---|---|
| 1. General Safety Characteristics ($s_1$) | 20 | Points are assigned for freedom, generally, from potential safety hazards such as fire, atmosphere contamination, explosion, bacteriological problems, crew injury, and equipment damage to other sub-systems. High-risk range (0-5 pts.); moderate risk range (6-15 pts.); low to insignificant risk range (16-20 pts.). |
| 2. Operating Complexity of the System ($s_2$) | 18 | Highest points are assigned for greatest simplicity of operating procedures and least technical complexity in hardware functions. Favorable consideration is also given to higher potential for effective, reliable automation of operations; reduced crew time and stress during maintenance; and ease of modularizing equipment. Excessive complexity range (0-4 pts.); moderate complexity range (5-14 pts.); low to insignificant complexity (15-18 pts.) |

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Table 5-I. (continued)

| Comparison Category | Weighting Factor (maximum point value) | Point-assignment Criteria |
| --- | --- | --- |
| 3. Simplicity of Interfacing ($s_3$) | 12 | Highest points are assigned for least requirement for interfaces with other spacecraft sub-systems and services for operation of the candidate-process sub-system. Typical interfaces include vacuum source, oxygen or nitrogen supplies, water supply, biocide source, power connections, plumbing, etc. Excessive interfacing complexity range (0-3 pts.); moderate interfacing complexity range (4-8 pts.); low to insignificant interfacing complexity range (9-12 pts.). |
| 4. Adaptability to Flight Conditions ($s_4$) | 16 | Points are assigned proportional to an estimated probability that the candidate-process sub-system will be operational for an assumed application (in the 1980-1990 time period) based on confidence in information and approaches to problem solutions (i.e., fail-operational/fail safe; failure-mode effect analysis). Includes consideration of potential sensitivity to flight conditions (zero-g, vibration and shock, etc.). |

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Table 5-I. (continued)

| Comparison Category | Weighting Factor (maximum point value) | Point-assignment Criteria |
|---|---|---|
| 5. Versatility ($a_5$) | 7 | Points are assigned according to the potential adaptability of the candidate process sub-system to various mission applications. Involve variable such as crew size, power and heat sources availability (i.e., solar cells, radio-isotope sources, etc.), spacecraft configurations (e.g., vehicle free volume, equipment load capacity, etc.), and mission duration. Low versatility range (0-1); moderate versatility range (2-5); high to ideal versatility range (6-7). |
| 6. Penalties ($a_6$) | 27 | Points assigned proportional to actual estimated values for installed weight, spares weight, volume, power and thermal rejection requirements for each candidate process sub-system, all converted to equivalent-weight values for simplicity in points assignment. |

TOTAL MAXIMUM VALUE FOR $\Sigma a_i$: 100 Points range of scoring values for the critical, potentially abortive or catastrophic factors (system go/no-go importance) $M_{CS}$ and $M_{CP}$ in the model was selected to be zero (preemptive rejection of the candidate) to one (no likelihood of problems, and therefore no impact on the selection of this candidate). Criteria for the assignment of scoring values for these two coefficients involved estimates of probabilities that no critical safety or performance problems will be likely to occur in operational design version of the candidate process sub-system, based upon currently available information.

5.2 Assessment of Penalty Values for the Candidate Processes:

All but the last ($s_6$) of the comparison categories described in Table 5-I involve scoring criteria based upon qualitative judgment factors which the Study Group had to derive from the general data and information obtained for the candidate processes, and calculations accomplished for material- and energy-balance closure in the as-tested and standardized cases. For comparison category $s_6$, however, it was necessary to compile best-estimate values for weight, volume, power and thermal penalties, on a component-by-component bassis, for the standardized process flowsheet for each candidate process. The basis for these estimated penalty values is discussed below for the major components of the three standardized flowsheets developed in Section 4 of this report.

GARD Dry-incinerator Process

1. Reverse-osmosis unit (this is common to all three standardized flowsheets and the penalty values presented here will be the same for the G.E. RITE and the Lockheed Wet-ox processes, which follow):
   a. Duty cycle -- 8 hours during 14-hour daylight period (Ref. 5.1).
   b. Electric power penalty (lbs/watt), AC power -- 0.351 (Ref. 5.2).

c. Heat rejected from tank heatup -- 32 watts (estimated from W Cp $\Delta$t calculations, with W determined from the flow rate per 24 hours, from the standardized input values to the RO unit; then rejection taken as approximately 10 percent of this heatup, to represent losses).

d. Thermal rejection penalty (lb/watt) to air -- 0.25 (Ref. 5.2).

e. Thermal input for tank heatup and pumping (see c, above, and Ref. 5.1) -- 330 watts.

f. Installed weight of unit (reported values, averaged) -- 205 lb. (Ref. 5.1).

g. Spares weight (reported values, averaged) -- 90 lb (Ref. 5.1).

2. Trash-shredder Unit (this is common to all three standardized flowsheets and the penalty values presented here will be the same for the G.E. and Lockheed processes).

In seeking a common design, two tested options are available. Both Lockheed and G.E. have designed and tested trash grinders; GARD has not. The Study Group chose to use penalty values for the Lockheed unit. Although it showed higher penalty values, it has been tested on a more representative trash-model input and possibly offers more realistic penalty values. The choice does not affect the overall comparison of penalty values for the alternative processes since each process flowsheet was burdened the same for the trash-grinder unit.

a. Duty cycle -- 10 minutes (estimated from Lockheed test data to date).

b. Electric power input (2 hp motor operating for 10 min.) -- 11 watts.

c. Electric power penalty (continuously regulated AC to accomodate large surges) -- 0.725 lb/watt (Ref. 5.2).

d. Thermal rejection penalty (to air) -- 0.25 lb/watt (Ref. 5.2).

e. Thermal rejection calculated as 30 percent of input as thermal loss from motor -- 3 watts (see b, above).

f. Installed weight of unit; estimated from components -- 210 lbs.

g. Spares weight; estimated as 40 percent of installed weight -- 84 lbs. (see f, above).

