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AN ECONOMIC FEASIBILITY STUDY ON THE
SPACE-BASED PRODUCTION OF METHANE GAS FROM
HUMAN WASTE THROUGH ANAEROBIC DIGESTION
FOR USE AS AN ORBIT MAINTENANCE PROPELLANT

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science

Coral C. Fallstead, B.S.
Captain, USAF
December 1985

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Approved:

Accepted:

Dean, School of Engineering
Preface

As our nation moves toward the goal of a manned presence in space, we have come to the realization that we must make every effort possible to reduce our dependencies on Earth resources if we are to maintain this presence and our economic well being. The high cost of transporting fuels and resources into space and returning waste products to Earth may make our stay in space a relatively short one. We must begin to nurture and research a space self-sufficiency concept which will allow us to exploit the resources of space without doing the same to the Earth.

I have often been intrigued by the man who powered his home with a wind generator and the farmer who ran his farm on the waste of his pigs and cattle. Why not this type of self-generated power in space? Is it economically feasible to develop a system that would turn our waste products in space into fuel energy? This research project explores this question with regard to the fuel energy created being applied to maintain a space station's orbit.

The energy generating concept proposed in this study is anaerobic digestion. This process has four benefits for space application; 1) it can stabilize human waste products, 2) it can reduce solid wastes, 3) it can provide a fairly clear effluent for water recovery, and 4) it can provide a fuel in the form of a gas. The method envisioned for employing this energy producing process was to first determine a scenario so that input load to the digester system would be known and also the size of the spacecraft, which would be "powered" by this energy source, could be defined. The size and shape of the vehicle is necessary in determining...
the atmospheric drag which must be opposed to maintain the orbit.

To properly analyze this concept it was necessary to research three distinctly unrelated areas; 1) simulation analysis of biochemistry, 2) thermochemical analysis and, 3) cost analysis. In performing the cost analysis it was necessary to determine an alternative system for comparison. The alternative selected was the transport of conventional propellants from the Earth. This alternative does not consider a replacement of the anaerobic digester with some other system which must be present to stabilize the waste products of the space station. Nor does it consider the additional benefits of the anaerobic digester listed in the preceding paragraphs. In this respect the analysis can only be regarded as a partial one; however, its utility lies in its use as a comparison tool which can be applied toward analysis of any other waste stabilization system that may be selected. The benefits may be taken as decision variables which would be considered in any decision of a waste treatment/fuel source decision.

A good deal of the foundation for understanding the biochemistry involved in anaerobic digestion, and the analytical descriptions of the methane generation process, came from Price and Cheremisinoff’s book, *Biogas Production & Utilization*. Their equations provided the primary relationships upon which the simulation model was built. During the study it was realized that the methane produced by the anaerobic digester would have to react with an oxidizing agent if there was any hope of the system making a significant contribution to the orbit maintenance requirement. Air Force Institute of Technology (AFIT) professor Dr. William Elrod’s assistance in the thermochemical analysis of this thesis is greatly appreciated. He dedicated many hours to enhancing my understanding of a subject area I knew very little about. I thank him also for the guidance he provided as a
reader in keeping this report accurate and on track. The computer program used in
the thermochemical analysis was a modification of a program by Capt. Robert
Demmick. His generosity, in letting me use his program, was essential in
completion of this project. Dr. Lynn Wolaver, Dean for Research and Professional
Development at AFIT, was also beneficial as a reader in keeping the biochemistry
aspects of this thesis accurate and concise. I truly appreciate the giving of his
time from his busy schedule for the benefit of this project. My advisor, Dr.
Joseph Cain, Associate Professor of Economics at AFIT, deserves a great deal of
recognition for his guidance throughout this project, especially in the cost analysis
portion; thank you for your support. The experts also deserve recognition for
their time and support in providing me with the inputs I needed to configure the
digester system and cost the component parts; I thank David Hill and Richard
Westerfield, waste treatment engineers at the Dayton Municipal Waste Treatment
Facility. I also thank Gary Lubin at The Henry P. Thompson Company for his
assistance in the estimation of many of the digester system components. A
special thanks to Kathy Cook, superintendent of the waste treatment facility for
the city of Fairborn, for providing me with many of the EPA and Water Pollution
Control Federation documents used as references in this research work.

There are two other people who, though they did not contribute to this
thesis directly, were fundamental in its development and completion. The
appreciation I have for the support I have received from my wife, Edna, and my
daughter, Janae, cannot be expressed in words. I believe their devotion to this
effort has been greater than mine. Without them this thesis would not have been
possible. Thank you both.
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Abstract

This project explores the economic feasibility of creating fuel energy in space from human waste with application toward space station orbit maintenance. The energy generating concept proposed in this study is anaerobic digestion. This process has four benefits for space application; 1) it can stabilize human waste products, 2) it can reduce solid wastes, 3) it can provide a fairly clear effluent for water recovery, and 4) it can provide a fuel in the form of a gas.

The analysis is dependent upon a predetermined scenario defining the input load to the digester system and the size of the spacecraft. The size, shape, and altitude of the vehicle determine the atmospheric drag which must be opposed to maintain the orbit. The basic elements of the study involve 1) simulation analysis of biochemistry, 2) thermochemical analysis and, 3) cost analysis using the Monte Carlo method. An alternative system to which the digester is compared is transport of conventional propellants from Earth. This alternative does not consider a replacement of the anaerobic digester with some other system to stabilize the waste products of the space station, or the additional benefits of the anaerobic digester listed above. In this respect the analysis can only be regarded as a partial one; however, its utility lies in its use as a comparison tool which can be applied toward analysis of any other waste stabilization system that may be selected. The results of this study show a statistically significant advantage of the digester system over transported conventional propellants due to the high cost of space transportation. Recommendations are to investigate other altitude scenarios and to compare the digester to other waste stabilization methods.
I. INTRODUCTION

Background

Current procedures in disposal management of human waste in the space environment involve thermal drying or space vacuum drying of fecal solids and return of these solids to Earth. Both of these methods require energy expenditure. Heat is required in the thermal drying process, and energy is expended when returning the residual waste mass to Earth through a controlled reentry. As man extends his time in space the need to establish requirements for handling metabolic wastes within his space habitat over long duration missions will be the focus of much research and development efforts. These efforts will concentrate on the most efficient means of reducing and utilizing the waste. The high costs of space transportation places additional emphasis on recycling the wastes of a space habitat. By reclaiming energy from the waste materials through an anaerobic digestion process, reduction of these costs may be possible. (31:6; 32:82; 33:18; 34:53; 35:922)

In future long duration manned space missions, life support systems can be expected to supply by-product gases, mainly hydrogen, methane and carbon dioxide. All are candidate gaseous propellants which can be used for spacecraft attitude control. These gaseous outputs can be provided by various bioregenerative systems that use microorganisms to stabilize waste materials.
before they build up to toxic levels. With such systems, human and other waste products in the spacecraft are potential sources of future propellants. Utility in the production of energy biogas, through anaerobic decomposition of human waste solids, may provide a viable energy source on long duration space missions where quantities of wastes must be managed to provide the least amount of energy expenditure for the most amount of energy return. (45:228,469)

Though a limited amount of scientific study has been done on biogas production from solid waste materials on Earth, research proposals have only been suggested in this area of solid waste management applicable to space.

Problem Statement

The technological area of methane generation from human waste has received very little research attention for spacecraft application. Sufficient engineering data relating to the biological treatment of concentrated wastes for precise design calculations of components to be used in space are not available. Most of the technological developments to date are the products of research and applications relating to municipal waste processing. (30:24; 36:266)

The use of methane as a gaseous propellant for attitude control on spacecraft is already a well proven concept and hence is not presented as a main topic in this thesis research. However, analysis of methane quality, quantity, collection method, and the biogas process is presented in determination of concept validity. A specific scenario based on space platform mission provides the boundaries for modeling these factors. The scenario is based on previous studies performed by NASA which were concerned specifically with designing space colonies. In determining the economic feasibility of the methane generation concept, a comparison of acquisition and operating costs between propellant supply
via shuttle and space based methane generation is necessary. (30; 34; 45:228)

Purpose of Study

As manned mission requirements begin to extend up to one year and beyond, research and development efforts will seek life support systems and waste subsystems which will reduce weight and volume requirements of the total manned vehicle complex. At the same time, increasing fuel and transportation costs will require more conservative and possibly less sophisticated fuel sources if we are to remain guardians of the high frontier. The anaerobic digester provides one such waste subsystem which can reduce metabolic waste volume and provide a useful by-product gas which may satisfy some, if not all, of the orbit maintenance fuel requirements.

The focus of this initiative is to determine the cost advantage, if any, of generating methane gas from human waste in space (for use as an orbit maintenance propellant) compared to providing propellants from Earth via the shuttle. The term orbit maintenance is considered here as it applies to overcoming the Earth's atmospheric drag on a permanently manned space station, since this is the force that finally removes the satellite's energy and causes it to spiral inwards toward Earth. This problem will be addressed in four phases: 1) development of an applicable scenario to define propellant requirements, 2) sizing of the methane generation system in an attempt to meet these requirements, 3) estimation of the acquisition and operational cost of the system, and 4) comparison of the system costs with the logistics cost of transporting propellants. (44: 229)
Assumptions

The broad scope of this proposal requires a method of using established theory, simulation modeling and cost analysis, together with sound engineering principles. Existing data is used to the greatest extent possible and all methane generation modeling and volume and weight estimates incorporate mathematical relationships found in current literature applicable to Earth based systems. Cost estimations for this study are based on a comparison method or use current available costs on items having equivalent or existing counterparts.

The station will be assumed to have pseudogravity, due to the human physiological need for gravity on long duration space missions. Pseudogravity is artificial gravity created by rotation of the space station about a central axis. Use of analysis based on standard 1g Earth gravity is appropriate in specifying a system that will operate in a 1g pseudogravity environment. (34:21)

The space station will not be totally self sufficient and will be dependent on Earth's resources for such things as food. The location in space of the station, therefore, must be within the range of the shuttle and will be in a low earth orbit [LEO].

Size and weight of the space station is determined by the living and working space required for the crew members. In estimating crew size, area requirements, and structural mass, data from two programs in engineering design of habitats for sustaining life in space on a large scale will be used. The first design program was a 10 week study held at Stanford University and the Ames Research Center of the National Aeronautics and Space Administration in 1975. The results were published in a NASA pamphlet titled, Space Settlements, A Design Study. The second program was a similar study that took place in 1977. The technical
papers resulting from that program were published in a NASA pamphlet titled, *Space Resources and Space Settlements*. This study develops its scenario from NASA's work involved with the initial LEO operations which provide a staging base for assembly of lunar orbit payloads, space manufacturing, and laboratory experiments in simulated gravity. A modular habitat design is assumed to allow for future expansion and will accommodate 150–250 people. (30:66–71; 34:47).

Determination of the methane generator performance and size is dependent on the rate of methane expenditure for attitude control and can be interpreted as the generation rate requirement. Factors affecting methane generation are primarily temperature, moisture, input feed rate, residence time of waste material in the generator, degree of mixing, and loading rate. Using design criteria and formulas presented in Price and Cheremisinoff's book, *Biogas Production and Utilisation*, a continuous simulation model is developed in SLAM [simulation language for alternative modeling] with the above factors representing the input parameters. Input feed rate is dependent on the number of crew members selected, and human waste input rates are based on data obtained from studies done by NASA. (35:916, 41:97)

Since there is no night or day on a space station in a LEO, it is assumed that individuals aboard the station will work on shift schedules extended over 24 hour periods. Therefore waste feed input to the digester will vary on a six hour cycle following what would be the natural waste disposal flow of morning, noon, evening and midnight activities of the crews.

It has been shown that the main methane-producing bacteria are the mesophiles. These organisms are most active in the 30 – 40 °C range. Above this temperature no significant increase in gas production occurs until approximately
At this temperature the thermophilic bacteria are favored. Although there is a potential for increased gas production, the thermophilic temperature range is rarely used because it is impractical to provide the heat necessary to favor the bacteria. This study, therefore, will consider operating temperatures of the digester in the mesophilic range. (41:121)

One of the main objectives of all space based systems is the reduction of weight by integrating as many systems as possible. It is assumed that the anaerobic digester proposed in this study will be a subsystem of the life support system, and will be expected to provide a fairly clear effluent for water recovery. The digester shall therefore be a two stage system in which the first tank shall be used for digestion and be the primary methane generation source. The second tank will be for storage and concentration of digested sludge and will provide a relatively clear supernatant to a water recycling system. (41:93)

Though analysis of the water that may be recovered from the various cleaning, food preparation, and bodily waste activities has not been reported in the literature, it may be assumed that these waste waters will resemble domestic sewage with respect to the biological oxygen demand [BOD]. Calculations for methane generation rates involving BOD will use values from current literature on domestic sewage. (36:275)

Cost estimates for this initiative include the acquisition cost of the methane generation system, costs associated with placement and operating the system in space, and conventional propellant acquisition and shipping costs for comparison. Since a system of this type has not been designed for, or utilized in space before, costs are derived by comparison with similar systems on Earth. The life cycle cost of the system is calculated for a useful lifetime of approximately 30
years. Conventional propellant costs and shipping costs are based on current year dollars.

Methodology

The first step in handling a problem of this size is to partition the problem into its separate research components and to identify the relationships among those components. These relationships are shown in Figure 1. The following discussion will cover each of the four large blocks of research.
WHAT IS THE COST OF SPACE BASED METHANE GENERATION FROM HUMAN WASTE AND WHAT ARE THE COST ADVANTAGES, IF ANY, OF THE METHOD OVER SHUTTLED PROPELLANTS?

DEFINE THE SCENARIO
- Determine crew size
- Determine altitude
- Determine size and mass of vessel
- Determine orbit maintenance propellant expenditure rate
- Define requirements

DIGESTER PERFORMANCE
- Model digester
- Input parameters: Crew size/feed rate, and temperature
- Calculate output rate. Does it meet requirements? If not, what portion of requirement can be met?
- Calculate weight and volume of design

DIGESTER COST
- Calculate acquisition cost based on weight, volume and configuration
- Calculate cost of placing digester in space
- Calculate operational costs
- Amortize over 30 yrs
- Life cycle cost

COST SHUTTLED PROPELLANTS
- Determine amount of conventional propellant to meet requirement
- Determine cost to acquire and ship propellant via shuttle
- Life cycle cost
- Comparison of cost to generated propellants cost advantages?

Figure 1. Problem Research Procedure
Space Station Scenario. Crew size, altitude, and size and mass of the
space station are all based on previous studies done by NASA. Once location
and mass are determined, the force necessary to overcome atmospheric drag is
calculated from aerodynamic principles. This force is then interpreted in terms of
fuel requirements necessary to produce the change. The use of methane in a
cold-gas system and as a fuel in a bipropellant system is considered in
determining which method best meets orbit maintenance requirements. A cold-gas
orbit maintenance system is one which uses inert gas jets incorporating fast-acting
valves and receiving its propellant supply from pressurized cold gas supply tanks.
A bipropellant system requires two separate propellants, an oxidizer and a fuel. In
this case, methane provides the fuel. Various oxidizing agents, such as pure
oxygen, are considered. (30; 34; 45:204, 227)

Digester Performance. The digester is modeled using design criteria and
formulas presented in Price and Cheremisinoff’s book, *Biogas Production and
Utilization*. The model is formulated using FORTRAN statements in a SLAM
continuous simulation model. Input is feed rate based on the space station
population. The model allows for variation of the feed rate, as well as operating
temperature ranges. Outputs from the model are the volume rate of digester gas
produced and the volume requirement of the digester design. Analysis of the
output data will determine the proper combination of design parameters that meets
the methane rate requirement, and will also determine the required digester volume.
If the rate of methane production does not meet the requirement, all further
costing comparisons will be based on the portion of the requirement that can be
met. (41)

The modeled digester volume is used to estimate the weight of the
system components using comparable structural weights of hardware and materials appropriate for use in anaerobic digesters. Many of the component parts necessary to operate the digester have been sized by comparison to a small scale portable digester built by Bio-Gas of Colorado and through consultation with waste water treatment engineers. (2:102)

**Cost of Digester.** One of the more difficult phases of this initiative is estimating the cost of the methane generation system. Literature searches have not produced data on which cost estimates may be based. Therefore, the method used to base costs is comparison against similar systems on Earth. Factors used in estimating cost are the size of the digester required, selection of construction materials, fabrication, weight, temperature, and mixing requirements. Local experts, such as waste treatment plant contractors and engineers were contacted to obtain this information. The cost of placing the unit into space is based on shuttle transportation rates for weight and volume of the selected design.

Operating costs are derived from estimated labor, maintenance and energy requirements based on a comparison of the designed facility with a municipal waste treatment plant having anaerobic digesters. The energy requirement is based on a standard percentage of total facility cost. (47)

In costing a system of this type an important consideration is that stabilization of human waste must be performed by one means or another to prevent the spread of disease by reducing pathogenic organism content. Therefore, the system will have advantages associated with its function as part of a closed cycle life support system. This closed cycle system will be required to produce a fairly clear effluent to be used for drinking water recovery. There are many waste treatment techniques and facility designs capable of performing these functions.
Therefore, all costs incurred in acquiring, operating and placing an anaerobic digester in space should be weighed against the alternative systems costs in providing waste stabilization and against current water recovery methods. The depth of research and computational resource requirements involved in a study of this complexity is beyond the scope of this project. This study then represents only a partial analysis which can be used as a comparison against alternative systems. There are many factors which may influence the selection of a particular system. One such consideration is the advantage associated with handling a reduced amount of waste solids from the digester. These waste products could be vacuum dried using current waste handling methods and returned to Earth or possibly utilized in space in such projects as space produced fertilizer for crop growth on future fully self-contained space stations. (39:923)

Cost of Shuttled Propellants. The final phase of this initiative will compare the methane generator cost to the cost of supplying the required orbit maintenance propellant by the shuttle.

Since nitrogen is the most common cold gas propellant used in orbit maintenance systems, it will be used as the comparison standard in costing the delivered propellant price if the cold-gas method of orbit maintenance is selected as best in meeting orbit maintenance requirements. Determination on how much nitrogen is required will be made by using a mass density comparison of nitrogen to that of digester quality methane based on the volume of methane requirement established in the scenario phase. (45:228)

To determine if the methane generated would best be used in a bipropellant system to meet orbit maintenance requirements, comparison against conventional shuttle orbit maintenance bipropellants (Monomethylhydrazine [MMH])
and Nitrogentetroxide \([\text{N}_2\text{O}_4]\) is made. Determination of the conventional bipropellant quantity necessary to meet orbit maintenance requirements is made by comparing the exhaust velocity or the specific impulse of the conventional bipropellants with that of the methane generated, when used in a bipropellant orbit maintenance mode. Specific impulse is a rocket performance parameter which relates thrust to the propellant mass flow rate [See Appendix A for a more complete definition]. (1:13–8; 45:29, 297)

The cost of the required conventional propellants is based on current market price. Shuttle transport cost is based on current payload cost rates where both propellant and container weight will be considered. (34:145)

The value of methane generation in space for orbit maintenance is determined by tabulating the various costs incurred in each system, calculating a total life cycle cost, and comparing these costs. In using the generated methane as a bipropellant, the additional cost of providing an oxidizer propellant is considered. Uncertainties resulting from estimations or assumptions are reflected by stating a range in which the prices are valid and an uncertainty associated with the price range. All costing data acquired during this study are standardized to current dollars prior to making a valid cost comparison.

