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FINAL REPORT

FEASIBILITY INVESTIGATION OF AN INTEGRATED WASTE MANAGEMENT/ROCKET PROPULSION SYSTEM

BY: C. D. Good, E. W. Schmidt, J. E. Mars, et al.

PREPARED UNDER CONTRACT NO. NAS1-6750 BY

ROCKET RESEARCH CORPORATION
YORK CENTER
REDMOND, WASHINGTON 98052

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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LIST OF SYMBOLS

A_e	Nozzle exit area
A_t	Nozzle throat area
c*	Characteristic velocity, ft/sec
cc	Cubic centimeter
cm	Centimeter
cm^3	Cubic centimeter
C_f	Thrust factor
^oC	Degree centigrade
D	Diameter
g	Gram
g	Acceleration of gravity, 9.81 m/sec^2
F	Thrust, lbf
^oF	Degree Fahrenheit
ΔH_f	Heat of formation, kcal/mole
I_{sp}	Specific impulse, lbf-sec/lbm
I_{sp} vac	Vacuum specific impulse, lbf-sec/lbm
^oK	Degree Kelvin, absolute temperature
kcal	Kilocalorie
kg	Kilogram
lb	Pound
lbf	Pound force
lbm	Pound mass
L*	Characteristic length, inches
mg	Milligrams
ml	Milliliter
mm	Millimeter
mm Hg	Millimeter mercury pressure
M	Molarity, moles per liter
n	Burning rate pressure exponent
N	Normality, equivalent per liter
P_a	Ambient pressure
P_c	Chamber pressure
P_e	Exit pressure

psia	Pound per square inch, absolute
sec	Second
STP	Standard temperature and pressure (0°C, 1 atmosphere)
T	Absolute temperature, °K
V	Velocity, ft/sec or in/sec
$\dot{W}$	Mass flow, lb/sec
wt. %	Percent by weight
ΔP	Differential pressure
ΔV	Propulsion requirement, ft/sec
ΔV	Propulsion capability, ft/sec

GREEK SYMBOLS

γ	Ratio of heat capacities, C_p/C_v
ε	Nozzle area ratio A_e/A_t
η	Efficiency, percent
ρ	Propellant density, g/cm^3
$\Sigma\Delta H_f$	Sum of heats of formation

ABSTRACT

This report describes the work performed during a program to study the feasibility of an Integrated Waste Management/Rocket Propulsion System for potential use on advanced manned spacecraft.

Waste management propellant performance was successfully demonstrated over a wide range of compositions in a nominal 200-lb-thrust liquid injection type rocket engine. Formulations containing as much as 43 percent feces were found to sustain monopropellant combustion.

Theoretical performance calculations were performed over a wide range of waste management propellant compositions for use in conjunction with the rocket engine test program. Preliminary studies indicate that combustion chamber temperatures at or below the melting point of aluminum oxide may act as a limiting condition for propellant compositions which may successfully be fired in the monopropellant mode.

Propellant formulation studies, physiochemical, safety, and combustion characterization tests were performed with a wide variety of waste propellant compositions. Biological activity tests indicate that although waste is not sterilized by incorporation into the propellant formulation, bacterial growth is definitely inhibited. No degradation of the propellant was observed over a period of 18 months' storage at ambient temperature.

Feces samples obtained from a 60-day manned spacecraft simulation experiment were evaluated as propellant ingredients and were found to possess properties markedly different than feces produced under normal diet and environment.

A survey was conducted to determine the type and quantities of waste materials potentially available for propulsion use on selected manned spacecraft missions. The total impulse available from an Integrated Waste Management/Rocket Propulsion System on these proposed missions was compared with the total impulse required. Applications for waste propulsion on advanced manned space missions were found to include propulsion for drag make-up, spin/despin operations, midcourse guidance corrections, terminal braking requirements, and auxiliary or emergency propulsion. Maximum benefit from a waste management propulsion system will be achieved, however, with missions which are initially designed to accommodate the system.

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1.0 INTRODUCTION

Under National Aeronautics and Space Administration Contract NAS1-6750, Rocket Research Corporation has performed a feasibility investigation of an Integrated Waste Management/Rocket Propulsion System for possible application to manned spacecraft. Langley Research Center has provided overall technical guidance for this investigation.

1.1 CONCEPT DEFINITION

To date, spacecraft designers have considered life support systems and rocket propulsion systems as independent subsystems of a manned spacecraft. Each subsystem is currently optimized to perform a specific function, and spacecraft weight, volume, and power allotments are generally assigned on an independent basis. However, propellant formulation and combustion studies at Rocket Research Corporation have demonstrated that selected manned spacecraft life support system waste products can form an active propellant ingredient, with subsequent propellant combustion providing an effective means of removing spacecraft waste. Additionally, it is anticipated that the propulsion subsystem weight will be greatly reduced by the marriage of the propulsion and waste management subsystems. This unique concept marries two diverse technical disciplines, i.e. propulsion and spacecraft waste management, to form an integrated waste management/rocket propulsion system applicable to advanced manned spacecraft. Utilizing this concept, heretofore unusable manned spacecraft waste products, such as feces, carbon residue from the carbon dioxide reduction system, and other organic wastes, such as evaporator wicks, filters, food wrappers, and food wastes, become available as active propellant ingredients. Liquid wastes, such as urine, water from fuel cells, and other waste water, if not recycled, can similarly be utilized for propulsive purposes. These waste materials, when combined with powdered aluminum and ammonium nitrate produce a safe, thixotropic monopropellant having a nominal theoretical specific impulse of approximately 230 - 240 lbf-sec/lbm (1,000/14.7 psi). This family of propellants based on the utilization of waste has been designated MONEX W.

For manned space missions where on-board propulsion is required, the Integrated Waste Management/Rocket Propulsion System offers the following potential advantages:

a. The weight of an integrated system will be lighter than a spacecraft system in which the waste management and propulsion subsystems are separate entities. Weight reductions stem from smaller propellant storage tanks and a high "effective" specific impulse for the waste propulsion system, i.e. a significant fraction (25 to 45 percent by weight) of the combusted propellant is "free" as spacecraft waste and therefore is not charged against the propulsion system weight.

b. This concept presents a potentially effective and efficient means of disposing of spacecraft wastes, including feces, thus providing a more sanitary spacecraft environment.

c. High-temperature oxidation (combustion) of the waste material is expected to completely exclude any population of viable species in the exhaust products ejected from the spacecraft.

d. The performance of the Integrated Waste Management/Rocket Propulsion System is very insensitive to variations in amount of available waste. Propellant formulations may easily be modified to make maximum use of the available waste.

e. Growth potential of the integrated system is very high. Presently, it is envisioned that only two out of the three propellant ingredients will be boosted into orbit, thereby resulting in a significant weight savings and higher "effective" specific impulses ranging from 350 to 500 lbf-sec/lbm. Should aluminum be available from the spacecraft or the spent booster in usable form, effective specific impulses greater than 800 lbf-sec/lbm may be realized.

1.2 SCOPE OF WORK

This 12-month technical effort was directed toward performing a feasibility investigation of an Integrated Waste Management/Rocket Propulsion System. Objectives of this contract were:

a. To determine the type and quantities of spacecraft waste materials available for propulsion use and the mode of on-board propulsion required on advanced missions.

b. To establish analytically the relationship between propellant composition and propellant specific impulse.

c. To determine the physiochemical and storage characteristics of the propellant.

d. To determine the ballistic parameters of selected propellant formulations.

1.3 STATEMENT OF WORK

In order to accomplish the scope of work, six basic tasks were undertaken. A summary of these tasks as described in the contract Statement of Work is presented below for reference.

Task I - A manned spacecraft mission and propulsion system utilization mode survey shall be conducted to establish the types and quantities of spacecraft waste materials that will be available for propulsion use and the mode in which the on-board propulsion system will be utilized to perform mission requirements. Thrust-time requirements of the propulsion system shall be included. This survey includes a literature search and visits of NASA-Langley

Research Center, NASA-Houston, North American Aviation, Douglas Aircraft, Lockheed Missiles & Space Company, and The Boeing Company.

Task II - Thermochemical studies shall be conducted to determine performance, gas product composition, specific heat ratio, etc., of dry propellant formulations (i.e. formulation obtained with a closed water and oxygen life support system). Data shall completely definitize the specific impulse parameter from maximum to minimum impulse. One wet formulation shall be analyzed for comparative purposes.

Task III - Propellant preparation studies shall be conducted parallel with Task IV to determine the nature and quantity of the gelling agent, the blending technique required to produce reproducible propellant batches, etc.

Rheological tests shall be conducted in parallel with Task IV to render the flow properties of the given propellant formulations under study compatible with the flow characteristics as defined in Task I. The propellant formulations to be evaluated shall be the same as those used in the 150-pound nominal thrust injection motor tests. In addition, one wet formulation shall also be studied. The same formulation shall be used in propellant preparation studies.

The following physiochemical studies shall be conducted: (1) freezing point, (2) density versus temperature, (3) vapor pressure versus temperature, (4) rheological properties, (5) thermal stability, (6) card gap tests, (7) handling characteristics, (8) autodecomposition temperature, (9) biological activity, (10) compatibility tests, and (11) impact sensitivity. The formulations studies will be those utilized in the 150-pound nominal thrust injection motor tests.

Task IV - Combustion tests shall be conducted to determine the ignition characteristics, burning rates, and pressure exponents. Tests shall be conducted in a combustion bomb to screen candidate propellants prior to motor test firings and to establish the type and quantity of burning rate additives required. Four tests, each utilizing maximum waste content, shall be run at 10, 30, 40, 70, and 100 percent of the range between the attainable maximum and minimum specific impulse. Twenty tests shall be conducted.

A minimum of 18 tests utilizing an injection motor of 150-pound nominal thrust level for 3-seconds' duration each shall be conducted to determine the combustion efficiency as a function of chamber pressure and motor geometry. Two dry propellant formulations (selection requires NASA concurrence) identified from the combustion bomb screening tests shall be fired (and modified, if required) during the series to develop a usable waste propellant.

Task V - Propellant selected for use in the 150-pound nominal thrust tests shall be placed in storage at the end of the fourth month for representative storage periods as defined by mission survey results. Samples shall be inspected at 30-day intervals for gel structure integrity, biological activity, hydrogen gas evolution, and physiochemical properties. Samples of the propellant shall be fired before and after storage to verify ballistic properties. Samples of the exhaust gas shall be analyzed for biological activity.