3. Vapor Compression Unit (although both the GARD and the Lockheed "standardized" process flowsheets use VC units, they are used for different purposes and at different stream locations in the flowsheet, therefore, they will not be the same). For the GARD flowsheet:

   a. Duty cycle -- 8 hours.

   b. Feed rate (from standardized flowsheet, Section 4.3) -- 32,665 g/day.

   c. Electric power input (GARD data scaled by flow-rate ratio to standardized case) -- 480 watts.

   d. Electric power penalty (AC power, sunlit side) -- 0.351 lb/watt (Ref. 5.2).

   e. Thermal rejection (assumed to be 100 percent of electric power input, c above) -- 480 watts.

   f. Thermal rejection penalty (to air) -- 0.25 lb/watt (Ref. 5.2).

   g. Installed weight (values given in Ref. 5.1 were used as basis; one still was removed, its weight excluded, and then the remaining value was scaled by the flow-rate ratio to the standardized GARD case) -- 890 lbs.

   h. Spares weight (one standby still module) -- 261 lbs.

4. Incinerator Unit (unique to GARD process):

   a. Duty cycle -- 8 hr (Ref. 5.3 and 5.4).

b. Electric power input (from Table 4-XI) -- 8,246 watts.

c. Electric power penalty, regulated AC -- 0.351 lb/watt (Ref. 5.2).

d. Thermal rejection (from Table 4-XI) -- 9,873 watts.

e. Thermal rejection penalty (air and coolant values, averaged) -- 0.215 lb/watt (Ref. 5.2).

f. Installed weight (scale factor of 4 times GARD as-tested unit value, according to criteria developed in Section 4.3 of this report) -- 888 lbs.

g. Spares weight (40 percent of installed weight) -- 355 lbs.

G.E. RITE Process

1. Reverse-osmosis Unit -- (same as for GARD process, presented above).

2. Trash-shredder Unit -- (same as for GARD process, presented above).

3. G.E. RITE System (unique reactor and supporting components, omitting shredder and water-storage provisions):

   a. Duty cycle -- 24 hrs. (Ref. 5.5).

   b. Electric power input (from Table 4-XIII) -- 324 watts.

   c. Electric power penalty, regulated AC (averaged for all-day operation) -- 0.538 lb/watt (Ref. 5.2).

   d. Thermal rejection (from Table 4-XIII) -- 3,706 watts.

   e. Thermal rejection penalty (average values for air and coolant) -- 0.215 lb/watt (Ref. 5.2).

   f. Installed weight (average weight of 470 lbs. for the estimated flight-weight unit was obtained from Refs. 5.1 and 5.7, but omitting the weight of the commode, trash shredder and water storage facility; this weight was sealed by a factor 2 according to the criteria in Section 4.4 of this report for the "standardized" case) -- 940 lbs.

   g. Spares weight -- 376 lbs. (Ref. 5.1).

Lockheed Wet-oxidation Process

1. Reverse-osmosis Unit -- (same as for GARD process, presented above).
2. Trash-shredder Unit -- (same as for GARD process, presented above).
3. Wet-oxidation Reactor (unique to Lockheed process):
   a. Duty cycle (as discussed in Section 4.5 of this report) -- 16 hours.
   b. Electric power input (from Table 4-XV) -- 1,101.5 watts.
   c. Electric power penalty, regulated AC (averaged for all-day operation) -- 0.538 lb/watt (Ref. 5.2).
   d. Thermal rejection (from Table 4-XV) -- 1,740.5 watts.
   e. Thermal rejection penalty (average value for air and coolant) -- 0.215 lb/watt (Ref. 5.2).
   f. Installed weight (using a reactor weight of approximately 145 lbs. estimated by Lockheed, and scaled by a factor of 1.7 according to the criteria of Section 4.5, plus the weight of miscellaneous fluid-handling elements scaled by a factor of 2.5 according to the criteria of Section 4.5) -- 444 lbs.
   g. Spares weight (40 percent of installed weight) -- 178 lbs.
4. Vapor Compression Unit (follows the wet-ox reactor in the standardized flow sheet, as shown in Figure 4-3 of Section 4):
   a. Duty cycle (coinciding with the terminal phase of the reactor duty cycle) -- 8 hrs.
   b. Feed rate (from Figure 4-3) -- 37,833.6 g/day.
   c. Electric power input (Lockheed data scaled to standardized case by feed flow-rate ratio, standardized to as-tested) -- 559 watts.
   d. Electric power penalty (AC, sunlit side) -- 0.321 lb/watt (Ref. 5.2).
   e. Thermal rejection (assumed to be 100 percent of electric power input, c above) -- 559 watts.

f. Thermal rejection penalty (to air) -- 0.25 lb/watt (Ref. 5.2).

g. Installed weight (used values given in Reference 5.1, except one still was removed, its weight excluded, and then the remaining value was scaled by the input flow-rate ratio to the standardized Lockheed case) -- 1,035 lbs.

h. Spares weight (one standby still module) -- 304 lbs.

5. Catalytic Oxidation Unit (to treat reactor-product and dryer gases before interfacing with the cabin-atmosphere control system; no design data available, so Study Group's best-estimate calculations were used based upon conventional catalytic oxidation units):

a. Duty cycle (same as Wet-ox reactor) -- 16 hrs.

b. Electric power input (preheat of input stream, plus fluid-handling equipment) -- 150 watts (estimated).

c. Electric power penalty (AC, regulated power; averaged for all-day use) -- 0.538 lb/watt (Ref. 5.2).

d. Thermal rejection (assumed to be 100 percent of electric-power input, b above) -- 150 watts (estimated).

e. Thermal rejection penalty (to coolant) -- 0.18 lb/watt (Ref. 5.2).

f. Installed weight (Study Group's calculated estimate) -- 225 lbs.

g. Spares weight (assumed to be one-third of installed weight, f above) -- 75 lbs.