**Sequence of Presentation**

In the chapters that remain a detailed examination is made of the methane generation process and the SLAM model as well as a cost comparison of the anaerobic digester propellant generation system versus the transportation of conventional propellants to the space station. An extensive review of current literature related to anaerobic digestion, space station designs, handling of human waste products in space, and current methods of orbit maintenance, fuel energy,
and costing calculations are presented in Chapter II to provide background for the study. Chapter III provides a detailed description of the development of the SLAM model which is used in determining methane generation rate and digester tank volume. Data analysis is also presented in Chapter III. In Chapter IV the calculations made in determining space station size and orbit maintenance requirements are presented. The best method for utilizing the generated methane is selected and propellant requirement is weighed against available methane output. Also in Chapter IV, costing data of the anaerobic digester and shuttled propellants are determined and compared. In Chapter V a discussion of the results and conclusions are presented based upon the results of Chapters III and IV. Chapter V concludes with a summary of the study results and recommendations for further study and action. Appendix A lists definitions of terms used throughout this study. Appendix B through E provide an example of the SLAM model and typical output data. Appendix F is an explanation of the thermochemical calculations made in Chapter IV to determine combustion temperatures of methane with oxygen. Appendix G is the program listing including input and output for the cost analysis done in Chapter IV.
II. LITERATURE REVIEW

A thorough investigation of the current literature was undertaken to provide the knowledge and background in the areas of anaerobic methane generation, system modeling techniques, feasible space station concepts, astrodynamical principles with regard to atmospheric drag, space propulsion, and economics concerning anaerobic digester components and space transportation. This chapter provides a review of the information obtained during the literature search which is essential in establishing a foundation for the study of space-based methane generation from human waste and its role as an orbit maintenance propellant. Although much research has been done in the area of waste management in space and in using space trash as a solid propellant, very little attention has been given to the economic feasibility of providing a gaseous propellant from an environmental control life support subsystem. This review, therefore, starts by identifying approaches that may offer options feasible for the methane generation process with regard to its capabilities aboard a space station. A close look at the anaerobic process, space-applicable anaerobic digester systems, capacities, and throughputs is accomplished to provide an understanding of the feasibility of such a concept for biogas production in space. A suitable scenario specifying space station size and weight must be established in order to size a particular digester system to its load and determine its methane output rate. Therefore, following the methane generation review is an introduction to NASA's research work in the area of space settlements and what can be expected in a near-future LEO space station. A coupling of the astronaut's waste in the space
ation with the methane generator is accomplished by means of a computer simulation model in order to provide an accurate estimate of the methane output rate and the digester volume requirements in terms of weight and size. Following the methane generation review, a description of the simulation language SLAM [simulation language for alternative modeling] is presented as background for understanding the model presented in Chapter III. The concluding sections of this chapter provide an overview of information sources used in determining digester, conventional propellant and shuttle transportation costs. (18; 36)

The Anaerobic Process

Methane gas can be, and has been, produced under controlled conditions for many years. Sewage treatment facilities use anaerobic digestion extensively. To date many research organizations both public and private have realized the potential of producing heat energy from organic material which would otherwise be dumped, unstabilized, into our environment. Research efforts began as far back as 1939 with the Gobar Gas Plant fabricated at the New Delhi, India, Agricultural Research Institute. China currently has over half a million small scale digesters. India has installed some 100,000 such plants, and Korea is building 50,000 small-scale anaerobic operations. In 1976 the U.S. Energy Research and Development Administration awarded a research contract to Waste Management Inc. of Oak Brook, Illinois, to build a municipal trash anaerobic digestion facility in Florida to further study biogas production from municipal refuse. (2:95)

While looking toward the future, NASA has realized that permanent stations in space will present new problems, particularly in minimizing waste products and the use of consumables (e.g. propellants requiring resupply from Earth). A partial solution to both of these problems may be found in the research
work that has been done on producing energy from waste here on Earth. (15; 36)

The primary goal in the anaerobic process is to produce a stable sludge which is not subject to further biological decomposition, which is less odorous and putrescible, and to reduce the pathological organism content. The procedures which are used to accomplish these objectives result in a gaseous by-product often referred to as "sewer gas", "biogas", or "digester gas". This gas is not pure methane but rather an approximate 70/30 mix of methane/carbon dioxide, with small percentages of nitrogen gas, hydrogen gas, hydrogen sulfide gas and water vapor. Of all these gasses, only methane contributes any significant energy value. Pure methane, a colorless, odorless hydrocarbon is combustible at concentrations of 5 to 12% by volume in air and has an energy value of approximately 35,800 kJ/m$^3$ of methane. Since digester gas is about 70% methane, it has an energy value of approximately 25,000 kJ/m$^3$. By comparison, natural gas has an energy value of approximately 37,300 kJ/m$^3$. Throughout this study the terms methane and biogas will be used interchangeably. In addition to the gas produced during the stabilization process, a large percentage of the sludge is converted to liquid which can be reclaimed through water recovery subsystems. This conversion of the digester sludge to gas and liquid can reduce the waste products of a space station and can provide both a gas as a candidate propellant and a liquid for use in water recovery. (9:35; 41:104)

A detailed discussion of the microbiology and chemistry of anaerobic digestion is beyond the scope of this study and unnecessary to an understanding of the conditions required for the anaerobic digestion of organics to gas. For in-depth information regarding the biochemical aspects of anaerobic digestion the reader is referred to references (41) and (49) in the bibliography. A general
knowledge of the requirements of the anaerobic bacteria responsible for making digester gas is necessary. Therefore, an overview of the literature pertaining to these bacteria is presented here.

Anaerobic digestion is a complex biochemical process in which several groups of anaerobic organisms simultaneously absorb and break down organic material, human feces, industrial organic waste, and plant material in the complete absence of molecular oxygen. This process can be considered in two stages as shown in Figure 2. In the first stage the acid-forming organisms convert the complex organic substrate, which is in a particulate form, to volatile organic acids by attaching themselves to the particles and secreting extracellular enzymes. During the second stage the methane-forming bacteria use the acids to produce carbon dioxide and methane gas. It is in the second stage that waste stabilization occurs. The methane is insoluble in water and will escape as a gas. A means of collecting the gas must be provided and this also becomes a requirement for pseudogravity in providing a force for separating the gas from the liquid and the liquid from the sludge. (12:4-6, 4-7)

![Figure 2. Diagram of Waste Stabilization (12:4-6)]

The methane bacteria growth rate is relatively slow and ranges in time from 2 to 22 days depending on pH, substrate composition and temperature. The pH range tolerance for these bacteria is between 6.5 and 7.6. At a given temperature, if pH drops below 6.0, methane production stops and there will be no
decrease in the organic content of the sludge and no methane produced.

Compared to the acid forming bacteria the methane bacteria get very little energy from their food. Because of this they are fewer in numbers and are more sensitive to changes in temperature. Most digesters operate at temperatures between 26 and 43 °C, also known as the mesophilic range. Operating temperatures in the 45 to 55 °C, or thermophilic range, have have been investigated and show a slight increase in digester efficiency, but are more sensitive to temperature fluctuations and require more energy to operate at this higher temperature. (41:18, 88)

Based on the above criteria four conditions are identified as being essential for efficient digester operation and thus maximum methane production. These are:

1. An environment free of molecular oxygen.
2. A steady temperature in the mesophilic range [26 to 46 °C].
3. A proper pH between 6.5 and 7.6.
4. Sufficient retention time to allow methane bacteria regeneration.

When discussing the subject of temperature, the element of time cannot be ignored because solids stabilization cannot be accomplished at low temperatures unless sufficient time is allowed. Temperature and retention time for efficient digester operation are shown in Table I to illustrate this point. (12:4–13; 41:95)
Table I

Suggested Solids Retention Time for High Rate Digesters (41:95)

<table>
<thead>
<tr>
<th>Operating Temperature [°C]</th>
<th>Suggested Time [Days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>28</td>
</tr>
<tr>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>14</td>
</tr>
<tr>
<td>35</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

Methane Generation

There are two general digester processes which have evolved over the years. These two processes are referred to as standard rate digestion and high rate digestion. These two terms are somewhat deceptive in that they do not refer to the rate at which organic materials are converted to methane. However, the high rate digester does provide conditions which are more favorable to the anaerobic processes. From these two processes, variations in staging and mixing have resulted in several designs which will be considered here in selecting a digester configuration which is appropriate for a space station. (48:255)

In a standard rate digestion system the contents of the digester are unmixed and the processes of digestion, sludge thickening, and supernatant formation are carried out in stratified layers of the tank. As a result, actively digesting sludge occurs only in a portion of the total digester volume reducing the actual working volume of the digester tank. Because the tank is unmixed the feeding of the anaerobic bacteria is a very slow process taking between 30 to 60
days retention of the organic solids. The long solids retention time requires a large tank volume and a corresponding fresh sludge input rate usually in periodic steps of two to three times a day. (41:89; 48:255)

The high rate digestion process differs from the standard rate process in that the sludge is mixed and active sludge digestion takes place throughout the tank. This mixing provides improved heating and continuous feeding, allowing for a more complete interaction of the microorganisms with the organic sludge material. The mixing process requires a nearly continuous sludge input to the digester and therefore high rate refers to the organic loading rates possible rather than the methane generation rate. The incoming sludge displaces the digested sludge in the tank, therefore tank size is determined by how long the organic solids must remain in the tank [solids retention time], which is a function of temperature [Table I]. (48:255)

The high rate digestion process has the advantages of shorter solids retention time, continuous feed, smaller tank volume, and uniform heating throughout the tank due to mixing. Also because there is no supernatant separation, the total solids are reduced by 45 - 50% and given off as gas. These factors make the high rate digester process a natural choice for the space station. Because there is no supernatant separation in the high rate digester a second tank must be provided to allow settling of the digested sludge from the liquid. The second tank allows storage of the digested sludge until it is concentrated at the bottom and can be drawn off for subsequent conventional space vacuum drying. The supernatant can then be piped to the on-board water recovery system. Figure 3 is a simplified diagram of a high rate two stage digester. Both tanks are covered, and the gas collection system cross channeled between them. The second
tank will not produce much gas since most of the gas production takes place in the first tank. The second tank does contain a large volume of good active methane producing bacteria which can be used to seed the first tank if the digestion process slows down due to fluctuations in temperature or feeding rates. (12:4-11; 32:82;
35:922–923; 41:92)

![Diagram of a two-stage digester](image)

Figure 3. High Rate Two Stage Digester (12:4-10)

Mixing of the primary tank increases the volatile solids breakdown and increases the amount of gas produced. Mixing can be accomplished by artificial means both internal and external to the tank. Internal mixing can be accomplished through impellers or turbine wheels submerged within the tank. An important factor to consider in this method of mixing is exposure of the mixing blades to grit and debris. This can cause wear of the mixing impellers which will require shutdown of the digester for drainage and repair. A more acceptable means of mixing can be accomplished external to the tank through the use of a pump. The total capacity of the pump is generally less than the circulating capacity of the mixers. The pump also allows for the external heating of the tank by cycling the sludge through heat exchangers. By using external heating and mixing, equipment
failures can readily be handled without stopping the digestion process by switching the sludge recirculation flow to redundant equipment. (12:4–28)

The cover of the digester has some unique features which, though not critical to the results of this study, should be recognized here. The two types of covers are the fixed and floating cover. The fixed cover offers the advantages of simplicity in design. It must be equipped with a positive displacement feed and draw-off arrangement so that a negative gas pressure in the tank does not develop. If this were to happen, atmospheric air within the space craft could be drawn into the tank and mix with the methane producing an explosive mixture. The explosive limits of methane in air are between 5.3 and 14 percent. This means that a methane:air ratio between as little as 5.3 to 14 percent could present a hazardous situation. A floating cover design provides the greatest degree of safety since air cannot be drawn in by a negative pressure. The problems with this type design are maintaining the cover guides in a smooth operating condition and keeping the cover level. In either case the gas will be compressed and stored external to the digester to minimize any leakage and possible safety hazards. (12:29; 48:260)

The expected methane output from the anaerobic process varies from author to author. A popular figure based on actual data is about 1 cubic foot per capita per day. Anderson (2) cites a figure of 4 –5 ft³ for every pound of organic matter destroyed. Price (41) suggests the use of Michaelis–Menton type rate equations to determine quantity of methane generated based on biological oxygen demand [BOD] of the sludge, the quantity of biological solids added per day, and the efficiency of waste utilization. These equations are used in this study and coupled to the expected BOD and input loads rate, based on NASA studies, using
simulation modeling. The modeling and calculations of input parameters comprise a majority of this study and Chapter III describes the equations, the SLAM model and the input data used to determine the methane generation rate and digester volume. (2:95; 41:37-39, 94, 105-106, 121; 48:111)

The Scenario

In considering the future utility of space as a resource and as a laboratory, it is obvious that to fully exploit the potentials of space we must have a continuous manned presence in this new frontier. NASA has been the forerunner in looking toward man's future in space, and has sponsored several studies with the expert assistance of such space pioneers as Gerard O'Neill, which have put numbers to ideas in assessing the human and economic implications as well as the technical feasibility of settlements in space. As man moves toward establishing colonies in space one of the first steps that must be taken is the siting of small stations in low earth orbit for research, development, demonstration, testing and evaluation. Low earth orbit is necessary as a first location because materials must come from the Earth during the initial stages of space colonization, and transportation to this orbit by means of the Shuttle is much more technically and economically feasible than going directly to deep space orbits such as the Lagrangian liberation point \( L_5 \) or the Moon. The LEO space station will be capable of performing research in materials fabrication and assembly techniques, solar and nuclear power generation systems, and physiological effects of rotation and reduced gravity. (34:v, 1)

This study utilizes NASA's research as a basis for analyzing the feasibility of space-based methane generation. All figures relating to the size, shape, capacity and orbital altitude of the LEO space station come from research
work done by NASA and published in references (34) and (30) listed in the Bibliography.

Requirements for pseudogravity are also based on these studies, and past NASA research, which show the physiological consequences of a gravity free environment over a sustained length of time. Data from past space flights show that decalcification occurs at a rate of 1 to 2% per month in the absence of gravity, which can result in decreased bone mass and density. Other effects of gravityless environment include hormone and electrolyte imbalances and unstable protein and carbohydrate states. For these reasons pseudogravity must be provided for the people of the space station. The most feasible way of generating artificial gravity is to rotate the space station. However, a rotating system contains forces other than the centrifugal force which acts as the gravity. The coriolis force is one of the forces, caused by the speed of motion and its direction relative to the axis of rotation. Consequently, motion sickness can result even at low rotation rates due to the cross-coupled angular accelerations in the ear when the head is turned out of the rotation plane. People can adapt to rates below 3 rpm and for this reason the space station is designed for a rotation of 2 rpm. Lower rotation rates are preferable, but for a platform of small size this is not feasible due to the large radius of rotation required. Figure 4 depicts the radius of rotation required for various spin rates. (30:36, 40; 34:21, 22; 35:349–408, 37:154)
NASA's studies show that 200 people stationed in a LEO space station would be sufficient to perform the research and development missions on a 24 hour a day basis. This figure is used as a loading factor in determining the size and output of the anaerobic digester. To accommodate the 200 occupants the recommended configuration of the space station is two spheres connected by a corridor, or dumbbell. The dumbbell shape has the advantage of allowing the radius of curvature that holds the atmosphere to be small while the radius of rotation remains large. This shape also provides a unit modular design which could be expanded by adding additional spheres in a ring to form a final beaded torus design as shown in Figure 5. Parameters of the dumbbell shaped space station are...
presented in Table II. Note that an atmosphere equivalent to one-half of the Earth's atmosphere is considered in the structural design to determine the mass of the station. By using a lower atmospheric pressure inside the space station, less structural strength is required to hold the structure together against the vacuum of space. This is accomplished by increasing the amount of oxygen in the space craft while diluting it with an inert gas, such as helium or nitrogen, thereby bringing the total pressure to .5 atmosphere. (34:41, 144)

![Diagram of Dumbell and Beaded Torus Design](image)

**Figure 5. Dumbell and Beaded Torus Design**

**TABLE II. Space Station Parameters (34:46, 87, 147)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of Rotation [m]</td>
<td>236</td>
</tr>
<tr>
<td>Radius of Sphere [m]</td>
<td>33.3</td>
</tr>
<tr>
<td>Total Mass [kg]</td>
<td>1.45 x 10^6</td>
</tr>
<tr>
<td>Structural Mass, 1/2 atmosphere [kg]</td>
<td>3.63 x 10^6</td>
</tr>
<tr>
<td>Habitat Mass, 4.5 x10^8 kg/person [kg]</td>
<td>9.07 x 10^5</td>
</tr>
<tr>
<td>Atmospheric Mass [kg]</td>
<td>1.81 x 10^6</td>
</tr>
<tr>
<td>Orbital Altitude [km]</td>
<td>240</td>
</tr>
<tr>
<td>Population</td>
<td>200</td>
</tr>
<tr>
<td>Area/Person [m^2]</td>
<td>35</td>
</tr>
</tbody>
</table>
SLAM Model

Simulation modeling provides a means of representing a system in a mathematical form so that it can be exercised on a digital computer. SLAM was chosen as the simulation language to be used in representing the anaerobic digestion process in this study because of its capabilities to perform continuous simulation modeling. In this type of modeling the state of the system, in this case the volatile solids loading rate and methane generation rate, are represented by dependent variables which change over time. This time-dependent portrayal of the variables provides an output which can be analyzed to provide a realistic estimate of system performance. Chapter III explains how SLAM was used to generate time varying statistics on parameters such as methane generation, organic solids loading, and digester capacity. Detailed information on the syntax and operation of the SLAM program can be found in Pritsker's text, Introduction to Simulation and SLAM II. (42)

Cost Analysis

The cost analysis used for this study has to be flexible enough to allow for a technological uncertainty in pricing the components of a system that will be procured and operated many years in the future. It also must allow an input of the expert's "gut feeling" or past experience in determining where the actual price will fall in the uncertainty range. The Monte Carlo method is selected to be used as the analysis tool for forecasting the life cycle cost of the digester system and of the shuttled propellants, upon which the economic feasibility of the systems in question will be based. This method is recommend in the studies, Military Equipment Cost Analysis (43), and, Estimating Cost Uncertainty Using Monte Carlo Techniques (7), done by the Rand Corporation. The Monte Carlo
Technique requires that the expert express his opinion of the uncertainty in the price range selected by picking a beta distribution curve from a family of nine which best describes the variance of the price based on his experience. More information on the Monte Carlo Technique can be found in references (13) and (27).

The pricing of the components in the digester system requires that a system configuration be selected so that individual elements of the system can each be analyzed to determine a price range and uncertainty determined from its application and environment. The alternative system, shuttled conventional propellants, must also be analyzed to determine propellant costs. Each system, in addition to these acquisition costs, will have an operational cost which will require the estimation of future space shuttle transportation costs. A preview of the source of such costs is described below.

**Digester Costs.** Once system configuration is specified, the major components of the system can be identified and a cost value estimated for each. Consultation with waste treatment engineers with experience in design of various Environmental Protection Agency projects and municipal waste treatment facilities is the main source of information in costing the primary elements of the digester system. Due to the technological uncertainty in the application of equipment used strictly on Earth for anaerobic digesters to a space station environment, both equipment cost and weight must be determined using a Monte Carlo Technique.

Transportation costs are associated strictly with the initial transport of equipment to the space station and, in the case of using the biogas as a bipropellant, the transport of an oxidizing agent suitable for combustion with a methane/carbon dioxide mixture. These transportation costs are considered in the
life cycle cost analysis.

**Shuttled Propellant Costs.** The alternative to generating a biogas propellant from human waste is to transport conventional propellants on a regular basis to the space station. The life cycle cost of such an alternative must be compared to similar costs of the digester biogas generation system to determine if an economic advantage lies with either system. Pricing information on conventional propellants will be obtained from personnel in logistics centers responsible for purchasing propellants for NASA and the DoD. Transportation costs will reflect the quantity of conventional propellants required to produce the equivalent capabilities of the digester system. These costs will be based on propellant weight based on density.
III. SLAM MODEL FORMULATION

The purpose of the model is to generate data for analysis since actual data on small scale digesters applicable to a space station scenario are not available. Factors to be considered which effect the anaerobic process are the volatile solids retention time [SRT] in the digester and temperature. Equations used in formulating the model come from Price and Cheremisinoff's book, *Biogas Production and Utilization* (41) and are presented below.

\[ V_{\text{CH}_4} = [0.35 \text{ m}^3/\text{kg}] \times ([E]Q[S_o][10^3\text{g/kg}]^{-1})-1.42P_\dot{X} \] \[ \text{[1]} \]

and,

\[ P_\dot{X} = [YQ[E][10^3\text{g/kg}]^{-1}]/[1+k_dT] \] \[ \text{[2]} \]

where:

- \( V_{\text{CH}_4} \) = volume of methane produced, \( \text{m}^3/\text{d} \)
- 0.35 = theoretical conversion factor for the amount of methane produced from the conversion of 1 kg of BOD\(_L\)
- \( E \) = efficiency of waste utilization [.8 - .95]
- \( Q \) = flow rate, \( \text{m}^3/\text{d} \)
- \( S_o \) = organic material added [BOD\(_L\)] \( \text{g/m}^3 \)
- 1.42 = conversion factor for volatile biological solids to BOD\(_L\)
- \( P_\dot{X} \) = net mass of volatile biological solids [cell tissue] produced per day, kg/d
- \( Y \) = growth yield coefficient
- \( k_d \) = microorganism decay coefficient
- \( T \) = mean cell residence [solids retention] time
Lawrence and McCarty (23) have studied the growth kinetics of the methane producing microorganisms and have determined the anaerobic process to be rate limited. Their model, which describes the net growth rate of the microorganisms in a continuous flow completely mixed anaerobic treatment system, is represented by the expression:

\[
\frac{dX}{dt} = Y \frac{dF}{dt} - k_d X
\]

where;

\[
\frac{dX}{dt} = \text{microorganism net growth rate per unit volume of digester}
\]
\[
\frac{dF}{dt} = \text{rate of waste utilization per unit volume of digester}
\]
\[
X = \text{microorganism concentration}
\]
\[
Y = \text{growth yield coefficient}
\]
\[
k_d = \text{microorganism decay coefficient}
\]

Figure 6 contains the graph from Price and Cheremisinoff’s book used in determining the microorganism growth yield coefficient \([Y]\), and decay [endogenous] coefficient \([k_d]\). This is a typical plot from laboratory data in which the microorganism growth rate divided by the microorganism concentration \([\frac{dX}{dt} \div X]\), which is the reciprocal of the solids retention time \([\text{SRV}]\) is plotted against the rate of waste utilization divided by the microorganism concentration \([\frac{dF}{dt} \div X]\). The growth yield coefficient is then the slope of this line and the decay coefficient is the intercept.
Values of Solids Retention Time [SRT] which allow for maximum use of the waste solids by the methane bacteria are suggested by Price and Cheremisinoff for various temperatures [Table I, page 19] and have been plotted in Figure 7. For the mesophilic bacteria only temperatures in the 30 to 40 C temperature range must be considered.
This graph provides two equations for the SLAM model which will then determine the appropriate solids retention time for a given temperature. For the temperature range from 30 to 35 C, solids retention time, $T$, is:

$$T = -0.8(\text{TEMP}) + 38 \text{ days}$$

For temperatures between 35 and 40 C, $T$ is a constant 10 days.