To expedite testing, the nature of the waste materials, other than urine and feces, was simulated with commercial grade polyethylene powder and powdered carbon during the laboratory test series outlined in Tasks II through V, inclusive.

Task VI - The objective of this task is to evaluate waste management propellant produced from human waste generated by individuals participating in a 60-day manned spaceflight simulation study. A suitable method will be determined for feces collection and storage during a confinement period of 60 days in a manned spacecraft simulator. Feces will be collected from the four-man crew immediately following conclusion of the confinement.

Waste management propellants will be prepared from feces collected during the manned spacecraft simulation experiment. The formulation of the waste management propellants will be adjusted to contain quantities of fuel, oxidizer, and waste as specified by NASA.

Propellant formulations will be characterized by the following determinations:

a. Density (77°F)
b. Rheological properties (by capillary extrusion rheometer)
c. Storage stability test (77°F-6 months)
d. Composition (H_2O and ash content, elemental Al, N, C).

A representative waste management propellant will be test fired in a liquid injection type rocket engine at a nominal 200-lb-thrust level. Measured performance will include characteristic exhaust velocity (c*) and specific impulse (I_{sp}).

Additional waste (other than feces) generated in significant quantities during the manned spacecraft simulation experiment will be evaluated with respect to suitability for incorporation in waste management propellant.

2.0 MISSION SURVEY

The objective of Task I of Contract NAS 1-6750 was to determine the type and quantities of spacecraft waste materials available for propulsion use and the mode of on-board propulsion required on advanced space missions. This task is divided into (1) a study of life support systems to ascertain the types of available waste material and (2) a survey of advanced space missions to determine the quantities of available waste and the propulsion system requirements for potential modes of waste propulsion application.

2.1 SURVEY OF LIFE SUPPORT SYSTEMS

In order to obtain detailed information concerning recent research on waste management systems and subsystems, a literature search was performed and was supplemented by information obtained during discussions on information-gathering trips. A summary of the results of the literature search is given below.

The amount of waste available for an Integrated Waste Management/Rocket Propulsion System depends on the degree of closure of the ecological cycle. Three main steps in closing the ecological cycle may be discerned. These are listed in the order of sequence of increasing difficulty in realization: (1) regeneration of water, (2) regeneration of oxygen, and (3) regeneration of food. When compared on a weight basis, the regeneration of water is the most important of all three steps in achieving a closed ecological cycle. The regeneration of water may be divided into several subdivisions, depending on the source of water to be regenerated: (a) from cabin atmosphere condensates, (b) from wash water, (c) from urine, and (d) from feces. Again, the methods have been listed in the sequence of increasing required effort for realization.

Since the type of life support system chosen for water and oxygen reclamation greatly influences the performance of an integrated waste management/propulsion system, a short review was made of test-proven and projected life support and environmental control systems. It may be possible that certain subsystems (filters, tanks, pumps, etc.) can be used for the waste management system as well as for the propellant processing system, resulting in a lower overall system weight. In any integrated system the selection of a life support and environmental control system will probably be influenced by its relation to the propulsion system. An evaluation of recovery systems must also take into account the different electrical power requirements of each system and the resulting power system weight penalties (Refs. 1, 2).

2.1.1 Water Reclamation

Recovery of water is one of the most urgent problems on space missions of long duration. It strongly influences the overall weight of the life support system and of the vehicle to be launched into orbit. Water may be recovered from cabin or space suit atmosphere condensates, from wash water, from urine, and from feces. In general, it is not advisable to mix less contaminated water (e.g. cabin atmosphere condensate) with heavily contaminated water (urine). Instead, separate recovery systems are more economical with respect to energy requirements.

The expected typical daily water balance for a man in a normal space cabin environment is as follows:

Input (lb/man/day)		Output (lb/man/day)	
Drink and food preparation	7.49	Urine	3.30
Water in food	0.23	Fecal water	0.25
		Respiration - transpiration	4.89
	7.72		8.44

If all of the water were recycled and recovered, there would be a net gain in water of 0.72 pounds per man per day, since metabolic water is generated from ingested food during the normal metabolic processes of the body. However, total recovery of output water in a purified state represents a formidable technical task. The regeneration of water from wash water, urine, and atmospheric condensates is less difficult, and a number of water reclamation systems applicable to these areas have been demonstrated. Some of these systems are discussed in the following sections of this report.

Processing of feces for water reclamation is complicated and presents difficult technical problems at the present time. By neglecting recovery of water from feces, a simpler and more reliable life support system can be constructed, provided that a simple means of disposing of feces is available (see Par. 2.1.2). Collecting and processing urine and feces individually results in higher system weights. For propellant purposes, however, they may be collected and processed jointly, resulting in additional weight savings. Urine will probably be recycled on long-duration space flights so that only feces, urine residues, carbon from oxygen recovery systems, and general refuse will be available for propellant.

Of all closed system life support problems, the recycling of water appears to be the most simple. In spite of this, no water recovery system has actually been used in space flights to date. Many simulation experiments have been performed in closed chambers under ground conditions (Refs. 3, 4).

In addition to the reclamation process a water management system aboard a spacecraft must perform the following functions:

a. Storage of urine, used wash water, and humidity condensate

b. Collection and storage of reclaimed and purified water

c. Storage of emergency water supplies

d. Heating or cooling of potable water

e. Dispensing of water for drinking, food preparation, and washing

f. Transfer of water to and from tanks between reclamation systems and O_2 electrolysis system (if O_2 regeneration is included in life support system).

Design specification for a water management subsystem for space flights of extended time periods are described in Ref. 5.

2.1.1.1 Water Reclamation from Wash Water

The average daily need for wash water is generally set at six pounds per man. This value varies considerably with mission type and individual requirements. The recovery of reusable water from used wash water can easily be achieved by a combined charcoal filter/ion exchange resin system (Refs. 6, 7, and 8). For washing, a 0.05 to 0.1-percent solution of benzalkonium chloride may be used, which serves both as a detergent and disinfectant. A prototype flight system weighing 98.2 pounds was developed by the General Dynamics Corporation (Ref. 8). It was designed to enable three men to bathe every other day on a one-year mission, using four pounds of water per bath. If this system were used, the activated carbon filters (28.5 pounds) and ion exchange resin cartridges (47.3 pounds), in addition to the water contained in the system, could be considered for use as propellant components during final stages of the mission. On missions of longer duration, the filter and exchange units would be replaced several times.

2.1.1.2 Water Reclamation from Urine

Extensive research has been performed on water recovery from urine. An excellent review on existing and proposed systems is given in Refs. 9, 10, 11, and 12. Water recovery is possible by distillation, membrane permeation, zone melting, freeze-drying, electrodialysis, or electrochemical degradation. Water recovered by these methods generally needs further chemical treatment in order to remove volatile contaminants, especially ammonia, before it can be used as drinking water. These compounds are generally eliminated by chemical oxidation or adsorption on an activated charcoal filter.

The urine to be processed may also contain waste water from other sources, such as personal hygiene, wash water, or water from washing of clothes. As already indicated, however, it is uneconomical to mix urine with less contaminated water, which can be more easily regenerated by other means.

The common method for separation of water from dissolved contaminants is distillation. Distillation under zero-g conditions, however, requires special equipment, because the liquid and gaseous phases do not separate. Several distillation systems have been developed (Refs. 13, 14, 15, and 16). One of these methods (Ref. 13) condenses the evaporated water by vapor compression instead of cooling. This method simplifies separation of condensed water from uncondensed gases under zero-g conditions. Distillation may also be performed under reduced pressure (vacuum distillation).

The most promising approach appears to be the wick air evaporation urine distillation method, which was developed by Hamilton Standard (Ref. 17) and is presently being tested at NASA-Langley for application in the MORL mission. By this method, urine residues accumulate in disposable wicks. The wicks and residues would have to be disintegrated before they could be used as waste propellant. The wicks are expected to consist of polymer fiber, polypropylene, or similar plastics.

A special method of water recovery is that of freeze drying (Refs. 18, 19, and 20). This process does not require a gravitational field for phase separation as do normal distillation methods. However, it has the disadvantage of discontinuous operation.

Most methods of urine distillation generate residues either as a concentrated solution or a solid residue of urea and other compounds. These residues may also be included in a MONEX W waste propellant. As an alternative to using electrical or waste heat for distillation processes, radioisotope heating is being considered (Ref. 21).

The technique of water recovery from urine by membrane permeation makes use of the fact that in certain materials the permeability of water vapor is many times greater than the permeability of liquid water, ammonia, urea, uric acid, and other materials commonly found in human urine (Refs. 22, 23, 24). Thus, the permselective membrane (usually a silicone rubber film) is effective in separating not only the phases, but also chemical compounds. The residue is a slush of urea and other compounds that is not as dry as residues from freeze drying. One test model developed (Ref. 23) has a weight of 128 pounds and is able to recover 5,000 ml (approximately 11 pounds) of water per day; another model (Ref. 22) is designed for a capacity of 20 pounds per day.

Recovery of water from urine is possible by a liquid-phase enrichment of contaminants by membrane electrodialysis (Refs. 25, 26). The disadvantage of this technique is the requirement for additional pretreatment of the water to remove microbiological contamination and nonionized organic compounds.

A comparison by Ott (Ref. 27) shows that vapor compression and membrane electrodialysis have rather high power requirements, whereas freeze drying and vacuum distillation can be accomplished without direct use of electrical energy.

2.1.1.3 Water Reclamation from Feces

Although under consideration, there is presently no system under development that is concerned with reclamation of water from feces only. In those cases where water is recovered from feces, both feces and urine are collected by a single system and stored in a common storage tank. Processing of the collected wastes is by distillation, which is rendered more difficult than in the case of urine alone, due to the great amount of solid residues present. The "activated sludge" process of the MESA System (Refs. 28 through 32) is based on the growth of a microbiological population under aerobic conditions. This growth disintegrates the feces, resulting in a liquid waste that then can be fed to a centrifuge and distillation system. The MESA study was directed toward utilization of the effluent and/or bacterial cells by algae, higher plants, or even animals as part of completely closed ecological systems. A prototype system was tested for 30 days in a closed cabin test with a five-man crew under simulated mission conditions.