6. Dryer Unit (shown in Figure 4-3 to dry the concentrate stream from the Vapor Compression Unit, produce a dry-ash residue and recover additional water; based upon Study Group's best-estimate calculations):

a. Duty cycle (same as Vapor Compression Unit) -- 8 hrs.

b. Electric power input (to evaporate 331 g/day of water and allowing for losses) -- 35 watts.

c. Electric power penalty -- 0.351 lb/watt (Ref. 5.2).

d. Thermal rejection (assumed to be 100 percent of electric power input, b above) -- 35 watts.

e. Thermal rejection penalty (to coolant) -- 0.18 lb/watt (Ref. 5.2).

f. Installed weight (Study Group's estimate based on Lockheed design configuration) -- 20 lbs.

g. Spares weight (based on estimate of 50 percent of installed weight, f above) -- 10 lbs.

The various sources of penalty for the component units of each alternative process, listed above in this sub-section, were converted to equivalent weight values to provide a single penalty number for each process and simplify the scoring for Comparison Category $s_6$ in Table 5-I. These equivalent-weight values are summarized for each process, and its essential flowsheet components, in Table 5-II.

5.3 Evaluation Scoring Procedure and Results:

An evaluation "scoring" form was developed as a tool for applying the trade-off model described in Section 5.1. The form provided for the assignment of points to the various Comparison Categories ($s_1$ through $s_6$) and critical coefficients ($M_{CS}$ and $M_{CI}$) for each of the three alternative processes, and the final computation of total rating score ($S_{TOTAL}$) for each process.

The Study Group used this form and performed a concensus rating for the alternative processes based upon the penalty values summarized in Table 5-II and judgement derived from the data-base as-tested experience information as well as the standardized flowsheet activity. Initially the scoring was accomplished for the baseline mission model upon which this study was based (as discussed

Table 5-II. Summary of Penalty Values, in Terms of Equivalent Weight, for Standardized Flowsheet Components of the Three Alternative Processes.

| Alternative Process/Components | Electric Power Equiv. wt. (lb) | Thermal Rejection (Equiv. wt. (lb) | Installed wt. (lb) | Spares wt. (lb) | Total Equiv. wt. (lb) |
|---|---|---|---|---|---|
| **1. GARD Standardized Flowsheet:** | | | | | |
| Reverse-osmosis Unit | 116 | 8 | 205 | 90 | 410 |
| Trash-shredder Unit | 8 | 1 | 210 | 84 | 303 |
| Vapor Compression Unit | 168 | 120 | 890 | 261 | 1,439 |
| Incinerator Unit | 2,894 | 2,123 | 888 | 355 | 6,260 |
| Process Totals: | 3,186 | 2,252 | 2,193 | 790 | 8,421 |
| **2. G.E. Standardized Flowsheet:** | | | | | |
| Reverse-osmosis Unit | 116 | 8 | 205 | 90 | 419 |
| Trash-shredder Unit | 8 | 1 | 210 | 84 | 303 |
| G.E. RITE System | 174 | 797 | 940 | 376 | 2,287 |
| Process Totals: | 298 | 806 | 1,355 | 550 | 3,009 |
| **3. Lockheed Standardized Flowsheet:** | | | | | |
| Reverse-osmosis Unit | 116 | 8 | 205 | 90 | 419 |
| Trash-shredder Unit | 8 | 1 | 210 | 84 | 303 |
| Wet-oxidation Reactor | 592 | 374 | 444 | 178 | 1,588 |
| Vapor Compression Unit | 196 | 140 | 1,035 | 304 | 1,675 |
| Catalytic Oxidation Unit | 81 | 27 | 225 | 75 | 408 |
| Dryer Unit | 12 | 6 | 20 | 10 | 48 |
| Process Totals: | 1,005 | 556 | 2,139 | 741 | 4,441 |

in Section 1). The scoring form and the results of the Study Group's rating of the alternative processes are presented in Table 5-III.

**5.4 Analysis of the Scoring-evaluation Results:**

An analysis of the scoring-evaluation results shown in Table 5-III (based upon the trade-off model discussed in Section 5.1) was performed by the Study Group to determine the significance of these results and establish a basis for conclusions and recommendations. The analysis showed that for the six comparison categories ($s_1$ through $s_6$ in Table 5-III) the primary source of big differences in assigned scores among the processes was Penalties, and secondarily in Safety. The differences in the other categories were not very significant. It was also interesting to note that the preemptive Critical Coefficients ($M_{CS}$ and $M_{CP}$) did not change the rankings among the three processes that might have been derived from the sum of the $s_i$ values; the Critical Coefficients just reinforced these rankings.

The Lockheed Wet-oxidation Process, which uses high operating pressures and temperatures, was scored low with respect to safety ($s_1$ and $M_{CS}$). This resulted from the Study Group's informed anxiety (based on extensive experience with adequately similar systems in industry) concerning the potential for explosion, fire, equipment-damage and crew-injury hazards. This process was also secondarily penalized because of its many interface and expendables requirements (such as oxygen and nitrogen pressurization, heat exchangers, reactor catalyst makeup, and excessive post-treatment requirements). Finally, it was anticipated that its operating procedure would be difficult to automate and would impose requirements for more crew-time for maintenance.

The GARD Dry Incineration Process was scored low in the Penalties category because of the very likely excessive equivalent-weight values tabulated in Table 5-II. The GARD process, like the Wet-oxidation Process, was also secondarily

Table 5-III. Trade-off Scoring Form and Results of Study Group's Rating of Alternative Processes.

| Scoring Factors | Maximum Points (Weighting Factor) | Scoring for each Alternative Process: CARD Dry Incin. | G.E. RITE | Lockheed Wet-ox. |
|---|---|---|---|---|
| A. Comparison Categories ($S_i$): | | | | |
| 1. Safety ($s_1$) | 20 | 15.0 | 15.2 | 11.6 |
| 2. Operating Complexity of the System ($s_2$) | 18 | 12.6 | 12.8 | 10.6 |
| 3. Simplicity of Interfacing ($s_3$) | 12 | 8.8 | 8.6 | 7.2 |
| 4. Adaptability to Flight Conditions ($s_4$) | 16 | 11.8 | 11.8 | 10.0 |
| 5. Versatility ($s_5$) | 7 | 5.2 | 5.4 | 5.4 |
| 6. Penalties ($s_6$) | 27 | 9.6 | 20.6 | 15.0 |
| Totals ($\Sigma s_i$): | 100 (max.) | 63.0 | 74.4 | 59.8 |
| B. Critical Coefficients (M): | | | | |
| 1. Critical Safety Coefficient ($M_{cs}$) | 1.0 | 0.86 | 0.93 | 0.82 |
| 2. Critical Performance Coefficient ($M_{cp}$) | 1.0 | 0.87 | 0.92 | 0.82 |
| C. Computation of $S_{TOTAL}$: | | | | |
| $S_{TOTAL} = (M_{cs})(M_{cp}) \sum_{i=1}^{6} s_i$ | 100 (max.) | 47.1 | 63.7 | 40.2 |

penalized on the basis of its interface and expendables requirements (such as bearing coolant, liquid-solid separators, mechanical functions which appear to be very susceptible to excessive wear and the frequent need for replacement or repair).