Factors which also influence the solids retention time are the volatile solids loading on the digester, and the percentage concentration of volatile solids suspended in the raw sludge. For this study the percent solids in the raw sludge is 13%, based on the quantities of waste expected in a typical space station. A curve showing the relationship among solids loading, solids retention time, and sludge solids is presented in Figure 8. From this curve a constant of multiplication of 13 can be extracted for use in determining volatile solids loading from solids retention time for use in the digester model. (20:80; 41:97, 99)
Model Development

A continuous model was formulated to simulate the operational characteristics of the anaerobic digester. The program is written to allow flexibility of input parameters and monitoring of various internal factors necessary for model verification. Figure 9 depicts the interaction of the various parameters and references the equation or figure used in determining the structure of the model.

**Figure 9. Parameter Interaction**
A detailed description of subroutine STATE is now presented. It is included in the main program [Appendix B] and each fundamental line is listed here followed by a brief explanation of its contents and origin.

C EFFICIENCY:

\[
SS(7) = \text{RNORM (.875, .075, 2)}
\]

Allows for random variation of system efficiency within \(0.8 - 0.95\) range \(41:121\)

C TEMP CONSTANT:

C \(SS(11) = XX(1)\)

C TEMP VARIATION:

\[
SS(11) = XX(1) - 2.8*COS(8*PI*(TNOW-0.1042))
\]

Allows for test runs with either a constant temperature or with a temperature which simulates cooling of digester due to cooler waste inputs. The cycling of temperature lags behind the loading cycle by 15 minutes per hour to simulate heat transfer due to mixing.

C LOAD CONSTANT:

C \(SS(12) = 2.6*XX(2)*TNOW\)

C LOAD VARIATION:

\[
SS(12) = XX(2)*2.6*(1+0.4*COS(8*PI*TNOW))
\]

Allows for test runs with either a constant load or a loading which simulates six hour input cycles which would follow the normal activity cycles [prime waste facility use] of a crew working shifts over a 24 hour period. XX(2) is an input variable and represents
people on the space station. The total waste expected per person in a space station is 2.6 kg/person/day (20:80).

C FLOW:

\[ SS(1) = \frac{SS(12)}{100} \]

Converts load input [kg/day] to flow \([m^3]\).

C SOLIDS RETENTION TIME:

\[ SS(2) = 10 \]

IF \((SS(11) \text{ LT. 35}) \Rightarrow SS(2) = -0.8*SS(11)+38\)

Determines recommended Solids Retention Time in digester by using temperature and equations derived from Figure 7. Figure 7 is derived from tabulated data in Price and Cheremisinoff's book (41:95).

C TOTAL SOLIDS (13%):

\[ SS(3) = 0.13*SS(12) \]

Total of solids in raw sludge input are determined to be 13% of the weight of the raw sludge (20:80).

C VOLATILE SOLIDS CALCULATED (-3%ASH) (UNITS:KG/D):

\[ SS(4) = SS(3)-0.03*SS(3) \]

The volatile solids are calculated by subtracting 3% ash which has been experimentally determined to be the non-organic residue in the waste. (35:922)

C METHANE PRODUCED:

\[ SS(5) = 0.35E*SS(4)*SS(7)*[1-(0.0588/(1-0.033*SS(2)))] \]

This equation for the volume of methane produced is a combination of equations [1] and [2] and combines the constants \(Y\) and \(k_d\) derived from Figure 6 [slope and intercept respectively] with various
conversion factors.

**C** SOLIDS REMOVED:

\[ SS(6) = SS(3) - 1.059 \times SS(5) \]

This line of code provides information on the amount of waste remaining, after the anaerobic process, that will be removed from the digester and returned to Earth or could possibly be utilized as a fertilizer in plant growth experiments. It is calculated by subtracting the mass of the methane from the input solids. The figure 1.059 is a methane density conversion factor to convert methane volume to weight.

**C** VOLATILE SOLIDS LOADING (FIGURE 8) (UNITS: KG/M3/D):

\[ SS(8) = \frac{13}{SS(2)} \]

This equation uses the Solids Retention Time to determine the volatile solids loading per unit volume of digester. The equation was derived from Figure 8. The constant of multiplication \([k = SRT \times VS]\) is 13.

**C** DIGESTER VOLUME USED:

\[ SS(9) = \frac{SS(4)}{SS(8)} \]

This calculation determines digester volume from the volatile solids present and the required volatile solids loading per unit volume of digester calculated above.

**C** HYDRAULIC RETENTION TIME:

\[ SS(10) = \frac{SS(9)}{SS(1)} \]

This calculation determines how long the waste influent will remain in the digester.
The SLAM input program is written to produce an output graph and time averaged statistics on parameters which can be compared to theoretical values in verifying the model. The input statements are listed in Appendix B and a sample output run is included in Appendix C.

**Experimentation**

Model validation and verification requires a set of input statements which allows for several runs, providing output of average methane generated and average digester volume used for each run. This new set of statements is provided in Appendix D. Three input temperatures were specified and ten runs each performed with system efficiency being specified by antithetic random numbers to reduce variance. The output of the thirty runs is summarized in Appendix E.

The design of the verification phase provides a method of obtaining the grand mean of methane generated for comparison against published theoretical estimates. Average digester volume used is also observed to see if it varies between runs at set input temperatures. Since digester volume is a function of the required volatile solids loading compared to the actual loading, which is constant when averaged over time, no change is expected in the volume of the digester when operated at a specific input temperature. Changes would be expected though when the initial operating temperature is changed, which would determine a new solids retention time from Figure 7, and therefore affect the required volatile solids loading, Figure 9.

Validation provides a 95% confidence interval in which average methane generation can be expected to be valid for each of the three system operating temperatures. A 95% confidence interval is also generated on the mean difference
between the three systems to show that the difference in the amount of methane generated is due solely to the change in temperature and not the randomness of the system efficiency.

Output Analysis

The following table summarizes the grand mean methane generation rate, variance, and 95% confidence intervals for each of the three initial operating temperatures. The data from the thirty runs used to obtain the grand means is listed in Appendix E.

**SYSTEM TEMPERATURE = 32.8°C**

Grand Mean Methane Generation Rate: 18.1402 m³/day
Variance: 0.0152
Confidence Interval: 18.0521 to 18.2283 m³/day

**SYSTEM TEMPERATURE = 35°C**

Grand Mean Methane Generation Rate: 18.2424 m³/day
Variance: 0.0213
Confidence Interval: 18.1381 to 18.3467 m³/day

**SYSTEM TEMPERATURE = 37.2°C**

Grand Mean Methane Generation Rate: 18.2830 m³/day
Variance: 0.0214
Confidence Interval: 18.1784 to 18.3756 m³/day

The methane generation rate of approximately 18.2 m³/day agrees with
observed methane generation rates of 4 - 5 ft$^3$/lb organic matter, given by Anderson (2:95). In this model an average of 65.6 kg/day [144.3 lb/day] of organic solids are available. This corresponds to a theoretical value of 577.2 - 721.5 ft$^3$/day or 16.4 - 20.43 m$^3$/day.

The difference between methane generation rate means for the three operating temperature systems is tabulated below for each run together with the grand mean difference, variance and 95% confidence interval for the true mean difference. The small variance in difference mean is due to the change in system operating temperatures and not the randomness of the modeled efficiency. System A operates at 32.8°C, system B at 35°C, and system C at 37.2°C.

**DIFFERENCE IN MEAN METHANE GENERATION RATES FOR THREE OPERATING TEMPERATURES**

<table>
<thead>
<tr>
<th>Run</th>
<th>$D_{A-B}$</th>
<th>$D_{A-C}$</th>
<th>$D_{B-C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.102</td>
<td>-0.143</td>
<td>-0.041</td>
</tr>
<tr>
<td>2</td>
<td>-0.101</td>
<td>-0.141</td>
<td>-0.040</td>
</tr>
<tr>
<td>3</td>
<td>-0.104</td>
<td>-0.145</td>
<td>-0.041</td>
</tr>
<tr>
<td>4</td>
<td>-0.102</td>
<td>-0.142</td>
<td>-0.040</td>
</tr>
<tr>
<td>5</td>
<td>-0.100</td>
<td>-0.139</td>
<td>-0.039</td>
</tr>
<tr>
<td>6</td>
<td>-0.100</td>
<td>-0.144</td>
<td>-0.041</td>
</tr>
<tr>
<td>7</td>
<td>-0.102</td>
<td>-0.143</td>
<td>-0.041</td>
</tr>
<tr>
<td>8</td>
<td>-0.103</td>
<td>-0.144</td>
<td>-0.041</td>
</tr>
<tr>
<td>9</td>
<td>-0.104</td>
<td>-0.145</td>
<td>-0.041</td>
</tr>
<tr>
<td>10</td>
<td>-0.103</td>
<td>-0.144</td>
<td>-0.041</td>
</tr>
</tbody>
</table>
GRAND MEAN OF DIFFERENCE OF MEANS

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-0.1021</td>
<td>-0.1430</td>
<td>-0.0406</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.0015</td>
<td>0.0019</td>
<td>0.0007</td>
</tr>
</tbody>
</table>

CONFIDENCE INTERVAL (95%) FOR TRUE MEAN DIFFERENCE

A-B: -0.1010 to -0.1032
A-C: -0.1416 to -0.1444
B-C: -0.0401 to -0.0411

The increases in methane generation due to the increase in operating temperature is extremely small and it may not be economically beneficial in space to provide the extra energy required to increase the methane generation by operating in the upper mesophilic temperature range. Digester volume used remained constant for all three operating temperatures as was expected, and did decrease for increasing temperatures due to the increased metabolism of the methane producing bacteria at higher temperatures. Due to fluctuations in input loading, the max volume used [70.6 m³] will be the design parameter in sizing the digester tank.
IV. ANALYSIS AND DISCUSSION

Up to this point the anaerobic process has been described and modeled as it applies to a possible future space station scenario. Biogas output has been computed for a given space station population. In this chapter space station size will be determined based on the population selection and previous studies done by NASA on the future colonization of space. The mass and cross sectional area will be calculated so that an atmospheric drag can be determined for the altitude at which the space station will be orbiting. This atmospheric drag, which is an acceleration causing the space craft to spiral towards Earth, will determine what force must be provided by the attitude control system to maintain the orbit.

The use of the generated biogas as a cold gas propellant and as a fuel in a bipropellant rocket system is investigated in this chapter to determine which system would best provide the force necessary to overcome the atmospheric drag. The theoretical performance of each propulsion system is evaluated using thermochemical analysis techniques to determine reaction temperatures.

The remainder of the chapter compares the biogas generation system performance with conventional propulsion performance based on the orbit maintenance requirement and what portion of this requirement the biogas system can meet. The common reference used for comparison is the dollar. Cost estimates of the digester system are determined by the total acquisition cost, installation cost and operational cost, all amortized over an assumed lifetime of thirty years. This cost is then compared to the cost of providing the required attitude control with conventional propellant delivered by the Shuttle. All cost estimates are determined using a Monte Carlo technique.
**Space Station Population and Size**

As stated previously in Chapter II, the space station population has been selected based on previous work done by NASA. A population of 200 occupants was used in determining the output of the digester system. This figure is also used in determining the size of the space station. A brief survey of the literature indicates that for a small space station with this population a projected living area per person of 35 m$^2$ is sufficient and is equivalent to that found in some small French villages. As a comparison with an American city, the Manhattan Borough in New York has a per capita area of 38.2 m$^2$/person. Projected area is area of the largest plane perpendicular to the direction of the pseudogravity. Actual usable area can be made larger than the projected area by constructing levels within the habitat. (34:24–25,47)

With a population of 200 and a required area of 35 m$^2$/person, a space station of the dumbell design will have those parameters listed in Table II, page 26. These parameters are used to determine the acceleration due to drag on the space station. The formula for the acceleration due to drag is (3:423):

$$a_d = C_D(1/2)\rho(A/m)v^2$$  \[3\]

where:

- $C_D =$ Coefficient of Drag
- $\rho =$ atmospheric density
- $A =$ average cross sectional area
- $m =$ mass of space station
- $v =$ velocity of space station

The average cross sectional area of the space station, $A$, is different from the total cross sectional area due to the rotation necessary to provide a pseudogravity.
It is calculated from the formula (21:16):

\[ A = \frac{2}{\pi} [A_s + A_t] \]

where:

- \( A_s \) = cross sectional area of a sphere
- \( A_t \) = total cross sectional area [spheres and corridor]

For the space station the cross sectional area of a sphere is:

\[ A_s = \pi [33.3 \text{ m}]^2 = 3.48 \times 10^3 \text{ m}^2 \]

The area of the corridor connecting the spheres is:

\[ A_c = 2[2[236\text{ m}] - 2[33.3\text{ m}][2\text{ m}]] = 1.62 \times 10^3 \text{ m}^2 \]

Therefore, the total cross sectional area becomes:

\[ A_t = 2[3.48 \times 10^3 \text{ m}^2] + 1.62 \times 10^3 \text{ m}^2 = 8.58 \times 10^3 \text{ m}^2 \]

And the average cross sectional area is then:

\[ A = \frac{2}{\pi} [3.48 \times 10^3 \text{ m}^2 + 8.58 \times 10^3 \text{ m}^2] = 7.68 \times 10^3 \text{ m}^2 \]

The velocity of the space station is dependent upon its orbital altitude and can be calculated from the formula for circular orbit speed (19:75):

\[ v = [\mu/r]^{1/2} \]

where:

- \( \mu \) = Earth's gravitational constant \([3.986 \times 10^5 \text{ km}^3/\text{sec}^2]\)
- \( r \) = radius of vehicle from Earth's center

Therefore:

\[ v = \left[\frac{[3.986 \times 10^5 \text{ km}^3/\text{sec}^2]}{[6378\text{ km} + 240\text{ km}]}\right]^{1/2} = 7.76 \text{ km/sec} \]

The density of the atmosphere at 240 km is selected from NASA tables of density for standard atmosphere at various altitudes and is \(1.24 \times 10^{-6} \text{ kg/m}^3\). (29:II-26)

The Coefficient of Drag is a dimensionless figure which carries over
from the early days of aerodynamics but remains applicable even for the conditions in which spacecraft operate. It is dependent upon free-molecule flow at the orbital altitude and is calculated by assuming that the spacecraft is stationary and the air molecules are flowing past. It is assumed that the molecules have a Maxwellian distribution of thermal velocity superimposed on their uniform velocity, \( v \), and are temporarily retained on the surface after collision, then re-emitted. (21:13-14)

The drag coefficients of bodies of various shapes, at various angles to the air flow, and the average value for rotating bodies have been evaluated experimentally. For satellites with perigee heights between 180 and 500 km and orbital eccentricities between 0 and 0.2, the value of \( C_D \) is between 2.1 and 2.2 for a sphere, and approximately 2.15 for a cylinder rotating like a propeller in the air flow. Based on this information \( C_D \) can be approximated by a value of 2.2 with a standard deviation which should not exceed 5 percent. (21:15)

The acceleration due to drag, \( a_d \), is now calculated by substituting the above information into equation [3]:

\[
\begin{align*}
a_d &= 2.2 \left[ \frac{1}{2} \right] \left[ 1.24 \times 10^{-10} \text{ kg/m}^3 \right] \left[ 7.68 \times 10^3 \text{ m}^2 / 1.45 \times 10^6 \text{ kg} \right] \left[ 7.76 \text{ km/sec} \right]^2 \\
&= 4.19 \times 10^{-6} \text{ m/sec}^2
\end{align*}
\]

The next section uses this acceleration to determine the force requirement necessary to counteract the drag and how much of the force the biogas from the digester system can produce when used in a rocket system.

**Orbit Maintenance Requirements**

The force of drag on the space station must be counteracted by an opposite force provided by the propellant used in the orbit maintenance system. This force is equal to the mass of the space station times the acceleration due to
atmospheric drag acting on it.

\[ F = ma = [1.45 \times 10^6 \text{ kg}] [4.19 \times 10^{-6} \text{ m/sec}^2] \]

\[ = 60.8 \text{ kg-m/sec}^2 \]

In calculating the required flow rate necessary to provide this force, the use of the digester gas as a cold gas propellant is considered first. Assuming an approximate 70/30 mix of CH₄/CO₂, the biogas produced, the first step is to calculate the exhaust velocity of the gas as it exits from the orbit maintenance rocket nozzle. Exhaust velocity is a function of the rocket chamber pressure/exhaust pressure ratio and the specific heat ratio, and is proportional to the square root of the absolute temperature, at the rocket nozzle inlet, and the gas constant. (45:55–56)

\[ v_e = \sqrt{\frac{2gk}{k-1}RTc[1-(Pe/Pc)^{(k-1)/k}]^{1/2}} \]  

where:

\[ k = \text{specific heat ratio of the gas} \]
\[ R = \text{gas constant} \]
\[ Tc = \text{rocket nozzle inlet temperature} \]
\[ Pe = \text{exit plane pressure} \]
\[ Pc = \text{chamber pressure} \]
\[ g = \text{conversion factor} [32.2 \text{ lb-m-ft/lb-ft-sec}^2] \]

Note, since gas properties are tabulated in most reference books in English units, the following calculations will be made in English units and then converted to Metric.

The pressure ratio, Pe/Pc, is a function of the ratio of the nozzle exit area to the throat area. In this situation the nozzle design is an unknown, however the pressure ratio can be assumed to be very small since the pressure against the exit plane of the nozzle is the vacuum of space. In small rocket nozzle design the
nozzle exhaust area to throat area ratio can be made very large, also providing a very small pressure ratio. In calculation of exhaust velocity, therefore, it is assumed that the pressure ratio is negligible, and the value of the quantity within the square brackets, \([\), in Eqn [4] goes to unity. (8)

The gas constant, \(R\), depends on the molecular weight of the \(\text{CH}_4/\text{CO}_2\) mix. For the 70/30 mix combination:

\[
M_{\text{mix}} = \sum x_i m_i = 0.7[16 \text{ lbm/lbmole}] + 0.3[44 \text{ lbm/lbmole}]
\]
\[
= 24.4 \text{ lbm/lbmole}
\]

where:

\(x_i\) = percent of constituent by volume

\(m_i\) = molecular weight of constituent

therefore:

\[
R_{\text{mix}} = \frac{\mathcal{R}}{M_{\text{mix}}} = \left[\frac{1545 \text{ ft}-\text{lbf}/\text{lbmole-R}}{24.4 \text{ lbm/lbmole}}\right]
\]
\[
= 63.28 \text{ ft}-\text{lbf}/\text{lbm-R}
\]

where:

\(\mathcal{R}\) = universal gas constant (39.302)

The specific heat ratio of the gas is the ratio of the specific heat at constant pressure and the specific heat at constant volume. Each of these specific heats is dependent upon the \(\text{CH}_4/\text{CO}_2\) mix of the gas. The molar value of specific heat is first calculated as the sum of the mole fraction and the molar specific heat products of each of the constituents as was done for molecular weight. (8; 46:550)

\[
C_{p_{\text{mix}}} = \sum x_i C_{p_i} = 0.7[8.533 \text{ Btu/lbmole-R}] + 0.3[8.934 \text{ Btu/lbmole-R}]
\]
\[
= 8.6533 \text{ Btu/lbmole-R}
\]

\[
C_{v_{\text{mix}}} = \sum x_i C_{v_i} = 0.7[6.464 \text{ Btu/lbmole-R}] + 0.3[6.9536 \text{ Btu/lbmole-R}]
\]
\[
= 6.6109 \text{ Btu/lbmole-R}
\]
where:

\[ C_p = \text{specific heat at constant pressure} \]
\[ C_v = \text{specific heat at constant volume} \]

The ratio of specific heat, \( k \), for the gas mixture is then:

\[ k = \frac{C_p}{C_v} = \frac{8.6533}{6.6109} = 1.309 \]

Assuming a cold gas temperature of 530R [ambient temperature, approx. 70°F] and performing the calculations in Eqn [4], the velocity of the exhaust gas, \( v_e \), equals 3025 ft/sec [922 m/sec].

The next step is to determine the mass flow rate of the propellant gas, \( m \), required to oppose the atmospheric drag force, and compare this value with the mass flow rate of the generated gas. Using \( \dot{m} = \frac{F}{v_e} \), where \( F \) is the drag force, a value of mass flow rate of 5898 kg/day is calculated. The available mass flow rate of biogas is a product of the volume of the gas generated times its density. The density of biogas is approximately 1.06 kg/m³. (41:123)

\[ \dot{m}_{\text{available}} = \rho V = [1.06 \text{ kg/m}^3][18.2 \text{ m}^3/\text{day}] = 19.26 \text{ kg/day} \]

Clearly, the biogas produced if used in a cold gas orbit maintenance system will not meet even 1% of the propulsion requirement, and therefore is considered no further.