Another technical feasibility study (Ref. 1) proposes to use a single-purpose feces management system including partial recovery of water from feces. This system has a flush water cycle. Feces are flushed into a collection tank, and the water used in flushing is separated from the feces by evaporation at reduced pressure. The water vapor is condensed and stored in the flush water reservoir. The solid residue is then vacuum dried, sterilized by heating to 250°F, and compressed for storage.

2.1.2 Feces Management

Most preceding studies of waste management systems have tried to avoid water recovery from feces by simply vacuum drying and venting the water vapor to space or by storing the feces at low temperatures after chemical or thermal sterilization (Ref. 33). None of these systems are fully satisfactory for space application. The penalty for such a means of disposal of feces is added weight for processing equipment and the necessity of supplying water to replace that lost in the feces. Thus, it will be a great help to the designer if not only the feces problem can be solved, but additional propulsion capability can be obtained in the process.

Storage of feces (Ref. 34) at ambient temperatures is only feasible for missions of short duration. During the Gemini program, feces were collected manually in plastic bags, mixed with a germicide, sealed and stored. Essentially the same method has been adopted for the current Apollo program. Sterilization is necessary in order to avoid gas production (Ref. 35). Sterilization by manual mixing with a germicide is not considered sufficiently complete to allow feces bags to be jettisoned to space in the vicinity of planets. Due to incomplete mixing, the disinfectant effect is restricted primarily to the surface of waste particles. In addition to chemical methods, sterilization may be accomplished by heating and/or complete drying by evacuation to space. Some spore-forming bacteria, however, are very resistant and may survive even under these severe conditions.

The feces waste management system incorporated in a life support system test bed designed by General Dynamics (Ref. 4), under contract from NASA-Langley Research Center, consists of a feces collection unit and two drying chambers. The fecal collection assembly is similar to a conventional toilet stool. The feces are collected in a semipermeable bag through which an airstream passes to provide positive flow control. The bags are then hand loaded into one of two vacuum drying chambers, one of which is always exposed to vacuum. After drying, the feces still contained in the collection bag must be manually transferred to the storage area. This system is still unsatisfactory because it requires repeated manual handling of feces with all the accompanying psychological discomfort and danger of bacterial infection. The system weighs 160 pounds and occupies 35 cubic feet. The power requirement is 145 watts and a weight penalty of 290 pounds per kilowatt is not included in this hardware weight. This system was designed for an MORL-type orbital mission with a 90-day resupply frequency.

Another waste management unit, including feces storage, eliminating the need of manual transfer, was designed and built by General Dynamics (Ref. 36) for installation and evaluation in the Aerospace Medical Research Laboratories Life Support Systems Evaluator. Feces are collected and stored in a fiberglass-resin vessel surrounding a perforated stainless steel sphere. During the periods in which the feces management unit is not in use, the vessel is evacuated and vented to space.

In addition to vacuum drying, the following methods for storage and disposal of feces have been considered (Ref. 34):

1. Freezing of feces
   a. By thermoelectric cooling (Peltier - Elements)
   b. By radiation cooling
   c. By freeze drying with exposure to vacuum

2. Incineration of feces
   a. By electric heating
   b. By solar heating
   c. By utilization of waste heat from liquid metal power units (750°C).

A different system proposed by TAPCO, Division of TRW, Cleveland (Ref. 37), uses the heat of combustion of the organic matter in dried feces. Feces and urine are fed together into a heat exchanger, dried, and the solids burned with oxygen. One disadvantage of such a system is its high oxygen consumption.

A common problem to all waste management systems is the collection of urine and feces under zero-g conditions. Most systems collect urine and feces by inducing a positive airflow into the collection vessel. This method requires blowers and filter cartridges. A less complicated, manually operated collection unit employing collapsible bellows has been under development by American Machine & Foundry Company (Ref. 38).

2.1.3 Atmosphere Control Systems

Carbon dioxide, water and contaminants from exhausted air must be continually removed from the space cabin atmosphere in order to maintain comfortable non-toxic conditions. Normal carbon dioxide content of the earth's atmosphere is 0.03 percent by volume. Several carbon dioxide concentration systems have been developed.

2.1.3.1 Carbon Dioxide Removal

Carbon dioxide removed from the atmosphere may be either vented to space or reacted to form either water or oxygen. It may also be irreversibly absorbed by LiOH or Na_2O_2 and KO_2 canisters. The latter two compounds initially generate fresh oxygen by reaction with atmospheric water vapor.

Chemical removal of carbon dioxide is not applicable to long-duration spaceflight because of the high weight requirements of chemical absorbents. Therefore, reversible adsorption systems which have useful life times of up to several years are preferred. One of these systems employs molecular sieves. Although molecular sieves are good adsorbents for carbon dioxide, they are quickly inactivated by atmospheric moisture. Air must be passed through a drying system (usually containing silica gel) before entering these adsorption units. Several systems operating in this manner have been built (Refs. 39, 40, 41, 42). Activated charcoal, which is not as sensitive to atmospheric moisture, is an alternate adsorbent for carbon dioxide (Ref. 43). The capacity of charcoal for carbon dioxide, however, is not as great as that of molecular sieves. Other regenerable adsorbents are under evaluation (Ref. 44).

When an adsorbent bed is saturated with carbon dioxide, the airstream is usually switched over to a second bed, while the first is regenerated. The carbon dioxide can be removed from the bed either by employing vacuum, high temperature, or a combination of both.

Other carbon dioxide concentration methods, such as gas diffusion cells (Ref. 45) or a carbonation cell developed by TRW, Inc. (Refs. 41, 46, 47, 48) allow an almost complete carbon dioxide removal from the atmosphere, but require considerable amounts of energy.

2.1.3.2 Carbon Dioxide Reduction

Two main methods for carbon dioxide reduction are under consideration, the Bosch process and the Sabatier process (Ref. 48):

Bosch Process

$$2H_2 + CO_2 \xrightarrow{Fe} C_{(s)} + 2H_2O$$

$$2H_2O \xrightarrow{\text{Electrolysis}} 2H_2 + O_2$$

Sabatier Process

$$CO_2 + 4H_2 \xrightarrow{Ni} CH_4 + 2H_2O$$

$$2H_2O \xrightarrow{\text{Electrolysis}} 2H_2 + O_2$$

Both reduction systems utilize hydrogen produced from the electrolysis of water. The reduction products are water and carbon from the Bosch process and water and methane from the Sabatier process. Methane can be converted to carbon and hydrogen in a follow-on process:

$$CH_4 \xrightarrow{Ni} C_{(s)} + 2H_2$$

The Bosch process allows unreacted hydrogen and carbon dioxide to be continually recycled until complete conversion is obtained, whereas the Sabatier process may produce incompletely reacted gases. This is the reason why the Bosch system is generally favored for long-duration space missions Refs. 41, 50, 51, 52). In a life support system study performed by General Dynamics (Ref. 4), both systems have been evaluated in parallel.

The solid carbon residue formed in the Bosch process or in the Sabatier follow-on process is a primary waste product. It can either be stored on board the spacecraft or jettisoned. It has been suggested that the carbon waste from these processes might possibly be of use as a substitute for activated charcoal for water purification and adsorption of atmospheric contaminants. It may also serve as a propellant ingredient for a MONEX W propellant, even after it has served the aforementioned purposes.

The properties of carbon formed by the Bosch process (particle size, purity, degree of graphitization) are expected to determine the quantity that may be used as a propellant ingredient. Preliminary information obtained from TRW, Inc. indicates that particle size is approximately 44 to 74 microns. A rather high iron content (10 to 20 percent) of the carbon obtained from the Bosch reactor is probably due to iron carbide. This apparently results from a side reaction occurring during the first step of the process in which an iron catalyst is employed. A sample of carbon formed by carbon dioxide reduction in a Bosch reactor has been supplied to Rocket Research Corporation for study purposes and propellant preparation (see Sec. 4.0).

Another advanced carbon dioxide reduction method is solid state electrolysis (Ref. 53, 54), by which CO_2 is first reduced to CO and O_2. CO is disproportionated to CO_2 and C over a nickel catalyst in a follow-on process. A sample of carbon produced by this method and supplied by Isomet Corporation to Rocket Research Corporation for further investigation contained nickel and exhibited magnetic properties. Waste carbon produced by this method could also be used as a propellant ingredient, provided that the metal catalyst content were not too high.

Other methods for recovery of oxygen from carbon dioxide that have been proposed, such as molten carbonate electrolysis (Ref. 52), sodium metal reduction, carbon dioxide pyrolysis (Refs. 52, 55) or photolysis, are still under consideration. Most of these systems would also produce elemental carbon as a residue.

2.1.3.3 Humidity Control

The proper water content of the space cabin atmosphere is essential for maintaining human comfort and ability to work. Excess moisture can be removed by freezing or by adsorption on silica gel. Both methods require further processing, including removal of bacterial contamination, to recover potable water. No significant residues are to be expected from this method of water recovery except for used activated charcoal filters which could be included in the propellant mixture.

2.1.3.4 Control of Atmospheric Contaminants

In a closed cabin environment toxic compounds of human origin as well as of cabin structure origin will accumulate which must be destroyed to prevent accumulation of toxic concentrations (Ref. 56). These contaminants can be removed by adsorption on activated charcoal (Ref. 57), or by catalytic combustion (Ref. 58). Activated charcoal, after saturation in an adsorption system, might eventually contribute to waste materials for use in waste propellant preparation.

2.1.4 Conclusions from Life Support Systems Survey

A study of the open literature on life support and environmental control systems shows that a great variety of systems are available or still under investigation. For water recovery, the air evaporation distillation system using a wick for phase separation is the most advanced system. There is still no final decision as to whether the Bosch or the Sabatier reaction is preferable for oxygen recovery systems.

In the preceding paragraphs, types of waste were reviewed for use in the Integrated Waste Management/Rocket Propulsion System. A summary of available waste products is given in Table 1. More detailed weight data will be given in the following sections on mission analysis, as these weight data differ for each mission, depending on the degree of closure of the ecological cycle. In the extreme case of a completely closed ecological system, only few waste products would remain. In the near future, however, no completely closed ecological system is expected to be available for use in manned spacecraft.