In general, the Study Group did not regard the safety-hazard potential for the radioisotopic heater in General Electric RITE Process to be very serious. The principal reason for this was the characteristic design of the unit, which does not show susceptibility to failure modes (over-pressure, explosion, etc.) that could cause loss of containment of the radioactive material. The RITE process is particularly attractive in its low equivalent-weight potential. This characteristic, together with the relatively high probability (in the Study Group's judgment) for operation without critical safety or performance problems, appear to account for the higher total score and top ranking by the Study Group in the trade-off analysis for the baseline mission-application case.

The Study Group realized that the tradeoff-model tool for management decision-structuring should not form the sole basis for decision making. As in all models, the results are sensitive to the criteria upon which the model is based. Therefore, it is very valuable to test the extent of this sensitivity. The Study Group performed such a test on the apparently controlling parameters of the trade-off model described in Section 5.1 and used by the Study Group in its comparative evaluation. The results of this sensitivity test are described in Section 6 of this report.

References for Section 5.


| Ref. No. | Citation |
| --- | --- |
| 5.1 | Yakut, M.M., "Cost Analysis of Water Recovery Systems," McDonnell-Douglas Report G-4632; Contract No. NAS 8-28377; NASA CR-111991; July 1973. |
| 5.2 | Space Station Program Definition Phase B-Final Report; SVHSER 5660; Hamilton Standard Division of United Aircraft Corporation; June 1970. |
| 5.3 | Personal correspondence with S.F. Fields and F. Budininkis, GARD, GATX. |
| 5.4 | Fields, S.F., L.J. Labak and R.J. Honegger, Development of an Integrated, Zero-G, Pneumatic Transporter/Rotating-paddle Incinerator/Catalytic Afterburner Subsystem for Processing Human Wastes Onboard Spacecraft," NASA CR 114764, General American Research Division, GATX; April 1974. |
| 5.5 | Schelkopf, J.D., F.J.Witt and R.W. Murray, "Integrated Waste Management-Water System Using Radioisotopes for Thermal Energy," G.E. Document No. 74 SD 4201, AEC Contract No. AT (11-1) - 3036; May 1974. |
| 5.6 | Jagow, R.B., "Design and Development of a Prototype Wet Oxidation System for the Reclamation of Water and the Disposition of Waste Residues Onboard Space Vehicles," NASA CR-112151; Lockheed Missiles and Space Co., Inc. for Contract NAS 1-9183; May 1972. |
| 5.7 | Personal communication with J.D. Schelkopf and R.W. Murray, General Electric. |

## 6. CONSIDERATION OF OTHER THAN BASELINE CRITERIA

As was discussed in Section 5, the Study Group felt that the tradeoff model should be tested for sensitivity to the baseline criteria upon which the model was based. Project resources did not permit an in-depth analysis of the effects of other than baseline mission cases. However, an indicative test was made in an effort at least to bracket sensitivity effects for one of the principal parameters in the model. The parameter that was selected for this test was "Penalties," Comparison Category $s_6$ in Tables 5-I and 5-III. As was discussed in Section 5.4, although this parameter was not the only controlling factor in the evaluation rankings that resulted from the trade-off analysis, it showed the largest difference in scores among the three candidate processes (as shown in Table 5-III). It also appeared to have the greatest inherent potential for sensitivity to changes in mission specifications.

In selecting a basis for the sensitivity test, the Study Group noted that the G.E. RITE process showed a significantly lower penalty factor, in terms of equivalent weight (Table 5-II) principally because that process uses the radioactive heat source and operates on a 24-hour/day (continuous) duty cycle. Therefore, it was decided that the sensitivity analysis would be based upon variations of the choice of heat source and duty cycles for the other two alternative processes. Table 6-I presents the two alternative test cases (cases 2 and 3) in comparison with the Baseline Case (case 1) upon which the trade-off analysis described in Section 5 was based.

In Case 2, both the GARD Dry Incineration Process and the Lockheed Wet-ox process are considered to be redesigned (if practical) to use a radioisotope source of heating, as in the case of the G.E. RITE Process. In addition, the

Table 6-1. Comparison of Criteria for Baseline and Sensitivity Test Cases.

| CASE | PROCESS CRITERIA | | |
|---|---|---|---|
| | G.E. RITE | WET-OX | CARD DRY INCIN. |
| **CASE 1. Baseline --** | | | |
| a. Duty cycle of auxiliary units: | 8 hr/day | 8 hr/day | 8 hr/day |
| b. Duty cycle of major process unit: | 24 hr/day | 16 hr/day | 8 hr/day |
| c. Thermal energy source: | RITE | Electric | Electric |
| **CASE 2. --** | | | |
| a. Duty cycle of auxiliary units: | 4 hr/day | 8 hr/day | 8 hr/day |
| b. Duty cycle of major process unit: | 24 hr/day | 24 hr/day | 24 hr/day |
| c. Thermal energy source: | RITE | RITE | RITE |
| **CASE 3. --** | | | |
| a. Duty cycle of auxiliary units: | 24 hr/day | 24 hr/day | 24 hr/day |
| b. Duty cycle of major process unit: | 24 hr/day | 24 hr/day | 24 hr/day |
| c. Thermal energy source: | RITE | RITE | RITE |