Additional energy can be extracted from the gas if burnt with an oxidizer. An oxidizer commonly used in space vehicles today is oxygen which is well suited as a combustion reactant with methane. The only portion of the biogas generated that will react with the oxygen is the 70% methane. The calculations used in determining the exhaust velocity of the hot biogas/oxygen combustion mixture are similar to those made for the cold gas system. The rocket nozzle inlet temperature in this case will depend on the heat of reaction of the methane with the oxygen:
\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]

The heat of reaction will also determine if dissociation of the gases will take place. Dissociation is the breaking of the gases into various elements and molecules, removing heat energy from the reaction and lowering the overall temperature of the reaction. (8)

To find the temperature of the reaction, thermochemical tables are used to balance the enthalpy of the reaction with the enthalpy change necessary to bring the products to adiabatic flame temperature in a trial and error fashion until a temperature can be located at which these quantities are equal. The trial and error calculations are presented in Appendix F. The equations used in the calculations are as follows [the subscripts \(p\) and \(r\) refer to product and reactant respectively]:

\[
\Delta H_r = \Sigma n_p \Delta H_f^p - \Sigma n_r \Delta H_f^r = Q_{\text{out}}
\]

\[
\Delta H_r = \Sigma n_p \int C_p \, dT = \Sigma n_p (H-H_{298}) = Q_{\text{in}}
\]

where:

\(\Delta H_r\) = heat of reaction

\(n\) = number of moles

\(H_f\) = heat of formation [kcal/mole]

\(H-H_{298}\) = change in enthalpy in going from reference temperature [298R] to adiabatic flame temperature

[from thermochemical tables]

\(Q\) = energy [kcal]

Various adiabatic flame temperatures are chosen until \(Q_{\text{out}} = Q_{\text{in}}\). In this case,
when dissociation is not considered, the resulting adiabatic flame temperature, $T_a$, would be approximately 4600K [See Appendix F]. At this temperature dissociation will take place and some energy will be absorbed in the process. In-depth thermochemical analysis is necessary to determine the exact composition and adiabatic flame temperature that will be produced in such a dissociation reaction. The calculations involve a trial-and-error simultaneous solution of mass balance and equilibrium equations, which is a problem of considerable complexity. For this reason a computer program is utilized in determining the adiabatic flame temperature. An explanation of the procedure, the computer program listing and output are also presented in Appendix F. A temperature of approximately 3380K is determined using the computer program, assuming a gas pressure of 100 psia.

The product gas used in calculating the adiabatic flame temperature is then used to calculate the ratio of specific heats. The constituents of the product gas are $H_2O$, $OH$, $O_2$, $O$, $H_2$, and $CO_2$. The additional $CO_2$ present in the biogas was considered in the thermochemical analysis, as shown below. The calculations are made on a molar basis. The number of moles of methane produced per day is equal to the percentage of methane in the biogas times the daily mass flow rate of the biogas divided by the molecular weight of the biogas:

$$\frac{.7[19.26 \text{ kg/day}]/[24.4 \text{ kg/kgmole}]}{.5525 \text{ moles/day} [CH_4]} = .5525 \text{ moles/day} [CH_4]$$

The number of moles of $CO_2$ present which acts as a diluent is:

$$\frac{.3[19.26 \text{ kg/day}]/[24.4 \text{ kg/kgmole}]}{1.386 \text{ moles/day} [CO_2]} = .1386 \text{ moles/day} [CO_2]$$

The left hand side of the reaction of methane with oxygen, including the carbon dioxide as a diluent is:

$$0.5525[CH_4 + 2O_2] + .2368CO_2$$

Using the number of moles of each constituent produced [Appendix F] the complete reaction can be written on a per mole $CH_4$ basis as:
\[
\text{CH}_4 + 2\text{O}_2 + 0.4286\text{CO}_2 \rightarrow 1.3322\text{H}_2 + 0.3173\text{OH} + 0.0968\text{O} \\
+ 0.1273\text{O}_2 + 0.2134\text{H} + 0.4025\text{H}_2 \\
+ 1.4286\text{CO}_2
\]

The right hand side is now used to determine the molecular weight of the product gas. First the mole fraction of each constituent is determined using the calculated total number of product moles, 3.918, listed in the program output (Appendix F).

Mole Fraction \([x_i]:\)

\[
\begin{align*}
\text{H}_2 & : 0.3400 \\
\text{OH} & : 0.0810 \\
\text{O} & : 0.0247 \\
\text{O}_2 & : 0.0325 \\
\text{H} & : 0.0545 \\
\text{H}_2 & : 0.1027 \\
\text{CO}_2 & : 0.3646
\end{align*}
\]

The molecular weight of the mix is then calculated as:

\[
M_{\text{mix}} = \Sigma x_im_i = 0.3400(18) + 0.0810(17) + 0.0247(16) \\
+ 0.0325(32) + 0.0545(1) + 0.1027(2) + 0.3646(44)
\]

\[
= 25.23 \text{ lbm/lbmole}
\]

where:

\[x_i = \text{mole fraction of constituent } i\]
\[m_i = \text{molecular weight of constituent } i \text{ (lbm/lbmole)}\]

The gas constant of the mix is next calculated:

\[
R_{\text{mix}} = \frac{\mathbf{g}}{M_{\text{mix}}} = \frac{[1545 \text{ ft-lbf/lb mole-R}]/[25.23\text{lbm/lbmole}]}{25.23\text{lbm/lbmole}}
\]

\[
= 61.24 \text{ ft-lbf/lbm-R}
\]
As the gas is expanded through the nozzle it experiences a drop in temperature and pressure. To determine the temperature at the nozzle exit, the expansion process is considered to take place such that the product gas composition at the nozzle exit is the same as in the combustion chamber. This condition is known as *frozen flow* or *frozen equilibrium*. The temperature of the product gas at the nozzle exit, $T_e$, is then calculated from the formula: (45:163; 8)

$$\frac{T_e}{T_c} = \left(\frac{P_e}{P_c}\right)^{k-1/k}$$

where:

- $P_e/P_c = \text{exit/chamber pressure ratio}$
- $T_c = \text{chamber temp. [adiabatic flame temperature]}$
- $T_e = \text{nozzle exit temperature}$
- $k = \text{ratio of specific heats}$

In making this calculation an estimate for the ratio of specific heats, $k$, and the pressure ratio, $P_e/P_c$, are made. As an initial guess, let $k = 1.3$. The pressure ratio of chamber pressure, $P_c$, to nozzle exit pressure, $P_e$, is assumed to be large, since the rocket operates in the vacuum of space, and a value of 1000:1 is selected.

The nozzle exit temperature is then estimated to be:

$$T_e = T_c\left[\frac{P_e}{P_c}\right]^{k-1/k}$$

$$= 3380K \times 0.001^{1.3-1/1.3}$$

$$= 686K$$

In reality the exit temperature will actually be somewhere in between the adiabatic flame temperature and the exit temperature calculated in *frozen equilibrium*; however, the temperature difference can be used to calculate an average specific heat for each product constituent using the formula:

$$C_p(\text{avg}) = \frac{\Delta H}{\Delta T}$$
where:

\[ \Delta H = \text{change in enthalpy in going from chamber temperature to exit temperature} \]

\[ \Delta T = \text{change in temperature between combustion chamber and exit nozzle} \]

A sample calculation is made here for \( H_2O \) using data from the thermochemical tables in reference (4). For ease of extracting data from the tables the adiabatic flame temperature is rounded to 3400K and the exit temperature to 700K.

\[
C_p(\text{avg}) = \frac{[(35.577 - 3.390)\text{ kcal/mole}]/[(3400 - 700)\text{ K}]}{11.92 \text{ cal/mole-K}}
\]

It can be shown that an increase in the pressure ratio has very little effect on the resulting \( C_p(\text{avg}) \) value and is not critical to the analysis. For example, if the pressure ratio were 2000:1, the resulting exit temperature would be approximately 600K and the resulting \( C_p(\text{avg}) \) value would be 11.8. Therefore, the remaining \( C_p(\text{avg}) \) values are calculated for a 1000:1 pressure ratio, a resulting exit temperature of 700K, and an approximate combustion temperature of 3400K.

Average specific heats \([C_p(\text{avg})]\) in cal/mole-K:

- \( H_2 \): 11.92
- \( OH \): 8.18
- \( O \): 4.99
- \( O_2 \): 9.01
- \( H \): 4.97
- \( H_2 \): 8.14
- \( CO_2 \): 14.17

The product gas specific heats are next calculated using the above \( C_p(\text{avg}) \) values and the mole fractions, \( x_i \), calculated earlier.
\[ \text{Cp} = \sum x_i \text{Cp}_i \text{avg} = 0.3400[11.92] + 0.0810[8.18] + 0.0247[4.99] + 0.0325[9.01] + 0.0545[4.97] + 0.1027[8.14] + 0.3646[14.17] \]
\[ = 11.4047 \text{ cal/mole-K} \]

and:
\[ \text{Cv} = \text{Cp} - \alpha \]

where:
\[ \alpha = 1.986 \text{ cal/mole-K} \]

therefore:
\[ \text{Cv} = 11.4074 - 1.986 = 9.4187 \text{ cal/mole-K} \]

The ratio of specific heats is then:
\[ k = \frac{\text{Cp}}{\text{Cv}} = \frac{11.4047}{9.4187} = 1.211 \]

When this new value of \( k \) is substituted into equation [5] the exit temperature becomes 1000K. Repeating the above procedures with this new exit temperature results in a ratio of specific heats of 1.206. An average value of \( k = 1.208 \) is now used in Equation [4] with \( T = 3380 \text{K} = 6084R \), and \( R = 61.24 \text{ ft-lbf/lbm-R} \) [assuming \( P_e/P_c \) negligible]:
\[ v = \left( \frac{2[1.208]}{0.208[61.24][6084][32.2]} \right)^{1/2} \]
\[ = 11,852 \text{ ft/sec} \]
\[ = 3611 \text{ m/sec} \]

The required mass flow rate is then:
\[ \dot{m} = \frac{F}{v} = [60.8 \text{ kg-m/sec}^2]/[3611 \text{ m/sec}] \]
\[ = 16.84 \text{ gm/sec} \]
\[ = 1454.8 \text{ kg/day} \]

This is the mass flow rate of the product gas of which 41.7% [mole fraction] was initially biogas. Therefore the required mass flow rate of the biogas
is 606.6 kg/day. A comparison of this figure with the mass flow rate available from the digester [19.26 kg/day] shows that the biogas will produce 3.2% of the force required to overcome atmospheric drag if reacted with approximately 60% oxygen [mole fraction]. An optimization of this percentage may be possible by decreasing the amount of oxygen in the reaction, thus providing a fuel rich mixture which could lower the molecular weight of the combustion product. Considering the uncertainty of the actual composition of the biogas, the 3.2% figure is sufficient.

Cost Analysis – Methane vs Shuttled Propellants

The remainder of this chapter deals with estimating the cost of providing the digester produced propellant and comparing that cost with the cost of supplying conventional propellants to the space station via the space shuttle. The acquisition and operational costs are the only costs considered in this analysis. It is assumed that a waste stabilization system of some type [biological, physiochemically, electrodialysis, reverse osmosis, etc.] would be necessary on a space station of this size, and that the development costs for all such systems would be similar. Development costs are therefore not considered to be a key factor in this study. Acquisition costs, however, are equipment dependent and would reflect the specific system used to process the waste materials, in this case anaerobic digestion. The cost of other systems which might be used to provide waste stabilization have not been balanced against the cost of the anaerobic digester because of the complexity involved in evaluating and costing the multitude of possible systems. (13:66-67; 26)

There are many other elements which may have a bearing on the value of a methane generating system that have not been considered in the cost analysis because of the difficulty in placing a number on their value. These include the
value of the effluent returned from the system after digestion, the value in reducing the mass of waste products, and the utility value of stabilized waste material in space, to mention a few. Since the value of these elements are unknown, this study can only be considered to be a partial analysis; however, these factors must be included in any decision to use such a system.

The Monte Carlo cost estimating technique is used in this study to estimate the acquisition and operational costs of the digester system. It is also used to provide a cost estimate of the conventional propellant requirement necessary to provide the additional 3.2% thrust energy equivalent of the digester produced methane propellant for the cost comparison. The balance of the thrust requirement, the additional 96.8%, must be provided by conventional propellants in either case, and is therefore not considered as a cost element in this study.

**Monte Carlo Cost Estimating Technique.** The anaerobic digester proposed in this study is based on principles developed on Earth for large scale municipal waste treatment. Scaling down a system of this type to a size capable of handling 200 people and requiring that the system operate in space places a good deal of uncertainty on the estimates of the resource requirements. There are two categories of uncertainty involved in estimating the resource requirements: requirements uncertainty and cost-estimating uncertainty. (13:205–207)

Requirements uncertainty refers to variations in the cost estimate due to various possible configurations of the system under study. Possible causes of requirements uncertainty may stem from assumptions regarding hardware characteristics or system operational concepts. Studies have shown that requirements uncertainty accounts for 70 to 80 percent of the total cost estimate. Uncertainties which may affect requirements for the anaerobic digester proposed
here include space applicable materials selection, for pumps and other components of the digester, configuration of the system design, and estimation of flow rates, system capacities and operational and maintenance requirements. (6:1)

Cost-estimating uncertainty refers to the variation in cost estimates due to the unpredictable nature of estimating relationships. In other words, there is usually some randomness in the variables that are chosen to predict a particular cost that must be accounted for in the cost estimating relationship. Sometimes this uncertainty can arise from the data that is used as a basis for the cost analysis. The data may be statistical, and therefore only as good as the observations from which it was based, in which case there is some random deviation of this data from the "true" value. The data may be based on past or current experience, in which case it must be realized that relationships which held in the past may not hold for future advanced systems. In estimating costs of future systems, necessity may dictate the extrapolation of relationships beyond the data base causing expansion of prediction intervals and inducing uncertainty into the estimates. (13:206–207; 27:IV–2 – IV–3)

The intent of the Monte Carlo method of cost estimating is to describe the above uncertainties for each of the cost elements of the system so that the extent of the uncertainty of the ultimate system cost can be anticipated and evaluated. In this way alternatives can be compared with respect to their expected cost and their uncertainties. (6:2,4)

The method requires the pricing expert to specify a highest and lowest expected value for each cost element of the system in addition to a selection of one of nine beta distributions which best represent the cost uncertainty of each cost element based on his experience. The beta distributions selected have many of the characteristics that would be expected in input uncertainties: upper and
lower bounds, continuity, and unimodal distribution. These distributions and their associated \( \alpha \) and \( \beta \) values are depicted in Figure 10. From each of these distributions a cumulative distribution is plotted (Figure 11). A random number between 0 and 1 is then generated and located on the vertical axis of the cumulative distribution plot. The corresponding \( x \) value from the horizontal axis is then placed in the formula

\[
C_i = C_L + (C_L + C_H)x
\]

where:

- \( C_i \) = the computed cost value for cost element \( i \)
- \( C_L \) = the lowest expected value
- \( C_H \) = the highest expected value

to determine a probable value of the cost element. This procedure is repeated for each cost element in the system and the computed value of each cost element is summed to determine a probable total cost of the system. The probable total cost estimate of the system is then computed over several iterations to produce a total system cost distribution. The use of this method requires that all the input parameters be mutually independent which is normally a valid assumption with cost factor inputs. (5; 7:15; 43:154–155)
Figure 10. Beta Uncertainty Curves (7:14)
In order to develop a system life cycle cost using the Monte Carlo technique a discount rate must be considered so that future dollars can be commensurate with today's dollars. The formula for computing the life cycle cost is then:

\[ LCC = \sum_{i=1}^{y} \left[ n_i C_i \left( \frac{1}{r + 1} \right)^y \right] \]

where:

- \( LCC \) = life cycle cost
- \( y \) = number of years from the present that cost element is purchased
- \( n_i \) = number of units of cost element \( i \) purchased
- \( r \) = discount rate

The life cycle cost is computed over all applicable major cost categories of the system [Development, Acquisition, and Operations] to develop a total cost estimate uncertainty. (7:16-18; 13:66-69)

Cost Categories. As was mentioned earlier, only two cost categories are considered relevant to this study: Acquisition and Operations. In the
Acquisition category of the digester system, the initial investment costs include the individual hardware components [pumps, tanks, plumbing, etc.], shuttle delivery costs, and labor to assemble the digester as cost elements. Shuttle delivery is a variable which is dependent on the weight of each individual component. Since it is unknown exactly what each component will weigh, the Monte Carlo technique was also applied to capture the weight uncertainty in the life cycle cost estimate.

A detailed cost breakdown of the cost elements under the Acquisition cost category is presented in Table III along with the selected beta uncertainty curve type and other information pertinent to the analysis. All acquisitions take place during the first year of the Acquisitions phase with the exception of construction and transport to space which takes place in the second and final year of the Acquisitions phase. Table IV contains the weight values of each cost element hardware component with the corresponding beta distribution type describing the uncertainty. The hardware cost elements were based on a system configuration (Figure 12) developed with the assistance of waste management engineers to be compatible with the two stage high rate digester concept initially proposed. Cost element and weight element values were also acquired from these experts through personal interviews and correspondence. (17; 24; 47)

The system, as configured in Figure 12, is capable of handling the waste input of the entire space station. Redundancy is provided by locating a system of this type in each end of the space station. A waste transfer pipe running the length of the corridor will transfer waste from one unit of the space station to the other in the event of a system failure. Table III reflects the redundancy in the equipment and additional spare components.
TABLE III
Cost Elements for Acquisition Phase

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>Cost ['85$] Beta</th>
<th>Low</th>
<th>High</th>
<th>Curve</th>
<th>Quantity</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank</td>
<td>13,000</td>
<td>20,000</td>
<td>4</td>
<td>4</td>
<td></td>
<td>Includes delivery</td>
</tr>
<tr>
<td>Tank Insulation</td>
<td>6,000</td>
<td>7,600</td>
<td>2</td>
<td>2</td>
<td></td>
<td>3&quot; Fiberglass with service jacket</td>
</tr>
<tr>
<td>Pump 1</td>
<td>800</td>
<td>1,200</td>
<td>8</td>
<td>3</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Pump 2</td>
<td>2,200</td>
<td>2,600</td>
<td>8</td>
<td>3</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Pump 3</td>
<td>800</td>
<td>1,200</td>
<td>8</td>
<td>3</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Pump 4</td>
<td>800</td>
<td>1,200</td>
<td>8</td>
<td>3</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Compressor</td>
<td>800</td>
<td>1,200</td>
<td>8</td>
<td>3</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>610</td>
<td>1,000</td>
<td>1</td>
<td>3</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Temp Control Valve</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Pipe</td>
<td>15,587</td>
<td>17,100</td>
<td>7</td>
<td>1</td>
<td></td>
<td>2100' of 4&quot; Pipe and 475' of 1.5&quot; Pipe</td>
</tr>
<tr>
<td>Valve</td>
<td>270</td>
<td>300</td>
<td>9</td>
<td>16</td>
<td></td>
<td>4&quot; Valves, 2 spares</td>
</tr>
<tr>
<td>Coupling</td>
<td>13</td>
<td>15</td>
<td>9</td>
<td>105</td>
<td></td>
<td>4&quot; Couplings, 5 spares</td>
</tr>
<tr>
<td>Flame Trap</td>
<td>800</td>
<td>900</td>
<td>9</td>
<td>5</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Pressure Relief</td>
<td>590</td>
<td>700</td>
<td>9</td>
<td>5</td>
<td></td>
<td>Includes 1 spare</td>
</tr>
<tr>
<td>Valve &amp; Vacuum Breaker w/Flame Trap</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment &amp; Drip Trap Assembly</td>
<td>1,050</td>
<td>1,150</td>
<td>9</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen Tank</td>
<td>6,500</td>
<td>10,000</td>
<td>1</td>
<td>1</td>
<td></td>
<td>2300 ft³ tank @ 2200psi</td>
</tr>
<tr>
<td>Construction</td>
<td>30,200</td>
<td>50,400</td>
<td>4</td>
<td>1</td>
<td></td>
<td>Based on 30% total cost (47), includes space/grnd uncertainty</td>
</tr>
<tr>
<td>Shuttle Transport</td>
<td>656</td>
<td>2,647</td>
<td>6</td>
<td>wt.</td>
<td></td>
<td>$/lb. Based on STS or derived vehicle (25)</td>
</tr>
<tr>
<td>Weight Element</td>
<td>Low</td>
<td>High</td>
<td>Beta Curve</td>
<td>Quantity</td>
<td>Remarks</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>------</td>
<td>------</td>
<td>------------</td>
<td>----------</td>
<td>----------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Tank</td>
<td>13,000</td>
<td>18,000</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank Insulation</td>
<td>760</td>
<td>800</td>
<td>6</td>
<td>2</td>
<td>3&quot; Fiberglass with service jacket</td>
<td></td>
</tr>
<tr>
<td>Pump 1</td>
<td>50</td>
<td>75</td>
<td>9</td>
<td>3</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Pump 2</td>
<td>180</td>
<td>200</td>
<td>8</td>
<td>3</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Pump 3</td>
<td>50</td>
<td>75</td>
<td>9</td>
<td>3</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Pump 4</td>
<td>50</td>
<td>75</td>
<td>9</td>
<td>3</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td>50</td>
<td>75</td>
<td>7</td>
<td>3</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>300</td>
<td>500</td>
<td>4</td>
<td>3</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Temp Control Valve</td>
<td>10</td>
<td>20</td>
<td>9</td>
<td>3</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Pipe</td>
<td>20,000</td>
<td>23,000</td>
<td>6</td>
<td>1</td>
<td>Includes Couplings</td>
<td></td>
</tr>
<tr>
<td>Valve</td>
<td>35</td>
<td>40</td>
<td>4</td>
<td>16</td>
<td>Includes 2 spares</td>
<td></td>
</tr>
<tr>
<td>Flame Trap</td>
<td>40</td>
<td>50</td>
<td>8</td>
<td>5</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Pressure Relief Valve</td>
<td>40</td>
<td>50</td>
<td>8</td>
<td>5</td>
<td>Includes 1 spare</td>
<td></td>
</tr>
<tr>
<td>Valve &amp; Vacuum Breaker w/Flame Trap</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment &amp; Drip Trap Assembly</td>
<td>140</td>
<td>155</td>
<td>8</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen Tank</td>
<td>n/a</td>
<td>39,357</td>
<td>1</td>
<td>1</td>
<td>lbs oxygen/year + 11,000 lb tank</td>
<td></td>
</tr>
</tbody>
</table>
Key to Major Items:

P1 - Will be used to pump undigested sludge from one end of the space station to the other digester if a digester requires maintenance. It has a capacity to handle approximately 140 gals/day [.1 gpm] and can pump straight up to a height of 780 feet. At this height the center of rotation of the space station is encountered and there is zero gravity. Therefore the average height that the pump "sees" it must pump against is about 400 ft. At the center of the space station the sludge begins to travel "down-hill" toward the other half of the space station, assisted by artificial gravity.