2.2 PROPULSION REQUIREMENTS

A survey was conducted of advanced space missions which resulted in detailed information being obtained from the following studies:

a. Douglas Manned Orbital Research Laboratory (MORL) Mission Study
b. NAA Manned Mars and/or Venus Flyby Vehicle Systems Study
c. Lockheed Empire Planetary Flyby Mission Study
d. General Dynamics Manned Mars and Venus Exploration Study (MAVES)
e. TRW Manned Mars Landing Mission Study
f. NAA Manned Mars Landing and Return Mission Study

Propulsion requirements differ for each type of mission. Planetary flyby missions are the simplest interplanetary missions to perform. They require propulsion for heliocentric transfer orbit injection, attitude control, midcourse corrections, and planetary flyby corrections. In some cases, spin-up/despin or earth retropropulsion is required. Compared to flyby mission requirements, the propulsion necessary for planetary landing missions is far more complex. It includes braking into planet parking orbit (which is also aerodynamically possible), descent to planet surface, ascent from planet surface, and escape propulsion, in addition to those requirements stated for the flyby missions. Specific propulsion requirements for each advanced mission study are given in subsequent paragraphs of this mission survey.

For the purposes of this mission survey, a specific formulation of MONEX W has been selected for reference purposes. A composition containing 45 percent waste (including carbon), 30 percent ammonium nitrate, and 25 percent aluminum was assumed. Using an efficiency of 87 percent, a vacuum specific impulse of 222 lbf-sec/lbm has been calculated for this formulation (P_c = 1,000 psia, 50:1 nozzle area ratio). This performance may be achievable in well designed small engines of about 100-lbf thrust. For larger engines with thrust levels of 300 lbf and higher, an efficiency of 90 percent is assumed, resulting in a vacuum specific impulse of 229 lbf-sec/lbm.

TABLE 1

SUMMARY OF WASTE PRODUCTS PRODUCED WITH SELECTED LIFE SUPPORT SYSTEMS

(lb/man-day)

	No Reclamation	Urine Water Reclamation	Bosch Oxygen Recovery + Urine Water Reclamation	Sabatier Oxygen Recovery + Urine Water Reclamation	Urine Water Reclamation Oxygen Recovery + Feces Incineration
Waste Product					
Urine	3.30	--	--	--	--
Urine residues, dry	--	0.15	0.15	0.15	0.15
Carbon dioxide	2.32	2.32	--	--	0.05
Carbon	--	--	0.63	--	0.63
Methane	--	--	--	0.84	--
Excess metabolic water	0.72	0.72	0.72	0.72	0.72
Feces	0.33	0.33	0.33	0.33	--

If carbon is not included and feces is utilized as the only waste ingredient, a higher specific impulse may possibly be realized. For a composition of 43 percent feces, 37 percent aluminum, 15 percent ammonium nitrate, and 5 percent M-1, the calculated vacuum specific impulse is 247 lbf-sec/lbm (P_C = 1,000 psia, ϵ = 50, I_{sp} efficiency of 90 percent assumed).

"Wet" MONEX-W formulations containing both urine and feces as major waste ingredients (8:1 weight ratio) yield an even higher theoretical vacuum specific impulse, e. g. 265 lbf-sec/lbm under the same conditions as stated in the preceding material.

The 45-percent "dry" waste system (containing feces and carbon but no urine) has been selected as a reference formulation because it combines a moderately high specific impulse with relatively high waste content. Although the "wet" formulation yields higher performance, the available water for waste propellant preparation on long-duration space flights will probably be limited primarily to that contained in feces, as most of the other water is expected to be recycled for repeated use.

Variation of crew size influences the vehicle system weight and the propulsion requirements. Variation of vehicle weight, including spacecraft structure, life support, and supplies, with crew size was considered in those cases where available data were detailed enough to allow this.

2.2.1 Manned Orbital Research Laboratory (MORL) Mission Study

The basic MORL system concept has been studied by the Missile and Space Systems Division of the Douglas Aircraft Company, Santa Monica, California (Refs. 59, 60, 61, 62), under Contract NAS 1-3612 from NASA-Langley Research Center. The MORL was originally designed for six men and a lifetime of up to five years, with possible extension to a full decade. The crew may be increased to nine men by changing the operation mode and the resupply schedule. When in normal operation, initial supplies are sufficient for 147 days of operation. Normal resupply would be after each 90 days of operation, with 57 days as a backup period for safety.

Optimum payload and cost effectiveness are achievable with a 164-nautical-mile, 50-degree-inclination circular orbit. This is low enough to suffer no damage from the radiation belts but not high enough to be free from atmospheric drag. Alternate missions will be circular 164-nautical-mile orbits at 30- and 90-degree inclination and 19,350-nautical-mile (synchronous) orbits at 28.72-degree inclination. To make up for atmospheric drag and loss in velocity, additional propulsion is necessary to maintain orbit. Without propulsion, the laboratory's altitude decay rate in the lower orbits would destroy its usefulness in approximately six weeks of flight time. Thus, propellant, in addition to that necessary for attitude stabilization or station spin-up and spin-down, is required. Such functions may possibly be suitable applications for an Integrated Waste Management/Rocket Propulsion System.

2.2.1.1 MORL Environmental Control/Life Support System (EC/LSS)

The baseline EC/LSS for the advanced MORL (Ref. 61) has the following design characteristics:

a. A 50-percent O_2, 50-percent N_2 atmosphere at 75°F and 7 psia

b. Consumable oxygen is obtained by the electrolysis of water that is resupplied as required.

c. The water cycle is completely closed except for that water needed to provide oxygen. Urine water is recovered by evaporation.

d. Feces and other wastes are collected, dehydrated, and stored for ultimate disposal with the resupply module.

Oxygen supplied by electrolysis of water instead of by cryogenic storage (Ref. 59) has been chosen because the method is simpler, more reliable, and cheaper than cryogenic storage and transfer systems. Further advantages over the cryogenic storage of oxygen are the possible use of more palatable wet foods for the crew and the electrolysis of excess metabolic water, which reduces the oxygen resupply requirements by 20 percent. Typical metabolic data for the MORL design are listed in Table 2.

The composition of the expected wastes from the MORL system is given in Table 3. The waste to be expected per 90-day resupply period consists mainly of feces and urine residues. Since not all water recovery systems produce completely dry residues, an additional calculation has been made assuming 10 percent water in the urine residue. This data (10 percent water) has been used in the calculations of available impulse given below. The material designated as "other wastes" includes materials such as unused food, packaging materials, toilet paper, paper towels, hair, nail clippings, etc., that will accumulate and may be incorporated in the propellant. For the MORL, this amount is estimated as 0.9 pounds per day for six men and 1.35 pounds per day for nine men.

The feces collection system consists of a sphere with a porous felt liner. During defecation, a fan draws air through the container for odor removal and feces collection in zero-g state. After defecation, the sphere is closed, the air evacuated and recovered, and the contents of the sphere exposed to space vacuum. Evaporation cools the stored wastes, thus preventing excessive bacteria growth prior to dehydration. Three containers, each weighing 9.8 pounds, will be necessary for a six-man crew during 90 days; five containers will fulfill the 147-day operating capacity requirement. Filled containers will be returned to the resupply logistics module. The total collector system weight, including valves, blowers, filters, and five spheres, is 74 pounds.

2.2.1.2 MORL Propulsion Requirements

The on-board propulsion Reaction Control System (RCS) (Refs. 60, 62) has been designed to perform orbit injection, attitude control, and orbit-keeping velocity addition. The secondary system for spin/despin operations is located on the empty S-IVB Stage. As it has not yet been determined whether artificial

TABLE 2

MORL METABOLIC DATA

	Design Value (lb/man-day)
Oxygen consumption	1.92
Carbon dioxide production	2.32
Water consumption	6.17
Urine production, including solids	4.07
Urine solids	0.15
Respiration and perspiration, water production	2.78
Feces output, including solids	0.34
Metabolic water production	0.79

TABLE 3

WASTE PER 90-DAY RESUPPLY PERIOD (MORL)

	Water Recovery		No Urine Water Recovery[b]	
	6-Man Crew (lb)	9-Man Crew (lb)	6-Man Crew (lb)	9-Man Crew (lb)
Feces	183.5	276.0	183.5	276.0
Urine			2,198.0	3,297.0
Urine residues	81.0 (90.0)[a]	121.5 (135.0)[a]		
Wicks	14.6	21.9		
Charcoal (from urine recovery)	8.9	13.4		
Complexing agents	11.3	17.0		
Charcoal (wash water recovery)	8.6	12.9	8.6	12.9
Ion exchange resins	2.2	3.3	2.2	3.3
Millipore filters	1.0	1.5	1.0	1.5
	311.1 (320.1)	467.5 (481.0)	2,393.3	3,590.7
Other wastes	81.0	121.5	81.0	121.5
	392.1 (401.1)	489.0 (602.5)	2,474.3	3,712.2

[a] Numbers in parentheses include 10-percent water in urine residue

[b] Current MORL studies assume water recovery

gravity will be necessary, preliminary planning is for a nonrotating zero-g laboratory. The rotation is inconvenient for many tasks (e.g. astronomical observations, solar panel orientation to the sun, or rendezvous docking). The change from a zero-g to a rotating MORL causes a significant increase in propulsion system cost. The MORL propulsion system, as planned in the Phase IIA study (Ref. 60), would use inhibited red fuming nitric acid (IRFNA) and monomethyl hydrazine (MMH) as propellant. The oxidizer is changed to nitrogen tetroxide (NTO) in the updated system of the Phase IIB study (Ref. 62) and represents an increase in overall system performance.

The 50- and 100-lbf-thrust RCS engines are pressure-fed, radiation-cooled assemblies operating at 90-psia chamber pressure and an expansion ratio of 100. The delivered vacuum specific impulse is 303 lbf-sec/lbm. For small engines and pulse mode operation, the $I_{sp\ vac}$ will be somewhat lower. As indicated in Table 4, the required impulse per orbit or per year depends on the operating mode (rotating or nonrotating) and on the power supply system (solar panel or nuclear isotope system). In the latter case, the extended solar panels add considerable drag to the vehicle in contrast to nuclear isotope systems. The RCS impulse and propellant requirements and duty cycle are compiled in Table 4.

Attitude control requires frequent engine starts, even if a control-moment gyro system is used. Atmospheric drag makeup for the nonrotating mode requires one or two firings every 4 days. For the rotating mode, however, a series of one-second firings every 15 seconds is required.