Table 6-II. Sensitivity-analysis Comparison of Total Equivalent Weight Values for the Alternative Processes for Three Design Cases.

| CASE (see Table 6-1) | G.E. RITE (Equiv.wt.,lb) | Lockheed Wet-ox (Equiv.wt.,lb) | GARD Dry Incin. (Equiv.wt.,lb) |
|---|---|---|---|
| CASE 1 Baseline; same as values in Table 5-˜I): | 3,009 | 4,441 | 8,421 |
| CASE 2: | 3,009 | 4,000 (approx.) | 4,000 (approx.) |
| CASE 3: | 2,700 (approx.) | 2,400 (approx.) | 2,500 (approx.) |

major process unit (reactor and supporting hardware, but not including the auxiliary units added by the Study Group to complete the standardized flowsheets) of the GARD and Lockheed Processes is assumed to operate on a 24-hour duty cycle, similar to the major process unit of the G.E. process. However, the duty cycles for the auxiliary (standardized add-on) units remain the same as for the Baseline Case (Case 1). With these changes, new values for total equivalent weight were approximated for the GARD and Lockheed processes (values for the G.E. process would, of course, remain the same as for Case 1) for comparison with Case 1 values given in Table 5-II. The values for Cases 1 and 2, for all three processes, are presented in Table 6-II for comparison purposes. It can be seen that the reduction in penalty value for the GARD process becomes sharply reduced, and the G.E. process shows only about a 1,000 lb. penalty advantage over the other two processes for the Case 2 conditions.

In Case 3, the conditions for the choice of thermal energy source and duty cycle for the major process unit remain the same as for Case 2 for all three processes. However, additionally, the duty cycle for all auxiliary (standardized add-on) units is increased to 24 hours/day (continuous operation) for all three processes. The effects of this change on total equivalent weight values for all three processes also are shown in Table 6-II. As can be seen, this change has a dramatic equalization effect on the penalty values for the three alternative processes. This would cause a similar equalization in the values of $s_6$ (Table III) if a trade-off scoring were performed for this case.

The results shown in Table 6-II suggest that the "Penalties" Comparison Category, $s_6$, is very sensitive to design changes, such that it is quite reasonable to expect design improvements that will result in essentially the equalization of penalty values among the candidate processes. Other evaluation factors, particularly safety and performance factors, then will principally influence the trade-off analysis and selection of the best process for a particular application.

The Study Group had also desired to consider the effects of variations in crew size and mission duration on the trade-off comparisons. However, it was determined that insufficient data are presently available for the laboratory units in use by the contractors to provide estimates of the differences which will ultimately exist in requirements for expendable and resupply materials. In addition, real values for scaleup factors, based on thro[illegible] increases that would result from changes in mission parameters, are not a[illegible]able at present. Therefore, a reliable analysis of the impact of crew size and mission duration on the trade-off comparison presented in Section 5 will have to await the availability of adequate test data and detailed design calculations based on meaningful scaling experiments.

## 7. CONCLUSIONS

### 7.1 Conclusions:

The material presented in the previous sections of this report provided the basis for several conclusions. These are summarized below.

1. All three process concepts offer feasible and viable systems approaches to water and waste collection and processing to meet the standardized input and output specifications which provide the basis for this study.
2. Test data available for all three process concepts are not presently adequate for a complete definition of closed-system design specifications to satisfy the standardized input and output requirements of this study.
3. Based upon the Study Group's estimates of design requirements for the standardized flow sheets for the three alternative processes, and the trade-off model developed by the Study Group, the G.E. RITE process shows the greatest overall promise for satisfying the standardized input and output requirements. The promise is based principally on safety, performance and penalty factors, as specified in the trade-off model. It is also the most advanced, mature system from the standpoint of readiness and reduced requirements for as yet undeveloped auxiliary units.
4. The criteria for penalties assessment, associated with the Study Group's trade-off evaluation model, are sensitive to potential design changes. It is possible that further design refinements in the Wet-oxidation

and Dry-incineration processes might equalize the penalty values for the three alternative processes. Safety and performance factors in the trade-off model would then control the comparison. In the Study Group's judgment, the G.E. RITE system would still show the greatest promise for meeting the requirements of the standardized input and output specifications.

5. The Wet-oxidation process was considered by the Study Group to have moderately severe potential for safety and performance (including reliability and maintainability) problems in its present design. The Study Group was cautiously optimistic that some of these problems might be attenuated through further development, particularly to reduce operating-pressure requirements and simplify the operating complexity and interfacing requirements.

6. The Study Group judged that the Dry Incineration process would offer the potential advantages for use in meeting the standardized input and output requirements. However, it does provide for the separate processing of solid trash and feces without the necessity of combining these streams with water-recovery streams. In this case, the entire waste-processing procedure appears to be easier. NASA should seriously consider the potential for net advantages of this approach for certain types of manned missions. Further development of the Dry Incineration process then would seem to be justified (along the lines discussed in Section 7.2).

7. The reliable analysis of the potential impact of crew size and other mission parameters on the trade-off comparison performed on this study will have to await the availability of adequate test data and detailed design calculations based on meaningful scaling experiments. These were not available for the present study, and extensive estimating of design

requirements had to be accomplished.

8. The procedures employed on this study should provide NASA with an effective tool and guidelines for similar technology-status evaluation studies in the future.

## 7.2 Recommendations:

In addition to the recommendations implied in Section 7.1, the Study Group identified some specific areas for consideration by NASA. These are summarized below.

1. In future development work on any or all of the three alternative processes, emphasis should be placed on the thorough characterization of the composition, flow rate, temperature and pressure of all input and output streams (i.e., to develop a complete material and energy balance based on data). This is absolutely necessary to provide a basis for reliably evaluating the effectiveness of a process step, making design improvements to increase effectiveness, and design scaleup or adaptation to other performance specifications. Several very important data voids were identified on this study for each of the three processes, and these had a severe impact on the evaluation analysis. Specific problem areas were discussed in detail in other sections of this report.
2. Requirements for the catalytic oxidation of product streams (to "purify" them prior to interfacing with the spacecraft atmosphere-revitalization subsystem) were virtually ubiquitous in the Study Group's analysis of the flowsheets for the three alternative processes. However, very little design and performance data were attainable for catalytic oxidizer units. Available data suggested a very poor under-

standing of the processes a ociated with such units. This is an area of technology development which requires emphasized attention.