P2 - Will serve to carry the digested sludge through the heat exchanger and also to mix the contents of the tank for proper feeding of the organisms. The tank is complete mixed once per day. Pump capacity is about 13 gpm.

P3 - Pumps contents of mix tank [T1] to settling tank [T2] at the same rate as raw sludge is input into T1.

P4 - Will pump concentrated settled sludge from T2 to a sludge drying system of some type. The SLAM model predicts an output from T2 of about 107 lbs/day of digested sludge.

Compressor - Will compress "biogas", generated at a rate of .45 cfm [646 cf/day] to 100 psia.

H.E. - Heat exchanger. Water type heat exchanger heated by electric coils.

Figure 12. System Configuration
The Operations cost category includes the purchase and shuttle delivery costs of oxygen propellant, to be used as an oxidizer with the digester generated fuel propellant, and the operations and maintenance costs of the system. To determine the amount of oxygen required per year, the mole fractions of biogas and oxygen calculated in the last section were used. For the described reaction these were, for oxygen 58.3%, and for biogas 41.7%. The mass flow rate of biogas produced was calculated to be 19.26 kg/day having a molar weight of 24.4 kg/kgmole. Therefore the biogas molar portion of the reactants is:

\[
\frac{19.26 \text{ kg/day}}{24.4 \text{ kg/kgmole}} = 0.789 \text{ kgmole/day}
\]

and the oxygen molar portion of the reactants is:

\[
\frac{0.789 \text{ kgmole/day}}{58.3\%} \div \frac{41.7\%}{1.104 \text{ kgmole/day}}
\]

The molar weight of oxygen is 32 kg/kgmole, therefore the weight of oxygen required for the reaction per day is:

\[
\frac{1.104 \text{ kgmole/day}}{32 \text{ kg/kgmole}} = 35.31 \text{ kg/day}
\]
or 77.69 lbm/day at STP which represents a yearly requirement of 28,357 lbs of oxygen. Operations and maintenance costs include labor and materials and were derived from various EPA charts. Table V lists the values of each cost element in the operations phase with its corresponding beta distribution type describing the uncertainty. Costs which are based on historical data were adjusted to current year dollars by an appropriate inflation factor of 9% which is applicable to Defense Department studies. (10:Charts D-1 – D-14; 11:63-71, Figures A-17 – A-40; 14:A-3, A-4; 25:4-10; 47)
### TABLE V
Cost Elements for Operational Phase

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>Cost['85$] Beta</th>
<th>Low</th>
<th>High</th>
<th>Curve</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>1.0 M</td>
<td>1.4 M</td>
<td>3</td>
<td></td>
<td>4 Maint. Men, 1 Lab Tech. $120,000/yr/man</td>
</tr>
<tr>
<td>Maintenance Supplies</td>
<td>6,100</td>
<td>7,100</td>
<td>5</td>
<td></td>
<td>Pump belts, lubrication, etc.</td>
</tr>
<tr>
<td>Energy</td>
<td>10,200</td>
<td>16,600</td>
<td>1</td>
<td></td>
<td>Based on 10% of total cost</td>
</tr>
<tr>
<td>Oxygen Purchase</td>
<td>17,200</td>
<td>17,400</td>
<td>8</td>
<td></td>
<td>Based on $.05 per cubic foot at STP</td>
</tr>
<tr>
<td>Oxygen Transport</td>
<td>25.8 M</td>
<td>104 M</td>
<td>6</td>
<td></td>
<td>39,357 lbs [Oxygen + Tank] mult by Shuttle cost per lb.</td>
</tr>
</tbody>
</table>

The alternative to providing a portion of the orbit maintenance requirement with the digester produced propellant is to use conventional fuels to provide that portion. The life cycle cost of this alternative is computed using the same Monte Carlo method as before but considering only the Operations cost category since conventional propellants will be purchased, rather than produced, and delivered to the space station on a regular basis. The cost elements involved with this alternative are purchasing and shipment of the propellants and are listed in Table VI. Propellant purchase costs are standard stock fund prices for DOD and NASA. For MMH the price is $8 – $10 per pound and for N_2O_4, $2.50 – $2.75 per pound. The variation in price reflects the fluctuation observed during the 1985 calander year. (25.4-10; 28)
### TABLE VI
Cost Elements for Conventional Propellants [Operational Phase]

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>Cost [85$] Low</th>
<th>Cost [85$] High</th>
<th>Beta Curve</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant Tank</td>
<td>3,300</td>
<td>5,100</td>
<td>1</td>
<td>One Time Purchase, Resusuable</td>
</tr>
<tr>
<td>( \text{N}_2\text{O}_4 )</td>
<td>67,963</td>
<td>74,758</td>
<td>4</td>
<td>Based on 27,185 Ibm (28)</td>
</tr>
<tr>
<td>MMH</td>
<td>131,808</td>
<td>164,760</td>
<td>4</td>
<td>Based on 16,476 Ibm (28)</td>
</tr>
<tr>
<td>Propellant Transport</td>
<td>31.2M</td>
<td>126.0M</td>
<td>6</td>
<td>Based on cost/lb for 43,661 lbs propellant and a 4,000 lb tank</td>
</tr>
</tbody>
</table>

The life cycle cost is dependent upon the span of time over which the system is procured and operated, and the time frame of acquisition and operation to which the discount rate will be applied. In order to calculate a life cycle cost several assumptions were made in scheduling the acquisition and operational phases. After the development stage is completed acquisition and on-ground preassembly could take place in one year and packaging and shipping the next year. The operational phase would last a lifetime of 30 years beginning in 2005 and therefore the acquisition phase would begin in 2003. Actual start dates for these phases are not important in the analysis, but they do allow for a common reference point when applying a discount rate. An average discount rate of 10%, appropriate to Defense Department studies, is used in this project. (13:227)

**Equivalent Propellant Determination.** A comparison of the methane generated propellant to shuttled conventional propellant requires that the amount and cost of the conventional propellant be determined. To provide a convenient basis for comparison the Shuttle Orbital Maneuvering Subsystem [OMS] was selected as a typical propulsion system that could be employed on the space...
station to provide orbit maintenance functions. This system uses Nitrogen Tetroxide \([\text{N}_2\text{O}_4]\) as an oxidizer and Monomethalhydrazine \([\text{MMH}]\) as a fuel. The question is then, how much of these propellants are required to produce the additional 3.2% of the force required to overcome atmospheric drag if the biogas system were not used? (1:13-7)

The force required to counteract the atmospheric drag was calculated in the section before last [page 46] as being 60.8 \(\text{kg-m/sec}^2\). Three and two-tenths percent of this figure, or 1.93 \(\text{kg/sec}^2\) is then the required force that the conventional propellant system must provide. The Shuttle OMS system can provide a specific impulse of 313 seconds. Specific impulse is a rocket performance parameter which relates thrust to the propellant mass flow rate. Using the formula for specific impulse the mass flow rate required to produce a force of 1.93 \(\text{kg-m/sec}^2\) can be calculated:

\[
m = \frac{F}{[I_p g_c]} = \frac{1.93 \text{ kg-m/sec}^2}{313 \text{ sec} \times 9.8 \text{ m/sec}^2}
\]

\[
= 6.29 \times 10^{-4} \text{ kg/sec} = 1.38 \times 10^{-6} \text{ lbm/sec}
\]

where:

\(g_c\) = gravitational constant

This is equivalent to a propellant flow requirement of 43,561 lbm/yr. The mass ratio of \(\text{N}_2\text{O}_4\) to MMH for this system is 1.65 to 1, therefore this flow requirement equates to 16,476 lbm/yr of MMH and 27,185 lbm/yr of \(\text{N}_2\text{O}_4\). Since the shuttle can carry a maximum of 65,000 lbs to an altitude of 240 km, this will not pose a weight restriction on how much propellant can be delivered on a flight. To determine if there is a volume restraint on the volume of propellants which can be carried into space, the densities [at STP] of \(\text{N}_2\text{O}_4\) [89.1 lbm/ft\(^3\)] and MMH [48.6 lbm/ft\(^3\)] are used to calculate the volume of the above mass of propellants:

68
\[ V_{N2O4} = \frac{m}{\rho} = \frac{27,185 \text{ lbm}}{89.1 \text{ lbm/ft}^3} = 305.1 \text{ ft}^3 \]

and:

\[ V_{MMH} = \frac{m}{\rho} = \frac{16,476 \text{ lbm}}{48.6 \text{ lbm/ft}^3} = 339.0 \text{ ft}^3 \]

This represents a total shipping volume requirement of 644.1 ft\(^3\). The cargo bay of the Shuttle has a volume of approximately 10,600 ft\(^3\), and therefore the volume requirement of the propellants is not a restraint and shuttle transport costs can be calculated on solely a cost per pound basis. The transport cost element is reflected in Table VI together with the purchase cost. (1:13–6,13–7; 45:29, 297)

**Analysis.** In order to compute the life cycle cost of the systems a set of equations is used to determine the argument, \( x \), of the cumulative distribution function, \( F(x) \), of the nine possible beta curves in Figure 10. The equations were developed from tables of the incomplete beta function for the given \( \alpha \) and \( \beta \) parameters. One hundred points from the tables were placed in a regression program which computed the polynomials for the curves that best fit the data points. The equations were then used to create values and these were checked against the tables. The equations are:

<table>
<thead>
<tr>
<th>Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( x = 4.4519 F(x) - 11.425 F(x)^2 + 14.898 F(x)^3 - 7.3393 F(x)^4 )</td>
</tr>
<tr>
<td>2</td>
<td>( x = 1.5828 F(x) - 1.72666 F(x)^2 + 1.1339 F(x)^3 )</td>
</tr>
<tr>
<td>3</td>
<td>( x = -.25015 F(x) + 2.265 F(x)^2 - 3.2916 F(x)^3 + 2.2205 F(x)^4 )</td>
</tr>
<tr>
<td>4</td>
<td>( x = 3.5761 (F(x)+.05) - 9.6707 (F(x))^2 + 12.954 F(x)^3 - 6.2156 F(x)^4 )</td>
</tr>
<tr>
<td>5</td>
<td>( x = 2.233 F(x) - 3.6096 F(x) + 2.3389 F(x)^3 )</td>
</tr>
<tr>
<td>6</td>
<td>( x = -.37482 F(x) + 4.8703 F(x)^2 - 9.1390 F(x)^3 + 5.4841 F(x)^4 )</td>
</tr>
<tr>
<td>7</td>
<td>( x = 2.6547 (F(x)+.1) - 5.7211 F(x)^2 + 6.0833 F(x)^3 - 2.3001 F(x)^4 )</td>
</tr>
</tbody>
</table>
Type Equation
8 \[ x = 2.7511 \, F(x) - 5.0861 \, F(x)^2 + 3.2677 \, F(x)^3 \]
9 \[ x = 0.14397 \, F(x) + 3.3829 \, F(x)^2 - 7.1725 \, F(x)^3 + 4.5308 \, F(x)^4 \]

Constraints: \( 0 \leq F(x) \leq 1 \quad 0 \leq x \leq 1 \)

These equations do not fully describe the argument of the cumulative distribution functions but are adequate except at the extreme tails of the distribution. Very rarely the value of \( x \) may be computed outside of the constraint range, but this will have no impact on the final life cycle cost distribution. These equations were developed into a FORTRAN function called BETA and used to determine random variables for weight and cost using the related beta uncertainty curve for the particular cost element (5, 40).

The flow chart describing the FORTRAN program used in determining the system life cycle cost is shown in Figure 13. The range of possible life cycle cost values that the system could have is computed from the sum of the high and low values for each of the cost elements discounted back to 1985. This range is then divided into 100 intervals for later use in testing each life cycle cost generated to see which interval it is assigned to. The program then determines a weight for each cost element based on the high and low values given and the beta curve associated with the weight uncertainty. This weight is used later in the program for determining the shipping cost based on a per pound cost estimate for the shuttle. The life cycle cost of each cost element is then generated from the high and low values assigned to it and its corresponding beta uncertainty curve. This cost is then multiplied times the number of units needed and discounted back from the time purchased to 1985. The program repeats this process for each cost element then sums the life cycle costs to determine the total life cycle cost. The life cycle cost is then tested to find the interval to which it belongs on the histogram and is
counted for that interval. The above process then repeats itself for a total of 500 iterations and provides a count of each life cycle cost within each interval of the histogram. The same program was used to compute the life cycle cost of both the digester system and the conventional propellant alternative. The program listing with inputs and outputs is presented in Appendix G.

The program output of the life cycle costs have been converted to a graphic histogram, from tabularized data in Appendix G, and are shown in Figures 14 and 15 for the digester system and conventional propellants, respectively. A composite of these two charts is shown in Figure 16. It is noted from the means of these charts that the life cycle cost of the anaerobic digester system does have a cost advantage over the conventional propellants alone. The additional cost of some type of substitute waste treatment system to replace the anaerobic digester would raise the cost of the conventional propellant system. Even without this additional cost there is a large difference [22.1 M$] between the means of the two life cycle costs. The difference is due primarily to the high cost of space transportation and the requirement for heavy density liquid propellants. Where digester fuel requires the shipment of light oxygen gas compressed to 2200 psi, orbit maintenance requirements calling for heavier conventional oxidizer will increase shipping costs. The possibility that shuttle derived heavy lift vehicles will be available to place larger payloads into orbit at less cost is considered in the lower range of the shuttle transportation cost element. A comparison of the two graphs, in Figure 16, shows that within one standard deviation of either mean the gap is 16.5 M$. This comparison reflects the significance of the high cost of shipping involved in transporting conventional propellants over the life time of the space station.
INPUT
Costs, Weights, Beta Type, Discount Rate

Compute high and low value of LCC and values of increments for histogram

Compute weights of system using random BETA variable

Compute LCC of system using random BETA variable

Find interval of histogram where LCC lies

All Iterations Complete?
No

Yes

Calculate mean LCC and standard deviation

OUTPUT
Mean, Standard Deviation, Histogram

Figure 13. Flow Process For Life Cycle Cost
Figure 14. Life Cycle Cost for Digester System
Figure 15. Life Cycle Cost for Conventional Propellants

ITERATIONS: 500
MEAN: 76.9 M$
S.D.: 6.0 M$

Each increment is approximately 1.3 M$

Counts

0 10 20 30 40 50

0 61.3 67.9 74.6 81.2 87.9 94.5 101.2
Figure 16. Comparison of Life Cycle Costs
The gap between the two means can be statistically tested to see if the difference can be attributed to chance. At a 5% level of significance the test favors the fact that there is difference between the two means. Though these results may seem to favor the digestor system, it must be remembered that many other factors must be considered by the decision maker in a selection of anaerobic digestion as a means of waste stabilization and propellant production. Factors which should also be considered are the costs involved with rocket design for biogas combustion or alternatively, waste treatment facilities other than anaerobic digestion if considering conventional propellants. Weighing into the decision are the additional benefits of reduced waste products, a fairly clear effluent from the digestor for water recovery, and possible utility of the stabilized waste material.
V. CONCLUSIONS AND RECOMMENDATIONS

The previous chapters have brought together information and analysis from three widely separate disciplines; 1) simulation analysis in biochemistry, 2) thermochemical analysis, and 3) cost analysis. This final chapter provides a summary of the major topics of importance presented in the first four chapters and their relationship to one another. A brief overview of the scenario chosen will be presented with a short discussion of the change in output results that could be expected if specific input parameters were altered. With regard to the scenario, the output of the SLAM model is discussed and its relationship to the thermochemical analysis and the sizing of the anaerobic digester. A review of the key elements considered in the cost analysis together with their impact on the final life cycle costs is presented here. Also discussed are the items that were excluded from the cost analysis and their impact on future decisions. Based on the results of the analysis in the previous chapters, recommendations are presented for further study.

Study Conclusions

Scenario. It is clear from the literature review that there is a need to reduce the costs of space transportation and also a need for waste treatment on large scale space stations. The literature provides very little evidence that any research has been attempted to tie these two requirements together and provide a cheap space propellant from wastes. Therefore, to provide a stage for the study of such a proposal, a scenario was selected based on previous work done by NASA. This scenario was then examined to extract those elements that have a
bearing on the design of an anaerobic digester and an impact on its biogas output when considered for use as a propellant.

The scenario selected provided three critical inputs to the analysis of the methane generation and its value as an orbit maintenance propellant. These inputs were pseudogravity, the number of people aboard the space station, and the altitude. Pseudogravity was a requirement necessary for the anaerobic digester to operate. The separation of the insoluble biogas from the waste sludge is only possible if there is gravity to pull the heavy sludge to the bottom of the digester tank. The number of people on the space station was used as an input to the digester model in determining the amount of methane that could be expected to be generated. It was also a factor in determining the size of the space station. The size of the station was then employed in evaluating its mass and shape using as guidelines configurations and parameters previously defined by NASA in their studies of future space stations. The mass and shape of the space station, along with the orbital altitude, allowed a determination to be made of the drag force that would be necessary to overcome if the vehicle were to maintain its orbit. The altitude selected was compatible with the space shuttle's orbit since the space station is dependent on the Earth for a majority of its resources. Any increase in the orbit altitude would decrease the drag on the space station and increase the percentage of the force requirement that could be produced by the generated methane. Any change in population requirement would not only change the methane generation rate, but also the mass, surface area, and consequently the drag on the space station.

**SLAM Model.** The simulation language for alternative modeling, SLAM, was chosen to model the anaerobic digester because of SLAM's capability
to model a continuous process. In order to build the model it was necessary to have a basic understanding of the anaerobic process and describe it in analytical terms. This description was provided by work done by Price and Cheremisinoff in their book, *Biogas Production and Utilization*.

The only input to the model from the scenario was the number of people aboard the space station. This input was then transformed into flow rate, percent solids present, organic solids present, and biological oxygen demand, using information obtained from NASA's previous studies which looked at actual astronaut's waste product composition and the expected waste output during future space activities.

Other inputs to the model which were not dependent on the scenario were digester temperature and efficiency. A temperature range was selected, based on historical data of Earth based digesters, which would be most favorable to the mesophilic, methane producing, bacteria. To allow for a realistic modeling of the environment within the digester the temperature was varied to simulate the actual fluctuations expected in waste input loading. The efficiency was allowed to vary randomly so the methane generation rate would reflect a reasonable estimate of reality. Shifts in the temperature range selection were made in various runs of the model, providing output results that showed very little gain in methane production rates for the increase in thermal energy.

The model was constructed using many variables which have their basis in laboratory experiments and scientific reasoning. Variations in such things as suggested solids retention time in the digester, microorganism growth and decay rates, and expected waste concentrations on large scale space stations can be modeled, but in reality will require human monitoring and intervention to provide
Thermochemical Analysis. Once an approximate methane generation rate was determined it was then necessary to predict how to best use the biogas in providing a counteracting force to the atmospheric drag. It was determined by looking at the amount of biogas generated from the SLAM model, and its density, that the biogas itself would not suffice as a cold gas monopropellant. An oxidizer suitable for combustion with methane, in this case oxygen, was selected, and first cut thermochemical calculations were made to determine the temperature of the combustion reaction for input into formulas that would determine the exhaust velocity and the required mass flow rate to produce the force required. These initial calculations showed a temperature above which dissociation of the combustion products would take place. The dissociation would lower the combustion temperature and, therefore, it was necessary to incorporate in-depth thermochemical analysis into the study.

Thermochemical analysis is a science which is totally dependent upon laboratory data tabulated in JANAF (Joint Army, Navy, and Air Force) thermochemical tables. The results obtained provide the best estimate of temperatures that can be expected with given combustion reactants and expected products. Variables that could change the output temperature prediction are fluctuations in the expected 70/30 methane/carbond dioxide mix and deletion or addition of expected output combustion products.