2.2.1.3 Available Propulsion from an Integrated Waste Management/Rocket Propulsion System

Calculations were made of the available propulsion expected using an Integrated Waste Management/Rocket Propulsion System (Table 5) for both "dry" and "wet" MONEX W compositions. The available propulsion may then be compared with the propulsion requirements for the MORL shown in Table 4. Since the engine thrust requirements are on the order of 50 to 100 pounds, an I_{sp} efficiency of 87 percent was utilized in these calculations.

Results of the MORL studies comparing available impulse with the required propulsion impulse are also given in Figs. 1 and 2. Figure 1 shows that a waste management propulsion system can more than satisfy the drag makeup requirements of the MORL vehicle with a six-man crew when using a nuclear Brayton cycle power supply. The use of solar panels instead of a nuclear Brayton power supply causes an increased drag. As shown in Fig. 2, the waste management propulsion system can even meet the increased drag makeup propulsion requirements with a solar panel power supply; this is based on the presence of a nine-man crew, since the six-man crew waste is insufficient to meet the added propulsion requirements.

The MORL drag makeup propulsion requirement involves intermittent firings at the rate of one or two firings every 4 days. This requirement for repeated firings should be investigated in future waste propulsion engine testing (see Par 6.1). Spin/despin operation for the MORL vehicle is another potential application. The use of waste propulsion for this propulsion mode would be

TABLE 4

RCS PROPULSION REQUIREMENTS AND DUTY CYCLE (MORL)

Mode	Control Function	Vehicle Configuration	Impulse Per Orbit (lb-sec)	Impulse Per Year (lb-sec)	Impulse Per 90-Day Resupply Period (lb-sec)	N_2O_4/MMH Propellant Requirement (lb)
Zero-g	Drag makeup, 2 pulses every 4 days	Solar panel	150	0.862×10^6	2.15×10^5	
	Attitude control, random 50-ms pulses as required	Local horizontal	221	1.279×10^6	3.20×10^5	
	Drag makeup, 2 pulses every 4 days	Brayton cycle	90	0.516×10^6	1.29×10^5	1,867
	Attitude control, random pulses as required	Local horizontal	98	0.562×10^6	1.40×10^5	
Artificial-g	Drag, intermittent operation	Solar panel	500	2.86×10^6	7.15×10^5	
	Precession, random pulses		500	2.86×10^6	7.15×10^5	
	Drag, intermittent operation	Brayton cycle	420	2.41×10^6	6.02×10^5	7,388
	Precession, random pulses		420	2.41×10^6	6.02×10^5	
			Impulse Per 90-Day Cycle (lb-sec)			
	One spin-up and one despin	Solar panel or Brayton cycle	3×10^5			

TABLE 5

AVAILABLE WASTE PROPULSION FOR A 90-DAY RESUPPLY PERIOD (MORL)

Crew Size	MONEX W Formulation	Available Waste (lb)	Waste Propellant (lb)	I_{sp} vac[a] (lbf-sec/lbm)	Available Impulse (lb-sec)
6	Dry	401	891	222	1.98×10^5
9	Dry	602	1,339	222	2.97×10^5
6	Wet	2,474	5,492		13.3×10^5
9	Wet	3,706	8,240		19.9×10^5

(a) Assuming 87-percent I_{sp} efficiency

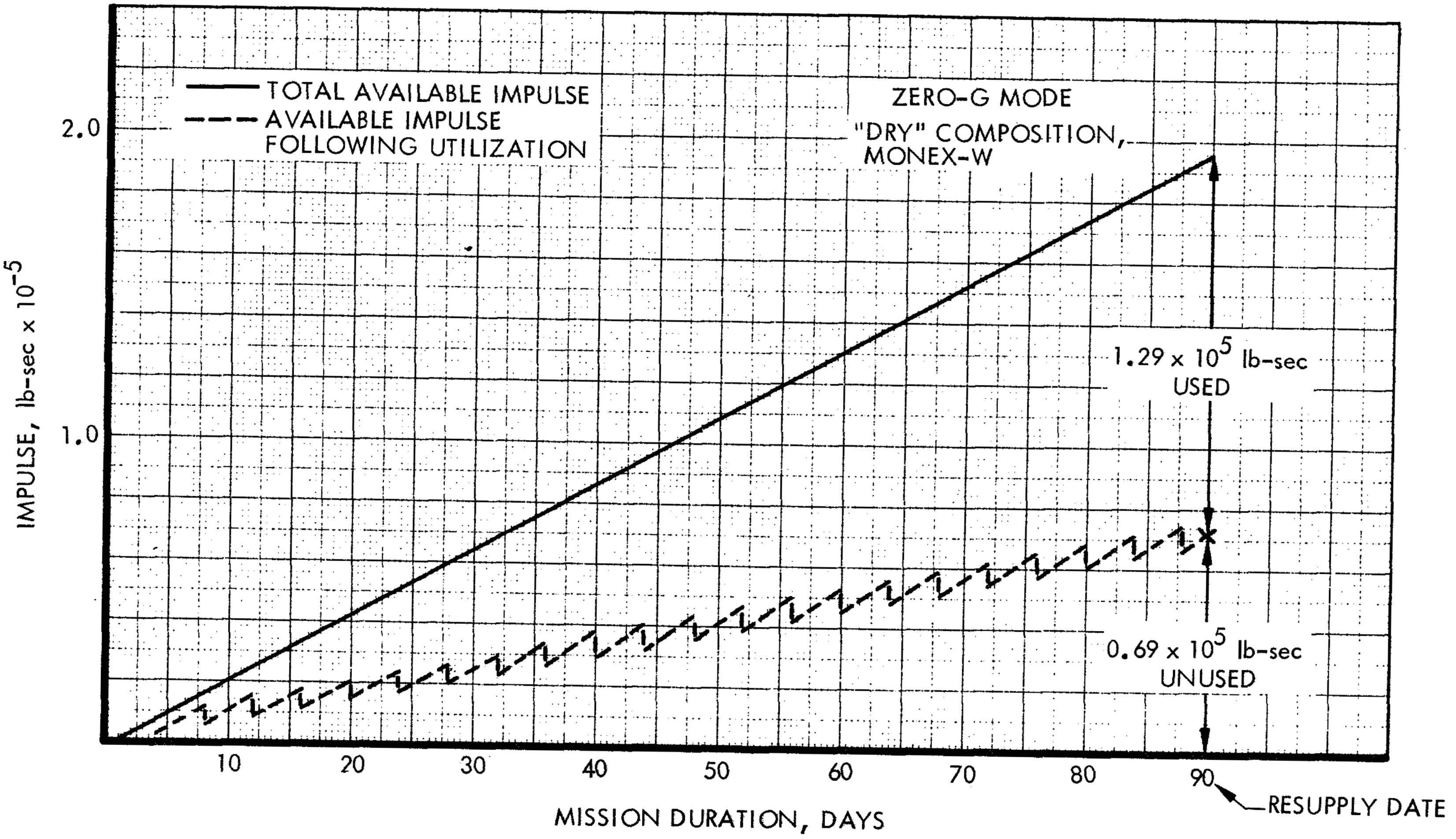

FIGURE 1. - MORL DRAG COMPENSATION UTILIZING WASTE PROPULSION NUCLEAR BRAYTON POWER SUPPLY (6-MAN CREW)

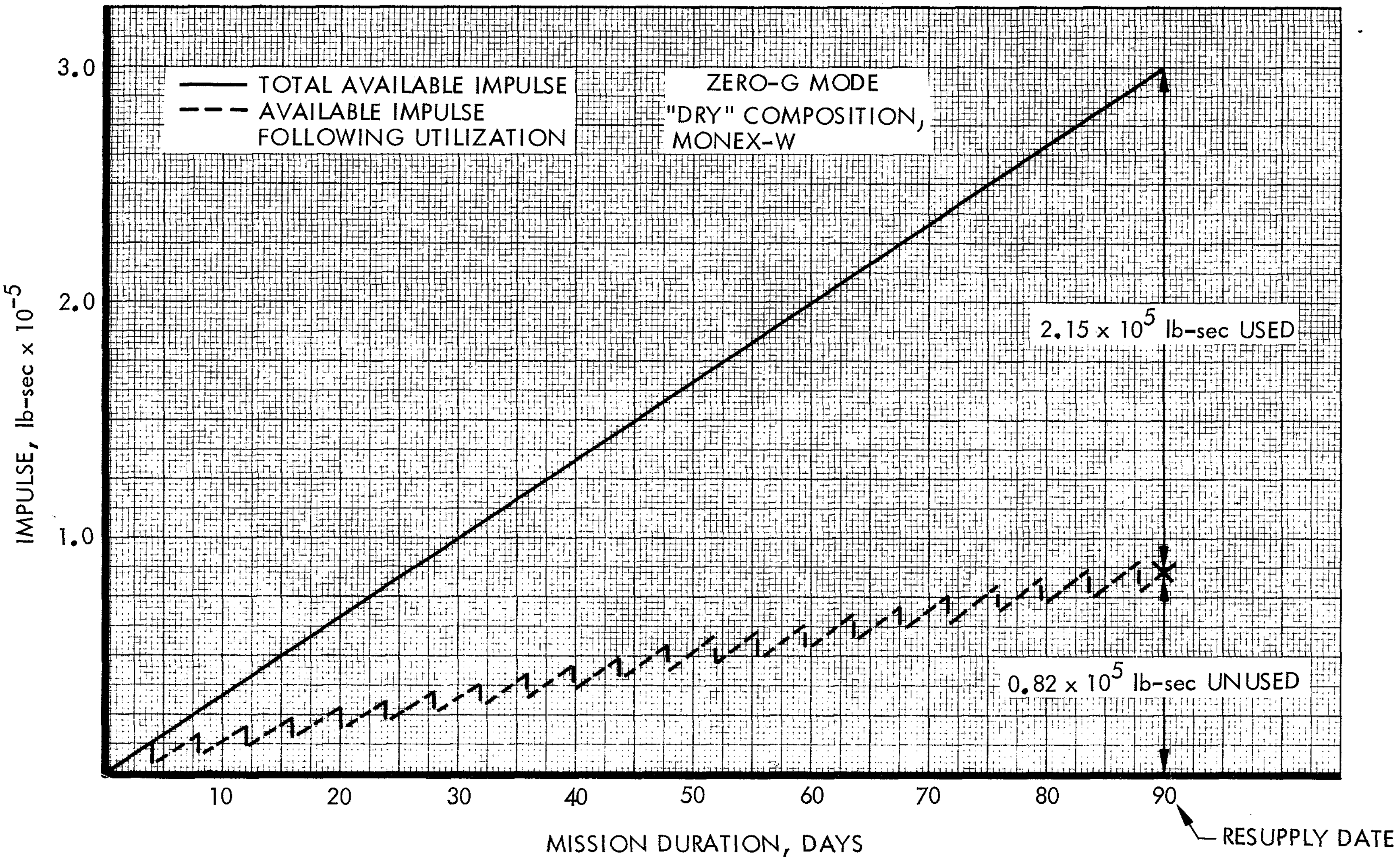

FIGURE 2. - MORL DRAG COMPENSATION UTILIZING WASTE PROPULSION, SOLAR PANEL POWER SUPPLY (9-MAN CREW)

limited to fewer spin/despin operations than indicated in the present studies (spin-up/despin every 150 days instead of every 90 days).