3. If the "standardized model" used in this study is of actual interest to NASA, major component development and testing should be accomplished in a timely manner for the appropriate auxiliary (add-on) units included by the Study Group in the standardized flowsheets for the alternative processes.

# APPENDIX I

## SUMMARY OF STUDY GROUP'S MEETING AND DISCUSSIONS WITH CONTRACTORS' REPRESENTATIVES

## LIST OF STUDY GROUP'S MEETINGS WITH CONTRACTORS' REPRESENTATIVES AND SITE VISITS ON THIS PROGRAM

| Date | Contractor | Site | Contractor Reps. | Remarks |
|---|---|---|---|---|
| 7/24/74 | G.E. | Philadelphia | Murray; Schellkopf | Followup to first preliminary mtg. on Task IV, 12/5/73. |
| 7/25/74 | GARD | Chicago | Budininski; Fields | Followup to John Manning's contacts with GARD in 1973. |
| 7/30/74 | GARD | Seattle | Budininski; | Followup to mtg. on 7/25/74; new data presented. |
| 8/_/74 | Lockheed | Palo Alto | Jagow; | Followup to contacts by Ross & Manning in 1973. |
| 9/8/74 | G.E. | Philadelphia | Schellkopf; | Followup by Monell, only, to mtg. on 7/24/74; clarification of data. |

**Summary of Study Group's Site Visit and Meeting with Contractor's Representatives at General Electric, 7/24/74**

I. **Attendees**: (1) Study Group -- J. Spurlock, M. Modell, W. Ross, D. Putnam, and J. Pecoraro.

(2) General Electric -- R. Murray, J. Schellkopf

II. Principal Discussion Topics and Activities:

A. Flow-sheet and Operational Details, Clarification Discussion --

1. Nature of the air sweep in urine transport.
2. "Pyrolyzer" is actually a catalytic oxidation unit.
3. Oxygen input rate to the evaporator.
4. Efficiency of the catalytic oxidation units.
5. Explanation of catalyst degradation reported by G.E.
6. Method, reliability of product water analysis
7. Clarification of significance of condenser vent data.
8. Explanation of low pH in product-water data reported by G.E
9. Explanation of significance of "$CH_4$" component, other species in analysis of steam-vent discharge stream, also, general discussion of alternative methods of determining (calculating) [illegible] rates of these species

B. Spacecraft Systems Design Considerations --

1. Solids handling capability in zero-g situation.
2. Weight, power and volume requirements (estimates) for components.
3. Effect of using washwater instead of washwater concentrates.
4. Effect of no-dump (overboard), closed loop operation
5. Effect of a standard-model operation, also, scale-up criteria.

**Summary of Study Group's Followup Meeting**
**with GARD/CATX Representatives in Seattle, WA, 7/30/75**

I. Attendees: (1) Study Group -- J. Spurlock, M. Modell, W. Ross, D. Putnam, and J. Pecoraro.

(2) GARD -- F. Budininski, L. J. Labak.

II. Principal Discussion Topics:

A. Characterization of Process Steps in the Incineration Cycle:
1. Review of strip-chart temperature histories.
2. Determination of the duration of the several events which constitute the incineration cycle.

B. Material and Energy Balance Values for the GARD Process:
1. Discussion of GARD's suggested values (see attached diagram with original and new values inscribed).
2. Discussion of adequacy and source of GARD values and possible reasons for differences between these and the Study Group's estimated values.

C. Additional Testing Needs to Improve Data Base:
1. Experiments with catalytic afterburner, using several promising catalysts, to obtain continous performance data for the complete incineration cycle and to identify the best catalyst and oxygen requirements using a realistic waste input to the incinerator.
2. Thorough analysis of all output streams.

## Summary of Study Group's Site Visit and Meeting with Contractor's Representatives at Lockheed, 8/2/74

I. **Attendees**: (1) Study Group -- J. Spurlock, M. Modell, W. Ross, D. Putnam, and J. Pecoraro.

(2) Lockheed -- B. Jagow;

II. **Principal Discussion Topics and Activities**:

A. Review of Current Status of Work Since Last Report (CR-112151)

1. General review of coupled-system tests, simulating spacecraft (input) conditions.
2. Grinder performance, problems; plans for use of trash.
3. Updated schematic diagram of current "system" (see attached handout) and feed-input model (source for as-tested operations (feed input reported in CR-[illegible] was Lockheed's estimate, not similar to current feed-input specified by NASA-JSC).
4. Method of sampling and analyzing gas and liquid product samples from the wet-ox reactor
5. Details of catalyst used, effectiveness, problems.
6. Clarification of effectiveness of [illegible] as an indicator of reactor conversion.
7. Detailed discussion of data (mostly results of gas analysis) available to date.

B. Spacecraft Systems Design Considerations --

1. Estimates of weight, volume and power requirements (see attached handout).
2. Reliability and safety of high-pressure components.