Cost Analysis. The cost analysis portion of this study is definitely the area where uncertainty has the greatest opportunity to alter the outcome of the comparison of propellant systems. One of the factors contributing to this
uncertainty is the time frame proposed for a space station of this scale. All that has been presented in this study is certainly within the limits of current day technology, and as such has been analyzed using current day engineering principles. However, technology does change and the systems of the future are dependent on that technology. Therefore, costs and weights and the associated uncertainty factors have been selected with their future application in mind to limit as much as possible the underestimation of the system's life cycle costs. Technology break-throughs pending, the estimates made in this study should provide a realistic costing estimate of future propellant systems.

Another factor that can affect the cost analysis outcome is design configuration of the anaerobic digestion system. The design selected for this study was one that is standard for large municipal high rate digesters. The sizing of the system was scaled down to accommodate the loads predicted from the SLAM model. It is probable that a system that would be placed in space would have an entirely different system configuration. One possibility is a "packaged" system that would contain all components; tanks, pumps, heat exchanger, etc., in a completely self-contained unit. Maintenance acquisition requirements to component parts of such a system would require it to be somewhat bulky, however design efforts could possibly overcome this difficulty. Another possibility is a single unit, rather than redundant units as proposed in this study, with additional equipment actually tied into the system but isolated from the flow with valves. This would provide quick response to system failures through the opening and closing of the proper valves. The first system provides convenience in packaging and shipping but more front end cost in design which would be hard to predict since digesters of this type and utility have not been attempted before. The
second system has the drawback of having to continuously pump sewage across the station.

For the system proposed the configuration allows for one digester to process the waste of the entire space station if necessary. Most of the time it will process the waste on its side of the vehicle while operating at half capacity. The configuration proposed also allows the system to be partially fabricated and assembled on the ground, with the final assembly being completed in space. This ground/space construction ratio is yet another factor which is unknown and can effect the labor cost element in the analysis. The uncertainty associated with this cost has been selected to hopefully capture the range of possibilities.

The outcome of the cost analysis shows a great deal of spread in the life cycle cost of the two alternatives presented. This spread is due primarily to the range of uncertainty in the transportation costs. The upper limit of the cost per pound transportation element is based on current non-government subsidized costs for the STS system. Unfortunately this cost is much higher than was originally anticipated for the space shuttle due to cost overruns and correction of many unforeseen technical problems on a new space transport system. The lower range is based on an unmanned heavy lift vehicle proposed by Martin Marietta. The beta distribution selected favors the Martin concept for future space transportation. If space transport costs remain as high as they are today, the spread of the life cycle cost can be expected to narrow while the mean increases.

The spread between the means of the two systems, approximately $22 M, is partially the effect of the initial premise of this study; the high cost of space transportation. Another factor which is reflected in this difference is the high cost of conventional propellants. As our technology base increases with our
increased man-hours in space there is a good possibility that the gap between the life cycles cost of these two systems will narrow. One indication of this is the lower cost per pound prediction for the shuttle derived vehicles which has been used as a parameter in the cost analysis in the lower limits of the cost range for space transport.

Additional benefits of reduction in waste have not been considered in this study, but may be a decision variable and are readily available from the SLAM model. The total reduction in waste processed through the system is approximately 7%. This is the percentage of waste converted to biogas. The percentage of effluent return to the water recovery system is approximately 84%. The remaining 9% is output from the digester in the form of digested sludge.

The conclusion reached from this analysis is that space generated propellants from human waste show a potential for lowering the cost of routine orbit maintenance for future space stations. The digester system can perform four functions; waste reduction, waste stabilization, effluent recovery, and production of a candidate propellant. These features can be tied directly into a closed cycle life support system and provide a propellant for future space missions. At higher orbital altitudes there is the possibility, with the reduced amount of air density, that the biogas propellant could provide 100% of the required force necessary to overcome drag. In the very distant future there is no doubt, in this author's mind, that long duration planetary missions will employ similar biological systems to reduce wastes and provide propellants which can be stored for use in attitude control, orbit maintenance, and landing control systems.

Recommendations

As mentioned early in this study, a valid and complete cost comparison
between the anaerobic digester and the system of conventional propellant transfer cannot be made without also considering the cost of the system that would have to replace the anaerobic digester if using conventional propellants and an alternative waste treatment system. It is recommended that the results of this analysis be coupled with a cost analysis of other systems capable of and feasible for space based waste stabilization. Such systems would include reverse osmosis, electrodialysis, and physiochemical processing. Also included in this study would be a weighted value of the benefits of the other systems being analyzed, and of the anaerobic digester. For the digester this would include effluent recovery, waste reduction, and possible alternative uses of the generated biogas.

As air density decreases with increasing altitude there will be some altitude at which the methane generated would be capable of providing all of the counter-force necessary to overcome atmospheric drag. This altitude could be found by an iterative method of guessing the altitude, generating the drag force at that altitude, and comparing the drag force with that which can be produced using the biogas/oxygen propellants. A study should be conducted to determine this altitude while considering the change in drag coefficient with altitude gain. This altitude would then be analyzed to see if it is within shuttle range and below harmful radiation belts.

The energy required in the operation of the anaerobic digester system was taken from rule of thumb estimations for Earth based digesters and then given a spread and uncertainty that would attempt to capture the value of space generated energy. It is recommended that analysis be done in the area of future space energy costs to narrow the spread and uncertainty of this cost element, and this new energy cost be incorporated in the cost analysis model. Other proposed
changes are the addition of costs associated with space based oxygen generation, to be used as an oxidizer agent in the biogas/oxygen reaction, and consideration of the generated biogas for attitude control and other uses.
BIBLIOGRAPHY


86
AN ECONOMIC FEASIBILITY STUDY ON THE SPACE-BASED PRODUCTION OF METHANE GA. (U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI. C C FALLSTEAD

UNCLASSIFIED DEC 85 AFIT/GSO/ENS/85D-8


APPENDIX A
DEFINITION OF TERMS

Adiabatic Flame Temperature. The highest possible temperature which can be reached given certain reactants. The reaction is calculated as going to completion [equilibrium is reached] and taking place adiabatically [without heat gain or loss]. (46:473)

Anaerobic Digestion. A continuous microbiological process that decomposes organic material, by the use of microorganisms that are capable of combining hydrogen with carbon in an anaerobic [oxygenless] environment. From a biological viewpoint this process can be described as taking place in two stages: [1] acid production, and [2] methane production. In the first stage, acid-forming organisms convert complex organic compounds into primarily volatile fatty acids, such as acetic, propionic and butyric. In the second stage, the acids are converted to methane and carbon dioxide by anaerobic bacteria. Factors which must be controlled for successful anaerobic digestion are: [1] the complete absence of oxygen, [2] digestion time, [3] temperature uniformity, [4] proper balance of organic carbon, nitrogen and phosphorus in the organic wastes, and [4] the absence of elements that are toxic to the bacteria. The major application of anaerobic digestion is the breakdown of organic matter in the concentrated sludges produced from the treatment of wastewater. (2:93; 41:1,88)

Antithetic Random Number. Random numbers generated which have a strong negative correlation to a previous set of random numbers to produce a small
variance in the dependent variable. This negative correlation is created by making the random numbers dependent of the initial set of random numbers. Generation is made by subtracting the initial set of random numbers from one.

**Biological Oxygen Demand [BOD]**. The oxygen used by the methane generating bacteria while they utilize the sewage as their food and energy source. BOD is determined by a standard 5 day test \([\text{BOD}_5]\) which accounts for the amount of oxygen utilized by the bacteria. \(\text{BOD}_L\) accounts for the maximum or ultimate oxygen demand on the sewage by the bacteria and can be determined from the amount of organic material added.

**Bipropellant System**. A rocket propellant system which uses two separate propellants, an oxidizer and a fuel. The propellants are stored separately and not mixed until injected into the combustion chamber. Most liquid propellant rockets use bipropellants. (45:204–205)

**Cold-Gas System**. A rocket propellant system which uses inert gas jets incorporating fast-acting valves and receiving its propellant supply from pressurized cold gas supply tanks. (45:227)

**Frozen Equilibrium** or **Frozen Flow**. A term used in describing the expansion of a gas through a nozzle for the purpose of analytical consideration. The composition of the product gas in the nozzle is assumed to be the same as that in the combustion chamber. This results in a conservative estimate of the exhaust velocity since in the product gas, in reality, will experience a drop in temperature.
and pressure and a conversion of the thermal energy to kinetic energy causing phase equilibria to occur between the gaseous and condensed phases of the constituents of the gas (called shifting equilibrium for a infinitely fast shift rate). Consideration of an appropriate equilibrium rate can be a complex analytical problem which is only possible if the correct rate information is known. (45:183–184)

**Per Capita.** The equivalence in people that it would take to produce a given amount of waste. A term used primarily in conjunction with municipal treatment facilities whose waste input comes from other than domestic areas (industrial waste, farm waste, etc.)

**Solids Retention Time (SRT).** The average time in days that waste solids remain in the digester.

**Specific Impulse** \(I_\text{s}\). The thrust that can be obtained from an equivalent rocket which has a propellant weight flow rate of unity. \(I_\text{s} = F/w = c/g\). Where \(F\) is thrust in pounds, \(w\) is the weight flow rate in pounds per second, \(c\) is the effective exhaust velocity, and \(g\) is the gravitational constant. Units of specific impulse are pounds of thrust per pound per second of propellant flow, or seconds. (45:30)

**Supernatant.** The liquid inside the digester. This liquid comes from the waste water input to the digester. In a two stage high rate digester, the primary mixing tank contains a supernatant which is a mix of the solids with the liquid. In the secondary settling tank, the supernatant is allowed to settle to remove the solids.
and withdraw the remaining supernatant as a fairly clear effluent.

Volatile Solids. Those solids coming into the digester that can be used by the bacteria as food material. This is determined by weighing a sample burned at 550°C to determine the ash content which is subtracted from the total solid weight. (49:4–21)
APPENDIX B
SLAM MODEL MAIN PROGRAM AND INPUT STATEMENTS

PROGRAM MAIN
DIMENSION NSET(10000)
COMMON/SCOM/ATRIB(100),DD(1),DO(100),DTNOW,II,MFA,MSTOP,NCLR
1,NCPR,NPNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
COMMON JSET(10000)
EQUIVALENCE (NSET(1),JSET(1))
NNSET=10000
NCPR=5
NPNT=5
NTAPE=7
NPLOT=2
CALL SLAM
STOP
END
SUBROUTINE EVENT
COMMON/SCOM/ATRIB(100),DD(100),DO(100),DTNOW,II,MFA,MSTOP,NCLR
1,NCPR,NPNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
RETURN
END
SUBROUTINE INTERVAL
COMMON/SCOM/ATRIB(100),DD(100),DO(100),DTNOW,II,MFA,MSTOP,NCLR
1,NCPR,NPNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
RETURN
END
SUBROUTINE OUTPUT
COMMON/SCOM/ATRIB(100),DD(100),DO(100),DTNOW,II,MFA,MSTOP,NCLR
1,NCPR,NPNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
RETURN
END
SUBROUTINE STATE

* %rj = RNORM(0.75, 0.75, 2)

TEMP CONSTANT: 
C SS(1) = x(1)

TEMP VARIATION:
C SS(1) = x(1) - 2.9*COS(8*PI*(TNOW-0.104))

LOAD CONSTANT:
C SS(2) = 2.6*SS(2)*TNOW

LOAD VARIATION:
C SS(2) = x(2) + 0.4*COS(8*PI*TNOW))

FLOW:
C SS(1) = SS(2)/100

SOLIDSRETENTION TIME:
C SS(2) = 10
IF SS(1), LT, 75) SS(2) = 0.8*SS(1)+30

TOTAL SOLIDS (%):
C SS(3) = 0.17*SS(2)

VOLATILE SOLIDS CALCULATED (-%): (UNITS =%D):
C SS(4) = SS(3)*0.85*SS(3)

METHANE PRODUCED:
C SS(5) = 0.35*SS(4)*SS(7)*1-(0.058*(1-0.25*SS(2)))

SOLIDS REMOVED:
C SS(6) = SS(3) - 1.65*9*SS(5)

VOLATILE SOLIDS LOADING (FIB):
C UNIT3 = SS(6)/SS(4)

DIGESTER VOLUME USED:
C SS(9) = SS(4)/SS(1)

HYDRAULIC RETENTION TIME:
C SS(10) = SS(9)/SS(1)
RETURN
END
INPUT STATEMENTS

SET: FLOW=0, ANAEROBIC DIGESTER, 5.10/988.

CONTINUOUS, 0.12, 4:17, N: 0 DIFF EDNS, 12 STATE EDNS, CALC EVERY 1 HR.

INTL. SS(1) = 0.72, SS(2) = 10.0, SS(3) = 0.3, SS(4) = 91.9, SS(5) = 0.3, SS(6) = 0.0,

SS(7) = 0.0, SS(8) = 0.0, SS(9) = 0.0, SS(10) = 0.0, SS(11) = 0.0, SS(12) = 0.0

REDO, SWTR, TIME; 0.124; PLOT POINT EVERY 1 HR

VAR: SS(1), Q, FLOW;
VAR: SS(1), R, SRT; SOLIDS RETENTION TIME
VAR: SS(3), S, TOTAL SOLIDS;
VAR: SS(4), V, VOLATILE SOLIDS; CALCULATED (#/D)
VAR: SS(5), M, METHANE GENERATED;
VAR: SS(6), D, SOLIDS REMOVED;
VAR: SS(7), E, EFFICIENCY;
VAR: SS(8), L, VOLATILE SOLIDS; LOADING FROM FIG. 6 (KG/M3/D)
VAR: SS(9), D, DIGESTER VOLUME USED;
VAR: SS(10), M, HRT; HYDRUALIC RETENTION TIME
VAR: SS(11), T, TEMP;
VAR: SS(12), I, TOTAL INPUT;
T: MST, SS(1), SRT;
F: MST, SS(3), TOTAL SOLIDS;
T: MST, SS(5), METHANE;
T: MST, SS(9), DIGESTER VOLUME;
T: MST, SS(10), HRT;
INITIALIZE, 0.4, 0; RUN 4 DAYS
END;
APPENDIX C
SLAM OUTPUT

SIMULATION PROJECT ANAEROBIC DIGESTER
BY FALLSTEAD

DATE  5/20/1985           RUN NUMBER  1 OF 1

SLAM VERSION JUN 84

GENERAL OPTIONS

PRINT INPUT STATEMENTS (I LIST): YES
PRINT ECHO REPORT (I ECHO): YES
EXECUTE SIMULATIONS (I AQ T): YES
WARN OF DESTROYED ENTITIES: NO
PRINT INTERMEDIATE RESULTS HEADING (I PRH): YES
PRINT SUMMARY REPORT (I SM R): YES

STATISTICS FOR TIME PERSISTENT VARIABLES

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<td>SS( 6) SOLIDS REMOVED</td>
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97
CONTINUOUS VARIABLES

NUMBER OF DC EQUATIONS (NAD20): 3
NUMBER OF SS EQUATIONS (NAESS): 1
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MAXIMUM STEP SIZE (DMAX): 0.4170E-01
TIME BETWEEN SAVE POINTS (DSTP): 0.4170E-01
ACCURACY ERROR SPECIFICATION (ERRI): NO ERROR
ABSOLUTE ERROR LIMIT (AREL): 0.1288E-04
RELATIVE ERROR LIMIT (AREL): 0.1288E-04

RECORDING OF PLOTS/TABLES

PLOT/TABLE NUMBER 1

INDEPENDENT VARIABLE: TNOW
IDENTIFIER: TIME
DATA STORAGE UNIT: VSSET/USSET
DATA OUTPUT FORMAT: PLOT
TIME BETWEEN PLOT POINTS (DTPLT): 0.4170E-01
STARTING TIME OF PLOT (TSTRT): 0.0000E+00
ENDING TIME OF PLOT (TEND): 0.4000E+01
DATA POINTS AT EVENTS (PREVT): YES

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INITIALZATION OPTIONS

BEGINNING TIME OF SIMULATION (TBEG): 2.0000E-20
ENDING TIME OF SIMULATION (TFIN): 4.0000E+01
STATISTICAL ARRAYS CLEARED (JICLR): YES
VARIABLES INITIALIZED (IJVAR): YES
FILES INITIALIZED (IJFIL): YES

NSET/QSET STORAGE ALLOCATION

DIMENSION OF NSET/QSET (NNSET): 10000
WORDS ALLOCATED TO FILING SYSTEM: 0
WORDS ALLOCATED TO INDEXED LIST TABLES: 0
WORDS ALLOCATED TO NETWORK: 15
WORDS AVAILABLE FOR PLOTS/TABLES: 9995

INPUT ERRORS DETECTED: 8

EXECUTION WILL BE ATTEMPTED
**SIMULATION PROJECT - ANAEROBIC DIGESTER**

**DATE** 5.20/1985

**CURRENT TIME** 0.1000E+01

**STATISTICAL ARRAYS CLEARED AT TIME** 0.0000E+00

**STATISTICS FOR TIME-PERSISTENT VARIABLES**

<table>
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<tr>
<th>Variable</th>
<th>Mean Value</th>
<th>Standard Deviation</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Current Time Value</th>
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<td>0.1200E+02</td>
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100
**STATE AND DERIVATIVE VARIABLES**

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Minimum: 0.1000E+00 0.9000E+01 0.1000E+01 0.3593E+02 0.5248E+02 0.3120E+03
Maximum: 0.1200E+00 0.2774E+02 0.1330E+01 0.7062E+02 0.3753E+02 0.7293E+03

101
| 0.192E+01 | + | R | + | T | D | I | + | M | + | + | T | L | D | L | I |
| 0.185E+01 | + | R | | | | | | | | | | | | | |
| 0.165E+01 | + | I | L | | | | | | | | | | | | | |
| 0.126E+01 | D | T | L | M | + | + | + | + | + | + | + | + | + | + | + |
| 0.136E+01 | R | D | + | I | M | + | T | + | + | + | + | + | + | + | + |
| 0.175E+01 | R | + | + | M | + | + | + | + | + | + | + | + | + | + | + |
| 0.175E+01 | R | + | + | + | D | I | + | + | + | + | + | + | + | + | + |
| 0.191E+01 | D | T | L | M | + | + | + | + | + | + | + | + | + | + | + |
| 0.191E+01 | R | D | + | I | M | + | T | + | + | + | + | + | + | + | + |
| 0.165E+01 | + | R | + | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.192E+01 | + | L | + | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.212E+01 | D | T | L | M | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.212E+01 | R | D | + | I | M | + | T | + | + | + | + | + | + | + | + |
| 0.221E+01 | R | + | + | + | + | D | I | + | + | + | + | + | + | + | + |
| 0.232E+01 | R | + | + | + | + | + | D | I | + | + | + | + | + | + | + |
| 0.229E+01 | + | R | + | + | T | + | M | D | I | + | + | + | + | + | + |
| 0.235E+01 | + | L | + | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.277E+01 | D | T | L | M | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.240E+01 | R | D | + | I | M | + | T | + | + | + | + | + | + | + | + | + |
| 0.250E+01 | R | + | + | M | D | I | + | + | + | + | + | + | + | + | + | + |
| 0.293E+01 | R | + | + | + | + | + | + | D | I | + | + | + | + | + | + | + |
| 0.278E+01 | R | + | + | + | + | + | + | + | D | I | + | + | + | + | + | + |
| 0.279E+01 | + | R | + | + | T | + | M | D | I | + | + | + | + | + | + | + |
| 0.287E+01 | T | L | + | + | I | + | D | + | + | + | + | + | + | + | + | + |
| 0.287E+01 | D | T | L | M | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.291E+01 | R | M | + | I | T | + | + | + | + | + | + | + | + | + | + | + |
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| 0.304E+01 | + | R | + | + | T | + | M | D | I | + | + | + | + | + | + | + |
| 0.306E+01 | T | L | M | + | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.312E+01 | + | R | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
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| 0.318E+01 | R | D | + | I | M | + | T | + | + | + | + | + | + | + | + | + |
| 0.321E+01 | R | + | + | + | M | D | I | + | + | + | + | + | + | + | + | + |
| 0.323E+01 | R | + | + | M | + | + | + | + | + | + | + | + | + | + | + | + |
| 0.379E+01 | + | R | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
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| 0.469E+01 | R | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
TIME

OUTPUT CONSISTS OF 99 POINT SETS (594 POINTS)

STORAGE ALLOCATED FOR 1426 POINT SETS (9982 WORDS)

STORAGE NEEDED FOR 99 POINT SETS (697 WORDS)
APPENDIX D

SLAM MULTI-RUN PROGRAM

***MULTI-RUN TESTING PROGRAM***

***INPUT STATEMENTS***

GEN,FALLSTEAD, AEROBIC DIGESTER: 0.1985, 0, NO, NO, NO, 5: 6 COLUMN WIDTH
CONTINUOUS, 0.12, 0.8417, NO: 0 DIFF EQNS, 10 STATE EQNS, CALL EVERY: HR.
INTLC, SS(1)=0.729, SS(1)=0.8, SS(1)=0.85, 4=x1, 3, SS(5)=0.8, SS(5)=0.8.