2.2.2 NAA Manned Mars and/or Venus Flyby Vehicle Systems Studies

As the mission requirements for flybys are low compared to planetary landing missions, spaceflights of this type could probably be performed during the next decade, whereas planetary landing missions may not be realized before the late 1980's.

Flyby missions are designated as lightside, darkside, low-energy, or high-energy flybys. The high-energy class of trajectories all pass inside earth's orbit, and the spacecraft performs about one-and-one-half solar circuits during each complete trip. The darkside flybys have lower mission requirements (mass in orbit and flight time); however, their scientific value is limited because they pass on the dark side of the planet, lessening the effectiveness of reconnaissance. An unusual type of flyby mission, possessing advantages for interplanetary exploration, is the multiplanet flyby. Both Mars and Venus can be reconnoitered for essentially the same propulsion requirements as a Mars flyby.

Manned Mars and/or Venus Flyby Vehicle Systems Studies (Refs. 63, 64) were performed by the Space and Information Systems Division of North American Aviation, Inc. The baseline of these studies was the use of as much available Apollo hardware as possible. Thus, the earth re-entry module is a modified Apollo capsule accommodating a four-man crew instead of a three-man crew. Descriptive data are given in Table 6 for three Mars/Venus Flyby Missions.

2.2.2.1 Vehicle Characteristics

The propulsion system uses existing engines; a summary of the propulsion system characteristics is given in Table 7.

The NAA study gives detailed weight data, which are summarized in Table 8. As exact weight data are not given for a dual planet flyby mission, corresponding data were taken from the Mars mission and modified, assuming that 6,000 pounds of probes are launched on each flyby. Considerable weight changes of 6,000 to 12,000 pounds are caused by launching the unmanned, instrumented probes to the surface of the planets. Additional weight changes are also caused by cabin leakage and propellant use for RCS, spin-up, and despin. Weight loss is assumed to proceed linearly with time on each leg of the mission.

2.2.2.2 Life Support System

The life support system for the NAA planetary flyby mission study is designed to use as much Apollo hardware as possible; however, the water recovery and carbon dioxide reduction system will be of completely new design. Water will be recovered from urine, wash water, and atmospheric condensates. Whereas nonregenerable CO_2 removal is used in the Apollo program, regenerable adsorbents are to be used for these long-duration missions, with LiOH canisters as backup for emergency situations. CO_2 reduction for oxygen recovery would be performed

TABLE 6

NAA PLANETARY FLYBY MISSION STUDY - WEIGHT CHARACTERISTICS[(a)]

Mission	Command and Service Module Weight (lb)	Mission Module (lb)	Probes (lb)	Total Injection Weight (lb)	Initial Return[(b)] Weight (lb)	Duration (days)
Venus 1972 Lightside Flyby	42,100	34,500	6,000	82,600	74,260	359
Mars 1973 Twilight Flyby	73,080	78,390	12,000	153,500	139,600	645
Venus/Mars 1973 Dual Planet Flyby Estimated Data	73,080	78,390	12,000	153,500	After Venus encounter 145,110 After Mars encounter 136,030	436

(a) 4-man crew

(b) At beginning of return phase of mission.
Detailed weight-loss data are given in Table 11.

TABLE 7

PLANET FLYBY [a] PROPULSION USING APOLLO ENGINES (NAA STUDY)

Function	Required ΔV (ft/sec)	Required Impulse (lb-sec)	Thrust (lbf)	Burn Time (sec)	Engine Starts	Applicable Apollo Engines
Midcourse correction	500		10,500 $I_{sp\ vac}$ = 305 lbf-sec/lbm	136 to 353	5	LEM descent engine
Retro firing prior to entry	6,800 to 12,400		2 x 10,500	581 to 1,744	1	LEM descent engine
Attitude control		~300,000	90	~375	<5,000	Service module RCS
Spinup and despin		1,500,000	25	1,293	<100	Service module RCS
Attitude control (during earth reentry)		<60,000	95	100	<3,000	Command module RCS

[a] Applies to Mars, Venus, and dual planet flyby missions

TABLE 8

WASTE MANAGEMENT SYSTEM AND WASTE PRODUCT WEIGHTS NAA FLYBY MISSIONS

Hardware	Weight and Power Requirements Weight (lb)
Waste collection unit	10
Storage and treatment	150
Containers	250
Charcoal filters	170
Total weight	580
Power requirement	100 Watts

	Weight	
Waste Products	lb/ man-day	lb/ 4-men day
Feces	0.33	1.32
Urine solids	0.15	0.60
Carbon	0.55	2.20
Paper towels	0.01	0.04
Food packaging	0.14	0.56
Miscellaneous waste (estimated)	0.50	2.00
Total weight	1.68	6.72

by a Bosch reactor, thus producing carbon as waste material. Waste would be collected in plastic bags and vacuum dried in a heated lock, venting the vapors to space. Data on this waste management system are given in Table 8 together with the waste products to be expected. The actual contribution from food packaging may be even higher, because up to 10 percent food remains unused in the plastic bags presently used in the Apollo mission.

2.2.2.3 Comparison of Available and Required Propulsion

A comparison of available and required propulsion for midcourse correction was made for four different missions (1972 Venus Lightside Flyby, 1973 Mars Twilight Flyby, 1977 Mars Twilight Flyby, and 1973 Dual Planet Venus/Mars Flyby) as shown in Table 9. The NAA study planned a three-man and a four-man crew as well. For this study, a four-man crew was assumed. Since it was not stated in the NAA study when the midcourse propulsion is to be applied, it is assumed to be divided into equal ΔV's for three firings on each leg of the mission.

For the results shown in Table 9, separate calculations were made assuming different weights for both the outbound and inbound leg. Weights were assumed to be constant throughout each leg of the mission. Table 10 shows how much propulsion could be provided by accumulating all waste during the first phase of the mission and using it after the flyby or for a final firing at earth arrival. Further advantages are shown by applying the time-dependent weight loss of the vehicle (Table 11) to calculations of available propulsion (Table 12).

The following assumptions were made for the calculations shown in Table 12:

a. No waste propellant will be used on the outbound leg of the mission.

b. The vehicle weight loss due to cabin leakage, RCS, and spin system operation is taken into account for each period between midcourse correction firings (Table 11).

c. Three midcourse firings will be performed. The first after 10 percent, the second after 50 percent, and the third after 90 percent of flight time.

Results given in Tables 9 through 12 and in Figs. 3 and 4 demonstrate that for the Venus mission the propulsion requirements can be met on the return leg of the mission, especially if waste is not used as a propellant during the initial phase of the mission but accumulated until the flyby has been performed. A conventional propulsion system is to be used for midcourse corrections on the first part of the mission. The same system provides abort capability during this period. The stepwise increase and the change in slope of the total available ΔV line in Figs. 3 and 4 is caused by reduction in spacecraft weight due to the launching of planetary probes during the flyby.

Impulse requirements for vehicle spin-up and despin could be met on the Mars missions and could be approximated on the dual planet flyby (Table 13). As indicated in Table 7, however, spin-up and despin is performed with a very low-thrust (25-lbf) engine and requires nearly 100 engine starts. Both requirements might not be easily fulfilled by a MONEX W system.

TABLE 9

COMPARISON OF REQUIRED AND AVAILABLE WASTE PROPULSION FOR MIDCOURSE CORRECTION - NAA FLYBY MISSIONS

Mission	Mission Phase	Duration (days)	Waste[a] (lbs)	Waste Propellant (lbs)	Vehicle Weight (lbs)	Available ΔV[b] (ft/sec)	Required ΔV (ft/sec)
1972 Venus Lightside Flyby	Earth-Venus	109	733	1,628	82,600	147	500
	Venus-Earth	250	1,680	3,733	74,260	381	500
1973 Mars Twilight Flyby	Earth-Mars	97	652	1,448	153,500	70	500
	Mars-Earth	548	3,683	8,183	139,400	210	500
1977 Mars Twilight Flyby	Earth-Mars	150	1,008	2,240	153,500	109	500
	Mars-Earth	534	3,589	7,974	139,400	435	500
1973 Dual Planet Flyby	Earth-Venus	122	820	1,822	153,500	88	333
	Venus-Mars	158	1,062	2,359	145,110	121	333
	Mars-Earth	156	1,048	2,329	136,030	128	333

(a) 100% of waste listed in Table 8 used, 4-men mission

(b) Available ΔV generated during each mission phase.