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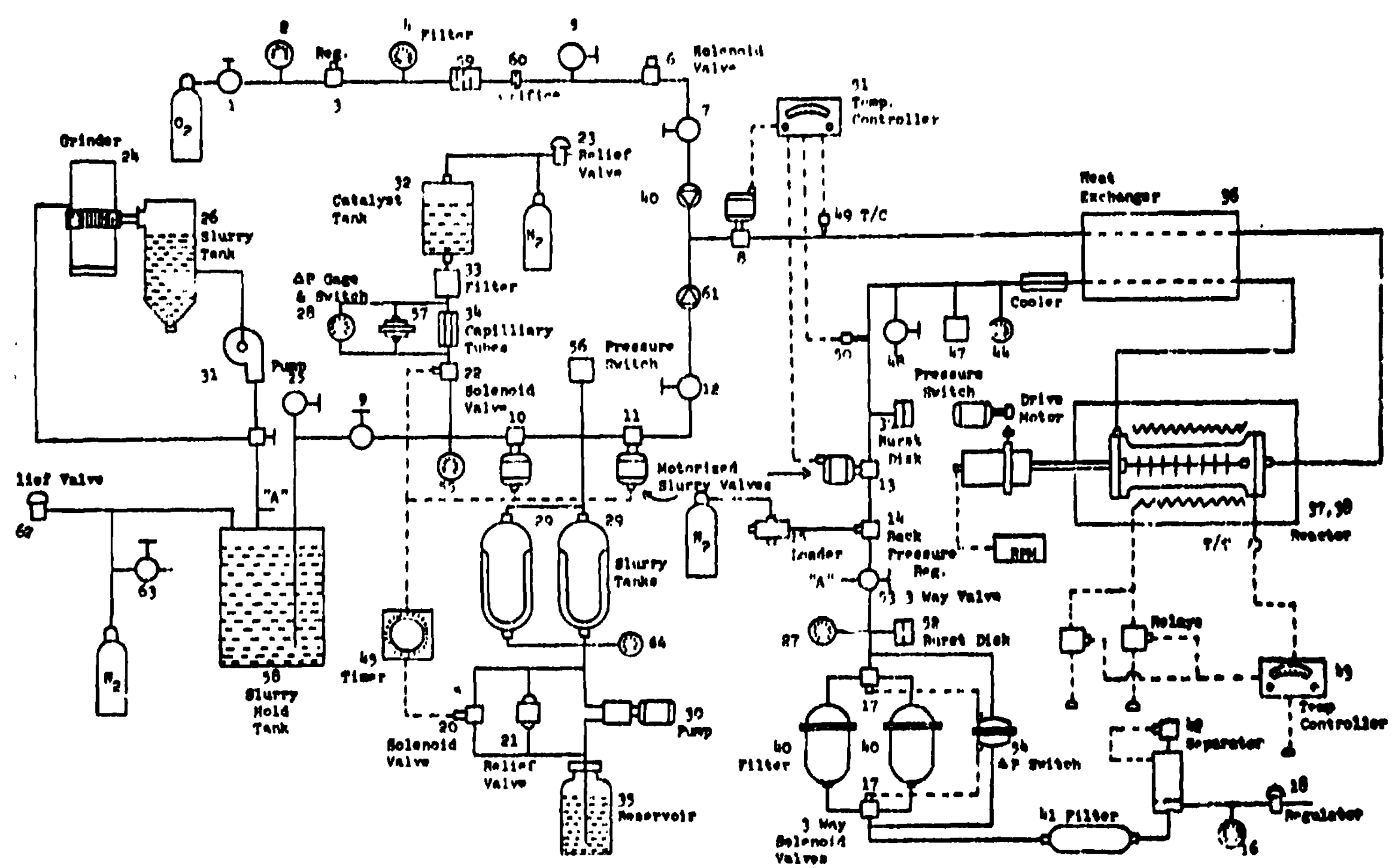
Lockheed Handout Sheet A



Wet Oxidation System Schematic

## Lockheed Handout Sheet B

### Detail Waste Model for NAS 1-11748

1) Mix in blender and dump into slurry hold tank:

   - 9850 cc of Urine (2 gallons + 2300 cc)
   - 770 gm of Feces
   - 7560 cc of Water (2 gallons)

2) Pour 7560 cc of Water (2 gallons) into grinder hold tank.

   Load the following materials into grinder feed [illegible] and operate grinder:

   - 362 gm Dog Food
   - 91 gm Aluminized Mylar
   - 406 gm Polyethylene
   - 362 gm Cotton Cloth
   - 227 gm Wash & Dry Towelettes
   - 35 gm Gauze
   - 10 gm "Q" Tips
   - 45 gm Mylar
   - 45 gm Teflon
   - 90 gm Pine Sol Disinfectant
   - 227 gm Paper Towels
   - 182 gm Polystryrene

**Lockheed Handout Sheet C**

**NASA WET OXIDATION GAS ANALYSIS**

| | | |
|---|---|---|
| $O_2$ | 75.4 | 75.8 |
| $N_2$ | 9.2 | 7.2 |
| $CO_2$ | 15.5 | 4.9 |
| $NH_3$ | $\leq$ 1 ppm | $\leq$ 1 ppm |
| $NO_2$ | $\leq$ 0.1 ppm | $\leq$ 0.1 ppm |
| NO | $\leq$ 0.1 ppm | $\leq$ 0.1 ppm |
| CO | 235 ppm | 550 ppm |
| $SO_2$ | $\leq$ 1 ppm | $\leq$ 1 ppm |
| THC | 89 ppm | 42 ppm |

## Lockheed Handout Sheets D

**WEIGHT, POWER, AND VOLUME STATEMENT**
**FOR NASA WET OXIDATION WASTE MANAGEMENT SYSTEM**
**(4.3-Man System; Based on 61.4 lb/day Model) (NASA 1-11748)**