xx(1) = TEMP, xx(2) = PEOPLE

TIMST, SS(5), METHANE;
TIMST, SS(9), DIGESTER VOLUME;
INITIALIZE, 0.4, 0; RUN 4 DAYS
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SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;
SEEDS, 501744845(2)/NO;
SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;
SIMULATE;

INTLC, xx(1)=0;
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SIMULATE;
SEEDS, 501744845(2)/NO;
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SIMULATE;
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APPENDIX E
SLAM STATISTICS FOR TIME-PERSISTENT VARIABLES

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ADIABATIC FLAME TEMPERATURE CALCULATIONS

I. Adiabatic Flame Temperature, no Dissociation

Reaction:

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$$

The actual reaction of biogas with \(\text{O}_2\) on a molar basis is:

$$0.5525[\text{CH}_4 + 2\text{O}_2] + 0.2368\text{CO}_2 \rightarrow 0.5525[\text{CO}_2 + 2\text{H}_2\text{O}] + 0.2368\text{CO}_2$$

On a per mole \(\text{CH}_4\) basis:

$$\text{CH}_4 + 2\text{O}_2 + 0.4286\text{CO}_2 \rightarrow 2\text{H}_2\text{O} + 1.4286\text{CO}_2$$

Then,

$$\Delta H_f = \Sigma n_p \Delta H_f^p - \Sigma n_r \Delta H_f^r$$

$$= n_{\text{CO}_2} \Delta H_f^{\text{CO}_2} + n_{\text{H}_2\text{O}} \Delta H_f^{\text{H}_2\text{O}} - [n_{\text{CH}_4} \Delta H_f^{\text{CH}_4} + n_{\text{O}_2} \Delta H_f^{\text{O}_2}]$$

$$= 1.4286(-94.054) - 2(57.797) - [(-17.89) + 0.4286(-94.054)]$$

$$= -134.365 - 115.594 + 58.207$$

$$= -191.7548 \text{ Kcal/mole CH}_4$$

If 191.7548 Kcal are added to the products, then by trial and error:

$$\Delta H_r = 191.7548 \text{ Kcal} = \Sigma n_p (H-H_{298})$$

$$= n_{\text{H}_2\text{O}}(H-H_{298})_{\text{H}_2\text{O}} + n_{\text{CO}_2}(H-H_{298})_{\text{CO}_2}$$

@ 5500K:

$$2(64.949) + 1.4286(74.433) = 236.233 \text{ Kcal}$$

@ 5000K:

110
\[ 2(57.829) + 1.4286(66.753) = 211.021 \text{ Kcal} \]

@ 4500K:
\[ 2(50.777) + 1.4286(59.122) = 186.016 \text{ Kcal} \]

@ 4600K:
\[ 2(52.181) + 1.4286(60.644) = 190.998 \text{ Kcal} \]

Therefore, the adiabatic flame temperature without dissociation is approximately 4600K. At this temperature dissociation would be taking place. A thermochemical analysis involving all the possible products must be accomplished to determine the proper adiabatic flame temperature.
II. Adiabatic Flame Temperature, Dissociation

Reaction:

\[ \text{CH}_4 + 2\text{O}_2 + 4.286\text{CO}_2 \rightarrow a\text{H}_2\text{O} + b\text{OH} + c\text{O} + d\text{O}_2 + e\text{H} + f\text{H}_2 + g\text{CO}_2 + h\text{CO} \]

where;

\[ a, b, c, \ldots = \text{Number of moles of particular product} \]

Writing mass balance equations for H, O, and C:

- H: \[ 2a + b + e + 2f = 4 \]
- O: \[ a + b + c + 2d + 2g + h = 4.8572 + 4 \]
- C: \[ g + h = 1.4286 \]

The equilibrium equations are:

- \[ \frac{1}{2} \text{H}_2 \leftrightarrow \text{H} \]
- \[ \frac{1}{2} \text{O}_2 \leftrightarrow \text{O} \]
- \[ \frac{1}{2} \text{H}_2 + \frac{1}{2} \text{O}_2 \leftrightarrow \text{OH} \]
- \[ \text{H}_2 + \frac{1}{2} \text{O}_2 \leftrightarrow \text{H}_2\text{O} \]
- \[ \text{C}_\text{solid} + \frac{1}{2} \text{O}_2 \leftrightarrow \text{CO} \]

By using these eight equations and the molar equilibrium constants, Kn below, a solution for the adiabatic flame temperature can be obtained by trial and error.

\[ \text{Kn}_e = \frac{n_H}{n_{\text{H}_2}^{1/2}} \]
\[ \text{Kn}_b = \frac{n_{\text{OH}}}{n_{\text{O}_2}^{1/2} n_{\text{H}_2}^{1/2}} \]
\[ \text{Kn}_a = \frac{n_{\text{H}_2\text{O}}}{n_{\text{H}_2} n_{\text{O}_2}^{1/2}} \]
\[ \text{Kn}_c = \frac{n_{\text{O}}}{n_{\text{O}_2}^{1/2}} \]
\[ \text{Kn}_h = \frac{n_{\text{CO}}}{n_{\text{O}_2}^{1/2}} \]
These molar equilibrium constants are related to pressure equilibrium constants, $K_p$, which can be looked up in thermochemical tables (4), by the following relationships:

$$
K_{n,e} = (K_p,e)(n/p)^{1/2}
$$

$$
K_{n,b} = K_p,b
$$

$$
K_{n,a} = (K_p,a)(n/p)^{-1/2}
$$

$$
K_{n,c} = (K_p,c)(n/p)^{1/2}
$$

$$
K_{n,h} = (K_p,h)(n/p)^{-1/2}
$$

where;

$n =$ total number of moles

$p =$ pressure in atmospheres

These relations can be rewritten in terms of the equilibrium mole numbers:

$$
n_H = (K_{n,e})n_{H_2}^{1/2}
$$

$$
n_{O_2} = (K_{n,b})n_{H_2}^{1/2}n_{O_2}^{1/2}
$$

$$
n_{H_2O} = (K_{n,a})n_{O_2}^{1/2}n_{H_2}
$$

$$
n_O = (K_{n,c})n_{O_2}^{1/2}
$$

$$
n_{CO} = (K_{n,h})n_{O_2}^{1/2}
$$

Substituting these relations into the mass balance equations:

$$
N_H = 4 = (K_{n,e})n_{H_2}^{1/2} + 2n_{H_2} + (K_{n,b})n_{H_2}^{1/2}n_{O_2}^{1/2} + 2(K_{n,a})n_{O_2}^{1/2}n_{H_2}
$$

$$
N_O = 4.8572 = (K_{n,c})n_{O_2}^{1/2} + (K_{n,b})n_{H_2}^{1/2}n_{O_2}^{1/2} + 2n_{O_2} +
$$

$$(K_{n,a})n_{O_2}^{1/2}n_{H_2} + 2n_{CO_2} + (K_{n,h})n_{O_2}^{1/2}
$$

$$
N_C = 1.4286 = n_{CO_2} + (K_{n,h})n_{O_2}^{1/2}
$$

where;

$N_i =$ Total number of atoms of that species

Using $N_H, n_{O_2}^{1/2}$ can be solved for in terms of $n_{H_2}$.
\[ n_{O_2}^{1/2} = \left( N_H - (K_{n,e}n_{H_2}^{1/2}-2n_{H_2})/( (K_{n,b})n_{H_2}^{1/2}n_{O_2}^{1/2} + 2(K_{n,a})n_{O_2}^{1/2}n_{H_2}) \right) = A \]

Substituting into \( N_0 \) and \( N_C \):

\[ N_0 = 2n_{O_2} + n_{O_2}^{1/2}( (K_{n,c}) + (K_{n,b})n_{H_2}^{1/2} + 2(K_{n,a})n_{H_2}) + 2n_{CO} + (K_{n,h})n_{O_2}^{1/2} \]

or,

\[ N_0 = 2A^2 + A((K_{n,c}) + (K_{n,b})n_{H_2}^{1/2} + 2(K_{n,a})n_{H_2}) + 2n_{CO} + (K_{n,h})A \]

and,

\[ N_C = n_{CO} + A(K_{n,h}) \]

The equations for \( N_0 \) and \( N_C \) are now in terms of \( n_{H_2} \) and known constants since:

\[ n_{CO} = 1.4286 - (K_{n,h})A \]

The computer program which follows is a modification of a program written by Capt Robert Dimmick (6) (dealing with two reactants and six products) and iterates on a guess of the one species, \( n_{H_2} \), which the equations are now in terms of, at an estimated adiabatic flame temperature. The actual adiabatic flame temperature is obtained by an analysis of the heat energies as was done previously when dissociation was not considered. For this case:

**Q1** -

The heat necessary to change the reactant from a liquid to a gas at the boiling temperature equals zero, since reactants are already in a gaseous form.

**Q2** -

The heat necessary to raise the reactants from their boiling temperatures to 298K also equals zero, since reactants are stored at room temperature (the reaction temperature).
Q3 -

The heat of reaction which, as stated before, is:

$$\Delta H_r = \Sigma n_p \Delta H_f^p - \Sigma n_t \Delta H_f$$

which in the program is written in the form:

$$\Sigma n_p \Delta H_f^p - 58.207 \text{ Kcal/mole}$$

Q4 -

The heat necessary to raise the products from the reaction temperature, 298K, to the combustion temperature (Tc), and as stated before as Q4, equals $$\Sigma n_p(H-H_{298})$$.

The program uses the heat balance equation;

$$Q_{total} = Q1 + Q2 + Q3 + Q4 = 0$$

to determine if the appropriate adiabatic flame temperature was chosen. If not the program calculates a new temperature and the mass balance equations are again iterated. In the program Q3 has a built in sign convention that negative is heat out so that $$Q1 + Q2 + Q4 = -Q3$$ maintains the proper sign.

The computer program and the last few iterations of program output follow.
1200 REM PROGRAM "FINAL"
1210 REM
1220 REM This program solves the equilibrium combustion problem for a chemical reactor. Iterations can find values for the
1230 REM net output. The gas temperature is:
1240 REM DATA INPUT ROUTINES:
1250 REM
1260 DIM PROD(8,10,3),HRE(8),MOLE(8)
1270 REM DATA TABLE DATA IS ENTERED IN THE ARRAY PROD(CHEM,TEMP,J)
1280 REM THE FOLLOWING VALUES ARE APPLIED TO THE ARRAY DIMENSIONS
1290 REM CHEM -- CHEM 1 = MONATOMIC HYDROGEN (H)
1300 REM CHEM 2 = DIATOMIC HYDROGEN (H2)
1310 REM CHEM 3 = MONATOMIC OXYGEN (O)
1320 REM CHEM 4 = DIATOMIC OXYGEN (O2)
1330 REM CHEM 5 = WATER (OH)
1340 REM CHEM 6 = CARBON MONOXIDE (CO)
1350 REM CHEM 7 = CARBON DIOXIDE (CO2)
1360 REM TEMP -- TEMPERATURE OF PRODUCTS IN DEGREES K
1370 REM J -- J=1 STORAGE OF TEMPERATURE DATA
1380 REM J=2 STORAGE OF H = H(298) DATA
1390 REM J=3 STORAGE OF LOG (KPI) DATA
1400 REM THE ARRAY HRE(CHEM) CONTAINS HEAT OF REACTION DATA (T=298 K)
1410 REM THE ARRAY MOLE(CHEM) CONTAINS THE EQUILIBRIUM MOLES OF PRODUCTS
1420 FOR CHEM=1 TO 8
1430 FOR J=1 TO 3
1440 FOR TEMP=8 TO 9
1450 READ PROD(CHEM,TEMP,J)
1460 NEXT TEMP
1470 NEXT J
1480 NEXT CHEM
1490 FOR CHEM=1 TO 3
1500 REM READ HRE(CHEM)
1510 NEXT CHEM
1520 REM PROD(CHEM,TEMP,J)
150 REM MAIN PROGRAM BEGINS
170 REM ENTER INITIAL GUESS FOR THE ADIABATIC FLAME TEMPERATURE
180 REM THE GUESS MUST BE IN THE RANGE 2000-3000 DEGREE K
190 REM
200 INPUT* ENTER INITIAL GUESS FOR Tc (ADIABATIC): "*Tc
210 Tc=1000*2000*.01
220 TEMP=INT(Tc)
230 SCALE=Tc-TEMP

1440 REM THE VARIABLE SCALE IS USED TO DO A LINEAR INTERPOLATION OF DATA
1450 REM COMPUTE K's FOR THE CHEMICALS
1460 KPH=10**(PROD(1,TEMP,3)+SCALE*(PROD(1,TEMP+1,3)-PROD(1,TEMP,3)))
1470 KPH2=10**(PROD(2,TEMP,3)+SCALE*(PROD(2,TEMP+1,3)-PROD(2,TEMP,3)))
1480 KPO=10**(PROD(5,TEMP,3)+SCALE*(PROD(5,TEMP+1,3)-PROD(5,TEMP,3)))
1490 KPD2=10**(PROD(4,TEMP,3)+SCALE*(PROD(4,TEMP+1,3)-PROD(4,TEMP,3)))
1500 KPDH=10**(PROD(6,TEMP,3)+SCALE*(PROD(6,TEMP+1,3)-PROD(6,TEMP,3)))
1510 KPDH2=10**(PROD(7,TEMP,3)+SCALE*(PROD(7,TEMP+1,3)-PROD(7,TEMP,3)))
1520 REM ENTER INITIAL DATA GUESSES FOR THE EQUILIBRIUM ITERATIONS
1525 NE=2.9 :REM NE is the guess for the total moles of products
1540 NH2=4 :REM NH2 is the guess for the moles of H2 product
1550 LHSO=4.2572 :REM LHSO is the total moles of O in reactants
1555 LHSO=1.4286 :REM LHSO is the total moles of C in reactants
1560 REM COMPUTE K's FOR THE PRODUCTS
1570 NH=KPH*SQR(PINE/P)
1580 NO=KPO*SQR(PIE/P)
1590 NH2=KPH2*SQR(PINE/P)
1600 NO=KPO*SQR(PIE/P)
1605 NO=KPO*SQR(PIE/P)
1610 REM (; EQUILIBRIUM CALCULATION ITERATIONS ;)
1620 J=0
1630 A=1+4*NH*SQR(NH2)-2*NH2: (KHONOH*SQR(NH2)+2*KHONOH2*NH2)
1640 NO2=A/2
1650 NO=NO*SQR(NO2)
1660 NH=NH*SQR(NH2)
1670 NO2=NO2*SQR(NO2)
1680 NO=NO*SQR(NO2)
1690 NO=NO*SQR(NO2)
1695 NO=NO*SQR(NO2)
1697 REM WE NOW CHECK THE ATOMIC BALANCE FOR OXYGEN

117
REM WE MAKE A NEW GUESS FOR NH2 AND ITERATE
1780 \( \text{NH}_2 = \text{NH}_2 - \text{ERROR} \times 1 \times 1 \)
1780 SOTO 1770
1790 REM WE NOW CHECK THE MOLE BALANCE FOR THE GIVEN NH2 AND NO2
1790 \( \text{NEE} = \text{NH} + \text{NH}_2 + \text{NO} + \text{NO}_2 + \text{NH}_2 + \text{NO}_2 + \text{NO} + \text{NO}_2 + \text{NO}_2 \)
1790 \( \text{ERROR} = \text{NEE} - \text{NEE} \)
1800 IF \( \text{ABS} \text{ERROR} > 0.001 \) THEN 1770
1810 PRINT: PRINT: PRINT: PRINT
1820 PRINT* NE,E:NE,E:NE,E
1830 REM WE ADJUST NE AND ITERATE AGAIN
1840 NE = 0.5*(NE + NEE)
1850 SOTO 1580
1860 REM (** OUTPUT EQUILIBRIUM CONDITIONS **) 1870 LPRINT* THE TOTAL NUMBER OF PRODUCT MOLES IS: \( \text{NEE} \)
1880 LPRINT* THE NUMBER OF MOLES OF H IS: \( \text{NH} \)
1890 LPRINT* \( \text{NO}_2 \) IS: \( \text{NH}_2 \)
1900 LPRINT* \( \text{NO} \) IS: \( \text{NO}_2 \)
1910 LPRINT* \( \text{NO} \) IS: \( \text{NO}_2 \)
1920 LPRINT* \( \text{CO} \) IS: \( \text{NO}_2 \)
1930 LPRINT* \( \text{CO}_2 \) IS: \( \text{NO}_2 \)
1940 LPRINT
1950 REM **) LOAD FINAL MOLE NUMBERS **)
1960 MOLE(1) = NH
1970 MOLE(2) = NH2
1980 MOLE(3) = NO
1990 MOLE(4) = NO2
2000 MOLE(5) = NOH
2010 MOLE(6) = NO2
2020 MOLE(7) = NOC
2030 MOLE(8) = NOC
2040 REM (** FINAL CALCULATIONS OF Q **)
2050 REM \( Q \) OUT REPRESENTS THE HEAT OF REACTION AT 298K FOR THE EQUILIBRIUM
2060 REM MOLE NUMBERS OF PRODUCTS
2070 REM \( \Delta H \) IN \( \text{NEE} \) REPRESENTS THE HEAT NECESSARY TO RAISE THE PRODUCTS FROM THE
REM \text{REACTION TEMPERATURE TO THE COMPLETE TEMPERATURE}
{REM} \text{SCALEH = A DUMMY VARIABLE USED TO PREVENT OVERFLOW FOR QAIN}
230 REM
230 FOR CHEM=1 TO 8
230 SCALEH=SCALEH*PROD(TEMP,TEMP)=PROD(TEMP,TEMP)
230 QAIN=MOLE(TEMP)=PROD(TEMP,TEMP/SCALEH)-QAIN
230 NEXT CHEM
230 FOR CHEM=1 TO 8
230 JOUT=-MOLE(TEMP)*HEAT(TEMP)-JOUT
230 NEXT CHEM
230 JOUT=JOUT=JOUT=JOUT
230 REM \text{\texttt{LPRINT} FOR A COMBUSTOR TEMPERATURE OF "TC: DEGREES"}
230 LPRINT* "TC IN IS:"Q1IN:" kcal"
230 LPRINT* "Q2 IN IS:"Q2IN:" kcal"
230 LPRINT* "Q3 OUT IS:"Q3OUT:" kcal"
230 LPRINT* "Q4 IN IS:"Q4IN:" kcal"
230 LPRINT
230 QTOTIN=Q1IN+Q2IN+Q4IN
230 REM \text{QOTOTOUT \text{\texttt{LPRINT}}} THE SUM OF THE HEAT OF REACTION FOR THE
230 REM \text{PRODUCTS AT 298 K MINUS THE HEAT OF REACTION FOR THE REACTANTS}
230 REM AT 298 K
230 QOTOTOUT=Q3OUT
230 DELT AQ=QTOTIN-QOTOTOUT
230 LPRINT* "TOTAL Q IN IS:"QTOTIN:" kcal"
230 LPRINT* "TOTAL Q out IS:"QTOTOUT:" kcal"
230 LPRINT* "THE Q NET IS:"ILDELT AQ:" kcal"
230 LPRINT:LPRINT:LPRINT
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
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230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
230 REM \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}} \text{\texttt{LPRINT}}
2420 REM / DATA FOR H
2430 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2450 DATA -1.803,-1.674,-1.555,-1.439,-1.322,-1.205,-1.088,-0.944,-0.834
2460 REM
2470 REM / DATA FOR H1
2480 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2500 DATA 0.0,0.8,0.8,0.8,0.8
2510 REM
2520 REM / DATA FOR D
2530 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2550 DATA -1.949,-1.805,-1.662,-1.519,-1.376,-1.233,-1.091,-0.947
2560 REM
2570 REM / DATA FOR O2
2580 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2600 DATA 0.0,0.8,0.8,0.8,0.8
2610 REM
2620 REM / DATA FOR OH
2630 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2650 DATA 0.869,1.01,1.158,1.305,1.451,1.597,1.744,1.890,2.036,2.182
2660 REM
2670 REM / DATA FOR H2O
2680 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2690 DATA 30.381,31.257,32.132,33.007,33.882,34.757,35.632,36.506,37.381,38.254
2700 DATA 1.747,1.917,1.087,1.942,1.024,1.12,1.287,1.453,1.619,1.785
2710 REM
2711 REM / DATA FOR CO
2712 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2715 REM
2716 REM / DATA FOR CO2
2717 DATA 3888,3100,3200,3300,3400,3500,3600,3700,3800,3900
2718 DATA 36.555,37.544,38.515,39.486,40.458,41.431,42.404,43.378,44.352,45.326
2720 REM

120
1715 REM DATA FOR RATE OF REACTION -- 168 x
1718 DATA 52.100,0.59,559,0.4,332,-50,754,-23,417,-74,954
1740 REM
1750 REM :: INPUT CHECK ::
1760 FOR CHEM = 1 TO 8
1770 FOR TEMP = 8 TO 9
1780 FOR J=1 TO 9
1790 LPRINT PROD CHEM,TEMP,J.
1800 NEXT J : LPRINT
1810 NEXT TEMP : LPRINT:LPRINT:LPRINT
1820 NEXT CHEM
1830 END
THE TOTAL NUMBER OF PRODUCT MOLES IS: 1.4286
THE NUMBER OF MOLES OF H IS: 1.21059
H2 IS: 1.402468
O IS: 0.8967492
O2 IS: 1.127308
OH IS: 0.017287
H2O IS: 1.00218
CO IS: 0
CO2 IS: 1.4286

FOR A COMBUSTOR TEMPERATURE OF 2280.15 DEGREES K
G1 IN IS: 0 Kcal
O2 IN IS: 0 Kcal
O2 OUT IS: 103.315 Kcal
G4 IN IS: 103.314 Kcal

TOTAL G IN IS: 103.315 Kcal
TOTAL O2 out IS: 103.315 Kcal
THE 3 NET IS: -2.27788E-03 Kcal

THE TOTAL NUMBER OF PRODUCT MOLES IS: 1.4286
THE NUMBER OF MOLES OF H IS: 1.21059
H2 IS: 1.402468
O IS: 0.8967492
O2 IS: 1.127308
OH IS: 0.017287
H2O IS: 1.00218
CO IS: 0
CO2 IS: 1.4286

FOR A COMBUSTOR TEMPERATURE OF 2280.17 DEGREES K
G1 IN IS: 0 Kcal
O2 IN IS: 0 Kcal
O2 OUT IS: 103.315 Kcal
G4 IN IS: 103.314 Kcal

TOTAL G IN IS: 103.314 Kcal

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TOTAL 2 out 1st: 1.37.716 kcal
THE Q NET 1st: 1.87583E-03 kcal.