TABLE 10

AVAILABLE WASTE PROPULSION AFTER PLANETARY ENCOUNTER-NAA FLYBY MISSIONS

Mission	Mission Phase	Duration (days)	Waste[a] (lbs)	Waste Propellant (lbs)	Vehicle Weight (lbs)	Available ΔV (ft/sec)
1972 Venus Lightside Flyby	Venus-Earth	109	733	1,628	74,260	164
	Total[b]	359	2,413	5,361	74,260	553
1973 Mars Twilight Flyby	Mars-Earth	97	652	2,448	139,400	71
	Total[b]	645	4,335	9,631	139,400	479
1977 Mars Twilight Flyby	Mars-Earth	150	1,008	2,240	139,400	120
	Total[b]	684	4,597	10,214	139,400	562
1973 Dual Planet Flyby	Earth-Venus	122	820	1,822	145,110	93
	Venus-Mars[c]	280	1,882	4,181	145,110	216
	Mars-Earth[d]	280	1,882	4,181	136,030	230
	Total[b]	436	2,930	6,510	136,030	362

[a] 100% of waste listed in Table 8 used, 4-men mission

[b] At earth arrival (no prior utilization)

[c] Immediately before Mars Flyby (no prior utilization)

[d] Immediately after Mars Flyby

TABLE 11

VENUS AND MARS FLYBY MISSION
AVERAGE WEIGHT LOSS

	Venus Mission (lb)	Mars Mission (lb)
RCS propellant	840	840
Environmental control system	105	105
Spin propellant	3,300	6,620
	4,245	7,565
Duration (days)	359	684
Loss day (lb/day)	11.82	11.06
Loss/day (including 10-lb/day cabin leakage)	21.82	21.06

TABLE 12

COMPARISON OF REQUIRED AND AVAILABLE WASTE PROPULSION[a] - NAA FLYBY MISSIONS

Mission	Mission Phase	Midcourse Firing (% time)	Day of Mission	Waste (lb)	Waste Propellant (lb)	Available Waste Propellant (lb)	Waste Propellant Used (lb)	Waste Propellant Unused (lb)	ΔV Available (ft/sec)	ΔV Used (ft/sec)	ΔV Required (ft/sec)	Weight Loss (lb)	Used Waste Propellant + Weight Loss (lb)	Vehicle Weight (lb)
1972 Venus Flyby	Venus-Earth		109	733	1,628	1,628	0	1,628	164	--	--	2,378	2,378	74,222
		10	134	901	2,001	2,001	1,638	363	203	166	166	2,924	2,924	73,676
		50	234	672	1,493	1,856	1,553	303	199	166	166	5,106	6,744	69,856
		90	334	672	1,493	1,796	1,470	326	203	166	166	7,288	10,479	66,121
		Final	359	168	373	699	Rest	0	81	--	--	7,833	12,494	64,106
1977 Mars Flyby	Mars-Earth		150	1,008	2,240	2,240	0	2,240	115	---	---	3,159	3,159	138,341
		10	203	1,364	3,031	3,031	3,031	0	165	165	166	4,275	4,275	137,225
		50	417	1,438	3,195	3,196	2,883	312	184	166	166	8,782	11,813	129,667
		90	631	1,438	3,195	3,508	2,712	796	215	166	166	13,289	19,515	121,985
		Final	684	356	783	1,504	1,504	0	95	---	---	14,405	24,140	117,360

[a] 100% of waste listed in Table 8 used, leakage loss taken into consideration, 4-men crew, using waste propulsion on return trajectory only.

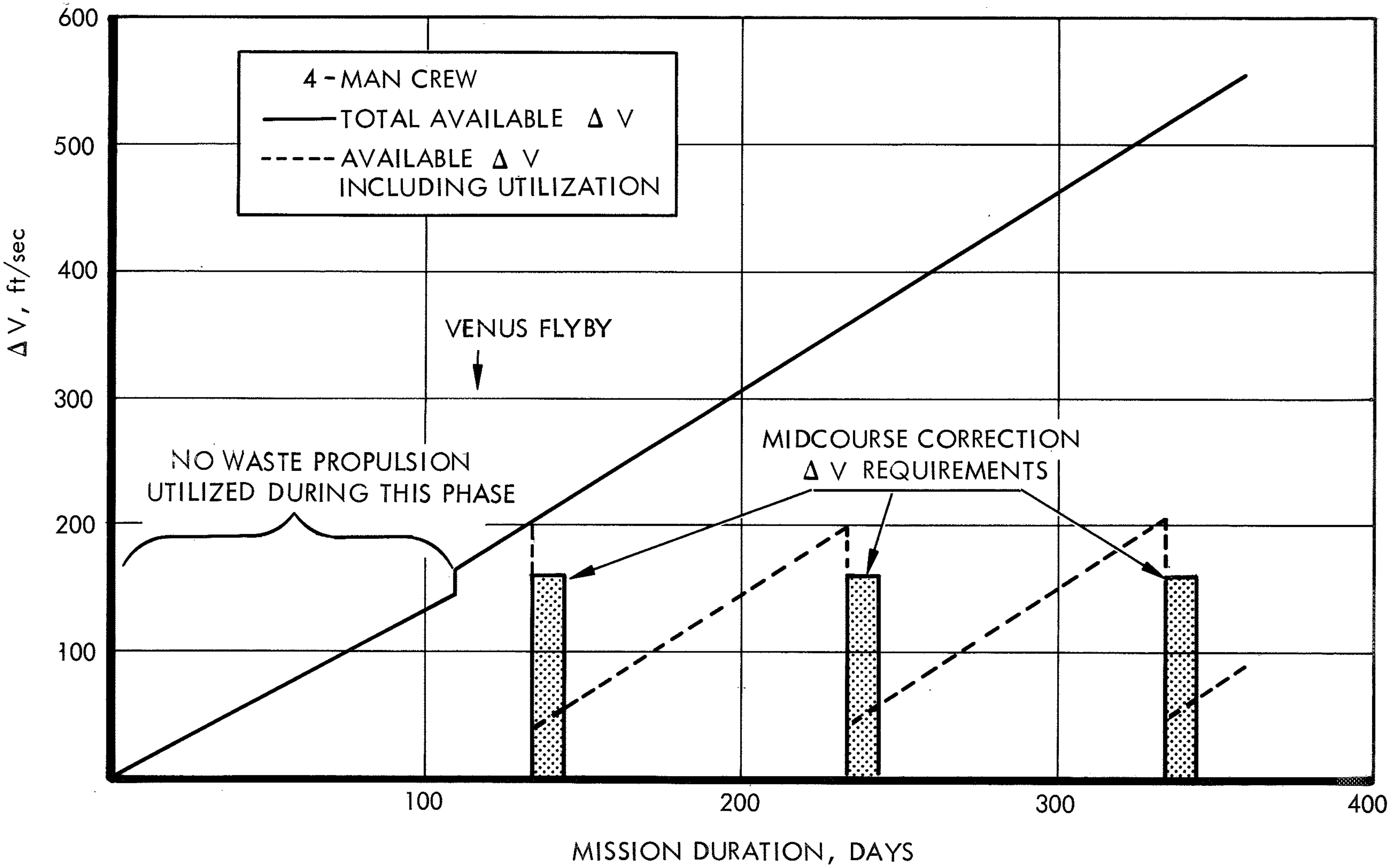

FIGURE 3. - APPLICATION OF WASTE PROPULSION TO MIDCOURSE CORRECTIONS ON 1972 VENUS FLYBY MISSION - NAA STUDY

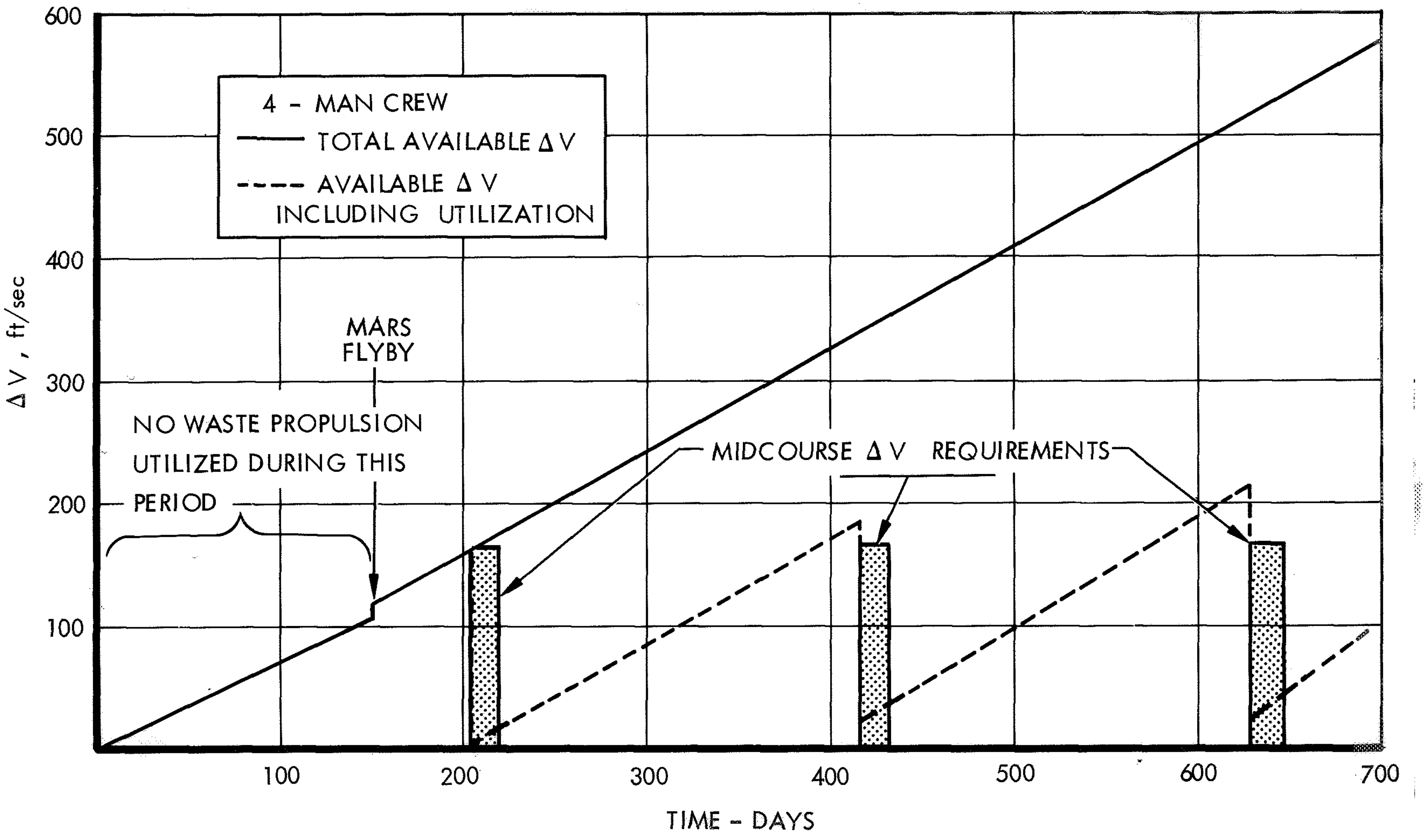

FIGURE 4. - APPLICATION OF WASTE PROPULSION TO MIDCOURSE CORRECTIONS ON 1977 MARS FLYBY MISSION - NAA STUDY

TABLE 13

COMPARISON OF AVAILABLE AND REQUIRED IMPULSE FOR SPIN-UP AND DESPIN - NAA FLYBY MISSIONS

Mission	Duration (days)	Available[(a)] Impulse (lb-sec)	Required Impulse (lb-sec)	Propulsion Task
1972 Venus Lightside Flyby	359	1.23×10^6	1.5×10^6	Spin-up and despin
1973 Mars Twilight Flyby	645	2.20×10^6	1.5×10^6	Spin-up and despin
1977 Mars Twilight Flyby	684	2.34×10^6	1.5×10^6	Spin-up and despin
1973 Dual Planet Flyby	436	1.49×10^6	1.5×10^6	Spin-up and despin

(a) From Waste Propulsion System

2.2.3 Lockheed-EMPIRE Planetary Flyby Mission Study

The Early Manned Interplanetary Mission Study (EMPIRE study), performed by Lockheed Missiles & Space Company (Ref. 65) under Contract NAS 8-5024, analyzed primarily three-man flybys to Venus or Mars in the years 1970 through 1975, including consideration of orbital stopover missions. Typical missions are described in the following paragraphs and analyzed with respect to the possibility of using waste propulsion during these missions. Heliocentric transfer orbit injection in the EMPIRE missions is achieved by a chemical or nuclear upper stage. Midcourse correction is planned with storable chemical propellants ($I_{sp\ vac} = 330$ sec). At earth reentry, either solid propellant retrorockets or an aerodynamic drag brake would be used.