| Description | Total Est. Wt. (lb.) | | Steady State Est. Power (Watt) | |
|---|---|---|---|---|
| Hydraulic Reservoir | 3.0 | (0) | | |
| Hydraulic Pumps (2) | 44.0 | (20) | 40 | (0) |
| Hydraulic Relief Valves (2) | 5.0 | (0) | | |
| Hydraulic Bypass Solenoid Valve | 3.5 | (0) | | |
| Hydraulic Pressure Switch | 2.5 | (0.5) | | |
| Hydraulic Pressure Gauge | 1.8 | (1.0) | | |
| Oxygen Shut-Off Valves (2) | 1.5 | (1.5) | | |
| Oxygen Aux. Inlet Valve | 0.6 | (0) | | |
| Oxygen Pressure Gauge (2) | 3.6 | (2.0) | | |
| Oxygen Pressure Regulator | 4.0 | (1.5) | | |
| Oxygen Filter | 0.4 | (0.4) | | |
| Oxygen Restrictor (2) | 0.3 | (0.1) | | |
| Oxygen Bleed Valve | 0.7 | (0.7) | | |
| Oxygen Solenoid Valve | 3.5 | (0) | 44 | (0) |
| Oxygen Check Valve | 0.3 | (0.3) | | |
| Catalyst Tank | 5.1 | (5.1) | | |
| Catalyst Pump | 8.0 | (2) | | |
| Catalyst Solenoid Valve | 1.0 | (1.0) | | |
| Slurry Accumulator Bladder Tanks (2) | 23.0 | (0) | | |
| Slurry Motor Actuated Valves (2) | 10.0 | (0) | | |
| Slurry Hand Actuated Valves (2) | 2.4 | (2.4) | | |
| Slurry Check Valve | 1.0 | (0.5) | | |
| Slurry Pressure Gauge | 0.5 | (0.5) | | |
| Terminal Board | 0.5 | (0.5) | | |
| Wiring (Total Module) | 2.2 | (1.5) | 20 | (14) |
| Timers (2) | 3.0 | (0.5) | 5 | (1) |
| Pushbutton Switch/Lites (10) | 1.8 | (0.5) | 1 | (1) |
| Plumbing (Total Module incl. Fittings) | 4.0 | (3.0) | | |
| Structure | 20.0 | (10) | | |
| Total Dry Weight Supply Module | 157.4 | (55.5) | 110 | (16) |
| Hydraulic Fluid | 16.7 | (0) | | |
| Catalyst Solution | 2.0 | (2.0) | | |
| Slurry | 16.7 | (1.0) | | |
| Total Liquids | 35.4 | (3.0) | | |
| Total Weight Supply Module (Wet) | 192.8 | (58.5) | 110 | (16) |

Total Supply Module Volume 8.67 $ft^3$ (6.1)

**Lockheed Handout Sheets D (continued)**

| Description | Total Est. Wt. (lb.) | | Steady State Est. Power (Watt) | |
|---|---|---|---|---|
| Reactor (Including Drive Motor, Insulation, Fan, Belt, RPM Meter, Tach. Adjust) | 90.0 | (65) | 265 | (200) |
| Reactor Motor Actuated Valves (2) | 10.0 | (5) | | |
| Reactor Regenerative Heat Exchanger | 50.0 | (25) | | |
| Reactor Back Pressure Regulator | 2.9 | (2) | | |
| Reactor Bleed Valve | 0.7 | (0.7) | | |
| Reactor 3-Way Recycle Valve | 0.5 | (0.5) | | |
| Reactor Pressure Switch | 2.5 | (0.5) | | |
| Reactor Pressure Gauge | 1.8 | (1.0) | | |
| Reactor High Pressure Burst Disc | 1.0 | (1.0) | | |
| Reactor Regen. Ht. Exchgr. Thermocouples (2) | 0.2 | (0.2) | | |
| Reactor Regen. Ht. Exchgr. Temp. Alarm Cntrlr. (2) | 3.0 | (1.5) | 10 | (5) |
| Reactor Temp. Controller | 8.5 | (1.0) | 15 | (10) |
| Cooler | 1.7 | (0) | | |
| Low Pressure Burst Disc | 2.0 | (0.5) | | |
| Filter Primary (2) | 8.0 | (4.0) | | |
| Filter Secondary | 2.5 | (1.0) | | |
| Filter Solenoid Valves | 7.0 | (2) | 44 | (0) |
| Filter Pressure Gauge | 0.5 | (0.5) | | |
| Filter Pressure Switch | 2.5 | (0.5) | | |
| Phase Separator | 5.1 | (4) | 27 | (20) |
| Phase Separator Control | 1.1 | (0.5) | 2 | (2) |
| Phase Separator Pressure Gauge | 0.5 | (0.5) | | |
| Phase Separator Liquid Back Press. Relief Valve | 0.3 | (0.3) | | |
| Pushbutton Switch/Lites (15) | 2.7 | (0.7) | 2 | (2) |
| Circuit Breakers (2) | 0.4 | (0.4) | | |
| Alarm | 1.0 | (0.5) | | |
| Relays (6) | 1.2 | (0.5) | 5 | (2) |
| Terminal Board | 2.3 | (2) | | |
| Wiring (Total Module) | 4.4 | (3) | 40 | (28) |
| Plumbing (Total Module Incl. Fittings) | 5.0 | (3.8) | | |
| Structure | 30.0 | (15) | | |
| Total Dry Weight Processing Module | 249.3 | (143.1) | 410 | (269) |
| Slurry/Effluet | 5.0 | (4) | | |
| Total Wet Weight Processing Module | 254.3 | (147.1) | 410 | (269) |
| Total Processing Module-Volume 17.33 $ft^3$ (11.2) | | | | |
| Total System Weight and Power | 447.1 | (205.6) | 520 | (285) |
| Total System Volume 26.00 $ft^3$ (17.3) | | | | |

Figures in parentheses indicate potential results which could be accomplished as a result of comprehensive flight design.

**Lockheed Handout Sheet E**

**Comparison of Waste Models for NAS 1-11748**

| | | LMSC | NASA-JSC |
|---|---|---|---|
| 1) | Urine | 24.0 | 21.7 |
| 2) | Feces | 2.6 | 1.7 |
| 3) | Flush Water | 30.0 | 33.4 |
| 4) | Food Wastes* | 2.7 | 2.5 |
| 5) | Wipes** | 1.3 | 1.3 |
| 6) | Housekeeping, Hygiene*** | 0.6 | 0.8 |
| | | 61.2 lb/day | 61.4 lb/day |

*Food Wastes:

| | |
|---|---|
| - Wet Food | 0.8 |
| - Aluminized Mylar | 0.2 |
| - Polyethylene | 0.9 |
| - Polystryrene | 0.4 |
| - Paper | 0.2 |
| | 2.5 lb/day |

**Wipes:

| | |
|---|---|
| - Utility | 0.8 Cloth |
| - Hygiene | 0.5 Towelettes (Wash & Dry) |
| | 1.3 lb/day |

***Housekeeping, Hygiene:

| | |
|---|---|
| - Gauze & "Q" Tipes | 0.1 |
| - Mylar | 0.1 |
| - Teflon | 0.1 |
| - Disinfectant | 0.2 |
| - Paper Towels | 0.3 |
| | 0.8 lb/day |