THE TOTAL NUMBER OF PRODUCT MOLES IS: 3.91681
THE NUMBER OF MOLES OF H IS: .211403
H2 IS: .40249
O IS: .0%7552
O2 IS: .177088
OH IS: .717272
H2O 1st: 1.53218
CO IS: 0
CO2 IS: 1.42E6
H2O IS: 1.33216
CO IS: 0
CO2 IS: 1.42E6

FOR A COMBUSTOR TEMPERATURE OF 3398.16 DEGREES K
O1 IN 1st: 0 kcal
O2 IN 1st: 0 kcal
O2 OUT 1st: 127.315 kcal
O4 IN 1st: 127.314 kcal

TOTAL O in 1st: 127.314 kcal
TOTAL O out 1st: 127.315 kcal
THE Q NET 1st: 1.87583E-03 kcal

THE TOTAL NUMBER OF PRODUCT MOLES IS: 3.91681
THE NUMBER OF MOLES OF H IS: .211403
H2 IS: .40249
O IS: .0%7552
O2 IS: .177088
OH IS: .717272
H2O 1st: 1.53218
CO IS: 0
CO2 IS: 1.42E6
H2O IS: 1.33216
CO IS: 0
CO2 IS: 1.42E6
FOR A COMBUSTOR TEMPERATURE OF 2320.17 DEGREES K

1. IN 15: 0 kcal
2. IN 15: 0 kcal
2. OUT 15: 133.515 kcal
3. IN 15: 107.714 kcal

TOTAL 2 IN 15: 133.514 kcal
TOTAL 2 OUT 15: 133.515 kcal
THE 2 NET 15: 9.4045E-04 kcal
APPENDIX G

MONTE CARLO PROGRAM FOR LIFE CYCLE COST

Program:

***BEGINNING OF PROGRAM***

C ACQUISITION COSTING ROUTINE TO DETERMINE LIFE CYCLE COST
C OF SPACE BASED ANAEROBIC DIGESTER.

*************************************************************************

**VARIABLE DEFINITIONS:**

**ARRAY VARIABLES**

C LA1) - HIGHEST POSSIBLE COST OF ACQUISITION COST ELEMENT
C LA2) - LOWEST POSSIBLE COST OF ACQUISITION COST ELEMENT
C LS1) - BETA UNCERTAINTY CURVE TYPE FOR COST OF ACQUISITION ELEMENT
C LY1) - YEAR IN ACQUISITION PHASE THAT COST ELEMENT IS PURCHASED
C NL1) - NUMBER OF ACQUISITION COST ELEMENT PURCHASED
C HW1) - HIGHEST POSSIBLE WEIGHT OF ACQUISITION COST ELEMENT
C LW1) - LOWEST POSSIBLE WEIGHT OF ACQUISITION COST ELEMENT
C LW2) - BETA UNCERTAINTY CURVE TYPE FOR WEIGHT OF ACQUISITION ELEMENT
C LH1) - HIGHEST POSSIBLE COST OF OPERATIONS COST ELEMENT
C LOWL) - LOWEST POSSIBLE COST OF OPERATIONS COST ELEMENT
C LWL) - BETA UNCERTAINTY CURVE TYPE FOR COST OF OPERATIONS ELEMENT
C LC1) - COST VALUE OF MID RANGE OF COST INTERVAL I ON HISTOGRAM
C NC1) - NUMBER OF COST ELEMENTS IN COST INTERVAL I ON HISTOGRAM

**INPUT VARIABLES**

C NUM - NUMBER OF ACQUISITION COST ELEMENTS
C NOL - NUMBER OF OPERATIONS COST ELEMENTS
C L1) - YEAR - NUMBER OF YEARS FROM 1985 TO START OF ACQUISITION PHASE
C L2) - L3) - NUMBER OF YEARS FROM 1985 TO START OF OPERATIONS PHASE
C L3) - L4) - NUMBER OF YEARS FROM 1985 TO END OF OPERATIONS PHASE
C ITER - NUMBER OF ITERATIONS OVER WHICH TO CALCULATE LCC
C INC - NUMBER OF INCREMENTS ON HISTOGRAM
C DR - DISCOUNT RATE
C SEED - STARTING NUMBER FOR RANDOM NUMBER GENERATOR

**COMPUTER GENERATED VARIABLES**

C LWL) - LOWEST POSSIBLE TOTAL WEIGHT
C HWL) - HIGHEST POSSIBLE TOTAL WEIGHT
C LCL) - LOWEST POSSIBLE TOTAL LCC ACQUISITION COST
C LWL) - HIGHEST POSSIBLE TOTAL LCC ACQUISITION COST
C LNH) - NUMBER OF YEARS IN OPERATIONS PHASE
C LCL) - LOWEST POSSIBLE TOTAL LCC OPERATIONS COST
C HWL) - HIGHEST POSSIBLE TOTAL LCC OPERATIONS COST
C LHL) - HIGHEST POSSIBLE TOTAL LCC COST

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**PROGRAM**

```
DIMENSION CLD(5), COL(5), LH(20), M(20), DLL(30), CH(30),
COUNT(100), N(100), MH(20), NL(30).

REAL MEAN
T=0.0
SD=0.0
MEAN=0.0
COUNT=0
CLD=0.0
COL=0.0
LH=0.0
M=0.0
MH=0.0
CALL OPEN 10, "DATA.IN";
CALL OPEN 11, "DATA.IN";
CALL OPEN 5, LIST;
READ 10, NUM, INP, I, NAR, LAST1, DR, NMO,
1: READ, SEED
2: FORMAT (4, 14, 14, 14, 14.2, 14, 14, 14.2)
WRITE 11, NUM, INP, I, NAR, LIST1, LAST1, DR, NMO,
3: RAND, SEED
4: T := T + 1
5: COUNT := 0

INPUT COST ELEMENT DATA FOR ACQUISITION

READ 1.4, COL(1), CH(1), LH(1), N(1), MH(1), NL(1),
1: (1, [W(1)], [I=1, NUM],
1: FORMAT (F9.0, F9.0, 12, 12, F9.0, F9.0, 12)
WRITE 1.4, COL(1), CH(1), LH(1), N(1), MH(1),
1: (1, [W(1)], [I=1, NUM]

INPUT COST ELEMENT DATA FOR OPERATIONS

READ 1.5, COL(1), CH(1), LH(1), N(1),
1: FORMAT (F9.0, F9.0, 12)
WRITE 1.5, COL(1), CH(1), LH(1), N(1),
1: (1, [W(1)], [I=1, NUM]
```
SUM TOTAL LWM AND HIGH WEIGHS

DO 8 I = 1, NUM
  WLM = TML + ML(I)
  TWL = WLM + WH(I)
8  CONTINUE

COMPUTE -1 LOW LC VALUES OF LIFE CYCLE COST AND
VALUE OF 1-C H INCREMENT OF HISTOGRAM

DO 6 I = 1, NUM
10 SIB = TAI
  CAL = (N(I)*CL(I)+1*(OR+I)**(1+EAR+IYR(I))
  CLA = CAL + CLA
  N+1B) = TWH
  CWH = -N(I)*CH(I))/((OR+I)**(1+EAR+IYR(I))
  CHA = CWH + CHA
6  CONTINUE

LASTYR-IYEARO
DO 7 J = 1, L
7  DO 7 I = 1, NUM
  CGL = CLD(J)/((OR+I)**(1+YEAR+J))
  CLOB = COL+CLB
  CCO = CHI(J)/((OR+I)**(1+YEAR+J))
  CDO = COH+CHO
7  CONTINUE

CALC = CHA+CHO
CLO = CLOB+CLA
INC = CLOL-CLLC+INC

BEGIN ITERATIONS OF LIFE CYCLE COST

DO 50 M = 1, ITER
  TCOST=0.0
  TCOST0=0.0
  TLCC=0.0
  N+1B) = 0.0
50  DO 51 I = 1, NUM

PLACE TOTAL WT OF ALL COST ELEMENTS IN ARRAY N(I,IB) - SHUTTLE
COST PER ELEMENT

IF (1, EQ. 10) THEN
      DO 20 J = 1, NUM
      MT = WL(J) + BETA*(WJ(J))*W(J) - WL(J))
      N+1B) = MT + N+1B)
20  CONTINUE
ELSE
      COST = N(I)*CL(I)+BETA*(IB(J)*CH(I)-CL(I))/((1+OR)**(1+EAR+IYR(I))
      TCOST = COST+TCOST
51  CONTINUE

DO 55 J = 1, L
55  DO 55 I = 1, NUM

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COST = CLC*T + BETA1 + BETA2 + BETA3 + CLC**2 + CLC**3 + CLC**4 + CLC**5
I * YEARS + J
TCOST = COST + COST
75 CONTINUE
CLCC = TCOST + TCCST
WRITE (1,10) ITERATION #: ITER

CALCULATE MEAN, STANDARD DEVIATION, AND HISTOGRAM

DO 41 I = 1, INC
 CI(I) = CLCC + VNC*1
41 CONTINUE
DO 42 I = 1, INC
 IF (CLCC .LE. CI(I)) THEN
 ICOUNT(I) = ICOUNT(I) + 1
 GO TO 45
 ENDIF
42 CONTINUE
TC = TC + CLCC
STLC = CLCC + CLCC + 5*STLC
60 CONTINUE
MEAN = TC / ITER
SD = ((ITER * STLC - TC)**2) / (ITER * (ITER - 1)) ** 0.5
WRITE (1,10) THE MEAN LIFE CYCLE COST IS: MEAN
WRITE (1,10) THE STANDARD DEVIATION IS: SD
WRITE (1,10) HISTOGRAM:
WRITE (1,10) THE LO VALUE ON THE HISTOGRAM IS: CLCC
WRITE (1,10) THE HI VALUE ON THE HISTOGRAM IS: CLCC
WRITE (1,10) EACH INCREMENT ON THE HISTOGRAM IS: VNC
WRITE (1,10) INCREMENT: UPPER LIMIT VALUE: COUNT WITHIN INCREMENT:
10 FORMAT (F10.0)
WRITE (1,10) COUNT(1), (7F10.2, 1X)
20 FORMAT (1X, 15.3, 1X, 10.2)
END

ROUTINE TO CALCULATE A RANDOM VALUE FROM BETA FUNCTIONS
BASED ON SELECTION OF BETA CURVES 1 THRU 9

FUNCTION BETA IS:
I = RAND(0)
GO TO 11, 12, 13, 14, 15, 16, 17, 18, 19, 20
11 BETA = 0.45194 - 11.245**2 + 14.898**3 - 7.1259**4
GO TO 20
12 BETA = 1.5(18 - 1.7256**2 + 1.125**4)
GO TO 20
13 BETA = 0.2515 + 2.285**2 + 3.291**3 + 5.280**4
GO TO 20
14 BETA = 5.5781 + 85.619**2 + 12.954**3 + 6.2156**4
GO TO 20
15 BETA = 2.253**3 - 3.869**2 + 2.3589**4
GO TO 20
16 BETA = 0.77482**4 + 4.6783**3 - 9.129**2 - 5.4641**4
GO TO 20
17 BETA = 2.6547**2 - 1.15 - 5.7211**2 + 6.8825**1 - 2.3081**4
<table>
<thead>
<tr>
<th>Loops</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.7911e-6</td>
<td>0.93e3</td>
<td>32.267e3</td>
<td>0.098127</td>
</tr>
<tr>
<td>19</td>
<td>0.014597e4</td>
<td>0.1829e3</td>
<td>3.1719e4</td>
<td>0.5838e4</td>
</tr>
<tr>
<td>20</td>
<td>CONTINUE</td>
<td>RETURN</td>
<td>RETURN</td>
<td>RETURN</td>
</tr>
</tbody>
</table>

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INPUT FOR ANAEROBIC DIGESTOR SYSTEM

(Data not in proper field locations)

CARD 1 (PARAMETERS)

<table>
<thead>
<tr>
<th>NUM</th>
<th>ITER</th>
<th>INC</th>
<th>IYEAR</th>
<th>LASTYR</th>
<th>DR</th>
<th>NUMO</th>
<th>IYEARO</th>
<th>SEED</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>10</td>
<td>100</td>
<td>18</td>
<td>50</td>
<td>0.10</td>
<td>5</td>
<td>20</td>
<td>0.327</td>
</tr>
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</table>

CARD 2 - 20 (ACQUISITION DATA)

<table>
<thead>
<tr>
<th>ITEM</th>
<th>CL(I)</th>
<th>CH(I)</th>
<th>IB(I)</th>
<th>N(I)</th>
<th>IYR(I)</th>
<th>WL(I)</th>
<th>WH(I)</th>
<th>IWBI(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank</td>
<td>13000</td>
<td>20000</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>13000</td>
<td>20000</td>
<td>4</td>
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<tr>
<td>Insulation</td>
<td>6000</td>
<td>7600</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>760</td>
<td>800</td>
<td>6</td>
</tr>
<tr>
<td>Pump 1</td>
<td>800</td>
<td>1200</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>50</td>
<td>75</td>
<td>9</td>
</tr>
<tr>
<td>Pump 2</td>
<td>800</td>
<td>1200</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>180</td>
<td>200</td>
<td>8</td>
</tr>
<tr>
<td>Pump 3</td>
<td>800</td>
<td>1200</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>50</td>
<td>75</td>
<td>9</td>
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<tr>
<td>Pump 4</td>
<td>2200</td>
<td>2600</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>50</td>
<td>75</td>
<td>9</td>
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<td>800</td>
<td>1200</td>
<td>8</td>
<td>3</td>
<td>1</td>
<td>50</td>
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<td>1</td>
<td>3</td>
<td>1</td>
<td>300</td>
<td>500</td>
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<td>Temp Cntrl</td>
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<td>5</td>
<td>3</td>
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<td>17100</td>
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<td>1</td>
<td>1</td>
<td>20000</td>
<td>23000</td>
<td>6</td>
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<td>Valve</td>
<td>270</td>
<td>300</td>
<td>9</td>
<td>16</td>
<td>1</td>
<td>35</td>
<td>45</td>
<td>4</td>
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<tr>
<td>Couplings</td>
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<td>15</td>
<td>9</td>
<td>105</td>
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<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Flame Trap</td>
<td>100</td>
<td>200</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>75</td>
<td>100</td>
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OPERATIONS DATA:

CARD 1 - 5

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INPUT FOR CONVENTIONAL PROPELLANTS

(Data not in proper field locations)

CARD 1 (PARAMETERS)

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<th>ITER</th>
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<th>LASTYR</th>
<th>DR</th>
<th>NUMO</th>
<th>IYEARO</th>
<th>SEED</th>
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CARD 2 (ACQUISITION DATA)

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OPERATIONS DATA:

CARD 1 - 3

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OUTPUT FOR ANEROBIC DIGESTOR

(All data within first 49 intervals)

THE MEAN LIFE CYCLE COST IS: $54771722.

THE STANDARD DEVIATION IS: $5309317.

HISTOGRAM:

THE LO VALUE ON THE HISTOGRAM IS: $31359310.

THE HI VALUE ON THE HISTOGRAM IS: $125958890.

EACH INCREMENT ON THE HISTOGRAM IS = $945996.

INCREMENT:  UPPER LIMIT VALUE:  COUNT WITHIN INCREMENT:

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</table>
OUTPUT FOR CONVENTIONAL PROPELLANTS
(All data within first 49 intervals)
The mean life cycle cost is: $76851730.
The standard deviation is: $6025964.

Histogram:
The lo value on the histogram is: $44007887.
The hi value on the histogram is: $176930740.
Each increment on the histogram is = $129229.

Increment: upper limit value: count within increment:
1  $45337116. 0
2  $46666344. 0
3  $47995573. 0
4  $49324801. 0
5  $50654030. 0
6  $51983258. 0
7  $53312487. 0
8  $54641715. 0
9  $55970944. 0
10 $57300172. 0
11 $58629401. 0
12 $59958629. 0
13 $61287858. 0
14 $62617086. 1
15 $63946315. 3
16 $65275543. 5
17 $66604772. 9
18 $67934000. 13
19 $69263229. 16
20 $70592457. 22
21 $71921686. 40
22 $73250914. 43
23 $74580143. 35
24 $75909371. 39
25 $77238600. 43
26 $78567828. 58
27 $79897057. 51
28 $81226285. 25
29 $82555514. 28
30 $83884742. 22
31 $85213971. 17
32 $86543199. 17
33 $87872428. 13
34 $89201656. 7
35 $90530885. 3
36 $91860113. 3
37 $93189342. 4
38 $94518570. 2
39 $95847799. 0
40 $97177027. 1
41 $98506256. 0
42 $99835484. 0
43 $101164710. 0
44 $102493940. 0
45 $103823170. 0
46 $105152400. 0
47 $106481630. 0
48 $107810860. 0
49 $109140080. 0
VITA

Captain Coral C. Fallstead was born on 24 September 1949 in Palo Alto, California. He graduated from high school in Redwood City, California, in 1967. He enlisted in the Air Force in April 1971, and was stationed as a Weather Equipment Repairman in the 6th Weather Squadron at Tinker AFB, Oklahoma. He was accepted to the Airman's Education and Commissioning Program in 1972, and graduated from Oklahoma State University in May 1974, receiving the degree of Bachelor of Science in General Engineering. Upon graduation he attended Officers Training School at Randolf AFB, Texas, and received a the commission of 2nd Lieutenant in the United States Air Force, 16 August 1974. He served as Deputy Commander, and Commander, Missile Combat Crew, 571 Strategic Missile Squadron, 390 Missile Wing, Davis Monthan AFB, Arizona, from August 1974 till Feberuary 1979. In February 1979 he was stationed at NORAD/Cheyenne Mountain Complex, Colorado, as Space Systems Senior Director and in August 1980 became Chief, Deep Space Analyst. From June 1981 through June 1982 he was Space Systems Director at the 13th Missile Warning Squadron, Clear, Alaska. In June 1982 he became the Space Surveillance Program Director for Ground Based Radars at Space Command, Peterson AFB, Colorado. He entered the Space Operations Management Course in the School of Engineering, Air Force Institute of Technology, in June 1984.

Permanent address: 5545 Galena Dr.

Colorado Springs, Colorado 80918
Title: AN ECONOMIC FEASIBILITY STUDY ON THE SPACE-BASED PRODUCTION OF METHANE GAS FROM HUMAN WASTE THROUGH ANEROBIC DIGESTION FOR USE AS AN ORBIT MAINTENANCE PROPELLANT

Thesis Advisor: Joseph P. Cain, PhD.
Associate Professor of Economics
This project explores the economic feasibility of creating fuel energy in space from human waste with application toward space station orbit maintenance. The energy generating concept proposed in this study is anaerobic digestion. This process has four benefits for space application; 1) it can stabilize human waste products, 2) it can reduce solid wastes, 3) it can provide a fairly clear effluent for water recovery, and 4) it can provide a fuel in the form of a gas.

The analysis is dependent upon a predetermined scenario defining the input load to the digester system and the size of the spacecraft. The size, shape, and altitude of the vehicle determine the atmospheric drag which must be opposed to maintain the orbit. The basic elements of the study involve 1) simulation analysis of biochemistry, 2) thermochemical analysis and, 3) cost analysis using the Monte Carlo method. An alternative system to which the digester is compared is transport of conventional propellants from Earth. This alternative does not consider a replacement of the anaerobic digester with some other system to stabilize the waste products of the space station, or the additional benefits of the anaerobic digester listed above. In this respect the analysis can only be regarded as a partial one; however, its utility lies in its use as a comparison tool which can be applied toward analysis of any other waste stabilization system that may be selected. The results of this study show a statistically significant advantage of the digester system over transported conventional propellants due to the high cost of space transportation. Recommendations are to investigate other altitude scenarios and to compare the digester to other waste stabilization methods.
END