The ΔV requirements for midcourse correction (2,000 ft/sec) given in the EMPIRE study are the highest of all missions considered for application of a waste propulsion system. These are probably very conservative data with more than enough margin for safety.

The life support system calls for water and oxygen recovery from urine and carbon dioxide. It was proposed that feces disposal be accomplished by incineration, for which there is a power requirement of 1.2 kilowatts. Food and drinking water are estimated to weigh 4,950 pounds for a 365-day mission and 7,700 pounds for a 600-day mission. In a utility water system, 440 pounds of water would be circulated. The water balance for long-duration spaceflights is considerably influenced by cabin leakage and lock losses, thus provisions must be made to store sufficient water on board the spacecraft. A parallel EMPIRE study was performed by Ford Aeronutronics Div. (Ref. 66).

2.2.3.1 Venus Flyby Mission

The propulsion requirements for a Venus flyby mission vary only slightly from year to year. The minimum mass required with a chemical escape system is just above the payload capability of a single Saturn V. The mission is easily achieved with a single launch if a nuclear escape stage is used.

2.2.3.2 Mars Flyby Mission

The comparisons performed in the EMPIRE study show that, for the later oppositions (1973 to 1975), the system weight requirements increase rapidly for the high-energy missions. Assuming chemical escape propulsion and earth entry retrofiring, this mission requires a take-off weight from earth orbit of about 900,000 pounds and a duration of 579 days. Employing nuclear propulsion and drag brake earth entry, lower weights are possible. Also, low-energy trajectories for the same mission year require only 700,000 pounds with the penalty of extended flight time up to 660 days.

2.2.3.3 Multiple Mars/Venus Flyby

Favorable opportunities for multiple planet flyby missions are scarce compared to single flyby missions. For minimum propulsion requirements, opportunities for multiple flyby missions will occur every 13 years.

The 1970 grand tour (Table 14) is taken as an example, as it offers minimum mass on parking orbit, although it will not be performed due to the lack of time for vehicle development. The same data also apply to a 1983 mission. The midcourse correction ΔV requirements for all missions indicated in the Lockheed report are extremely high and would be difficult to fulfill by a waste propulsion system. Because the report did not reveal the number of corrective maneuvers required, it is assumed that six equal midcourse ΔV's will take place, two on each phase of the mission. None of the propulsion requirements can be met completely, except when all waste is stored for the final corrective maneuver.

The results for application of waste propulsion to an EMPIRE-type space mission are unfavorable due to the small crew number and the high vehicle weight. In addition, vehicle weight for a flyby mission is not reduced by jettisoning entry or escape stages as is the case for planetary stopover missions. The situation would be considerably improved if a 12-man crew were involved.

As the carbon content of the MONEX W must be kept very low in order to maintain a propellant of sufficient liquid consistency to be useful in an injection-type engine, not all of the carbon and activated charcoal may be used. Preliminary test results indicate that a carbon content of greater than 17 percent in the final propellant may prevent achievement of adequate injector spray patterns. Accepting this limitation, only 69 percent of the available carbon would be of use as a propellant ingredient. In this particular study, calculations have been made of waste materials available for both 100-percent (Case I) and 69-percent (Case II) carbon utilization (Table 15). In an additional instance (Case III) it was assumed that sufficient urine might be available in order to prepare a propellant utilizing all the carbon without exceeding a carbon concentration of 17 percent.

A comparison of required and available waste propulsion capability (see Table 16) shows that even if additional water were allowed and use was made of all carbon (Case III), the ΔV requirement of 2,000 ft/sec for midcourse corrections cannot be met with a three-man crew.

2.2.4 Manned Mars and Venus Exploration Study (MAVES)

The MAVES study, a manned planetary landing mission, was prepared by General Dynamics/Convair (Ref. 67) under Contract NAS 8-11327 for the NASA Marshall Space Flight Center. The life support system for this mission was studied by General Dynamics/Fort Worth. The mission will consist of either a convoy of three independently maneuverable vehicles (namely a manned mission module accompanied by two unmanned service modules) or a composite of these designated as a "multiplex" vehicle.

Three basic transfer orbit profiles were taken into consideration during the MAVES study, the heliocentric earth approach retro (HEAR), the geocentric earth approach retro (GEAR), and the perihelion brake (PB) maneuvers. The GEAR maneuver requires high thrust over a short time duration, thus favoring chemical propulsion systems such as those using OF_2/MMH propellants. The

TABLE 14

EMPIRE MARS/VENUS FLYBY GRAND TOUR - 1970 - LOCKHEED STUDY

Leave earth	September 20, 1970
Pass Mars	December 5, 1970
Pass Venus	July 13, 1971
Return earth	May 3, 1972
Mission duration	86 + 220 + 295 = 601 days

Mass Summary	Weight (lb)
Retrorocket	29,762
Life support	17,218
Power supply	1,499
Shielding	5,004
Structure and equipment	5,512
Service module	8,025
Contingency	5,004
Midcourse Correction (Storable)	20,635
Mass on parking orbit (Chemical escape propulsion)	361,778
Escape payload	97,665

TABLE 15

WASTE MATERIALS AVAILABLE FOR PROPELLANT PREPARATION LOCKHEED EMPIRE STUDY (lb/day)

	Case I		Case II		Case III	
	100% Waste Used		Carbon Content Limited to 17% in Propellant		Additional Water Allowed - All Carbon Used	
	1 Man	3 Men	1 Man	3 Men	1 Man	3 Men
Feces	0.342	1.026	0.342	1.026	0.342	1.026
Urine residues[(a)] (including 10% water)	0.148	0.444	0.148	0.444	0.458	1.374
Urine	--	--	--	--		
Carbon	0.610	1.830	0.418	1.254	0.610	1.830
Miscellaneous wastes	0.200	0.600	0.200	0.600	0.200	0.600
Total	1.300	3.900	1.108	3.324	1.610	4.830

(a) Urine residue data shown in Empire study (30g/day) are too low. Data from Bioastronautics Data Book, Ref. 80 (60 g/day = 0.133 lb/day) are preferred here.

TABLE 16

COMPARISON OF REQUIRED AND AVAILABLE WASTE PROPULSION CAPABILITY

LOCKHEED STUDY - 3-MAN CREW

Mission	Mission Duration (days)	Case[a]	Waste (lbs)	Waste Propellant (lbs)	Vehicle Weight (lbs)	Available ΔV (ft/sec)	Required ΔV (ft/sec)	Propulsion Task
1972 Venus Flyby	348	I	1,357	3,016	97,700	231	2,000	Midcourse corrections
		II	1,162	2,582		198		
		III	1,680	3,735		288		
1971 Mars Flyby	579	I	2,258	5,018	97,700	389	2,000	Midcourse corrections
		II	1,933	4,296		332		
		III	2,797	6,215		485		
1970 Mars-Venus Flyby	601	I	2,344	5,209	97,700	404	2,000	Midcourse corrections
		II	2,007	4,459		345		
		III	2,903	6,460		504		

(a) Case numbers refer to Table 15

HEAR and PB maneuvers may be performed with low-thrust devices, e.g. a solar heat exchange thermal rocket propulsion system ($I_{sp\ vac}$ = 700 lbf-sec/lbm).

The 1981 Venus and 1982 Mars reference mission profiles are given in Table 17. A comparison of available waste propellant and propulsion requirements for these missions is given in Table 18.

It is assumed that only the independently maneuverable manned crew vehicle payload (150,000 pounds) would have to be propelled for certain maneuvers by an integrated waste management/propulsion system. The service vehicles would stay on the prescribed transfer path by use of independent propulsion systems.

The accumulation of waste (feces, carbon, urine residues including 10% water, and miscellaneous waste) during the MAVES mission was assumed to occur at a rate of 1.34 lb/man-day. If the carbon content in the final propellant was limited to 17%, such that only 68% of available carbon could be used, waste would accumulate at a rate of 1.14 lb/man-day.

Comparisons of available and required propulsion, as presented in Table 18, show that by use of all waste (described in the previous paragraph) it is possible to fulfill the ΔV requirements for midcourse corrections on the 12-man Mars mission on both the inward and outward legs. If only eight men are on board the spacecraft, or if the carbon content is limited, the propulsion requirements can be satisfied for the return leg only. For the Venus mission, the requirements can be met only for the return leg of the mission, for both eight-man or 12-man crews, using 100 percent of the waste as a propellant ingredient.

2.2.5 TRW Manned Mars Landing Mission Study

The Manned Mars Mission Study performed by TRW Space Technology Laboratories (Refs. 68, 69) is based on Saturn C-5 as a launch vehicle and requires three launches for a single mission. Earth escape and return propulsion are planned with either chemically propelled upper stages (fluorine and hydrogen) or nuclear stages. Midcourse propulsion is accomplished by using storable propellants ($I_{sp\ vac}$ = 333 lbf-sec/lbm) on both legs of the mission. A 1975 Mars mission with a Venus swingby on the inbound leg is chosen as the reference mission for comparison in this study. The Venus swingby has many advantages, as it reduces the earth re-entry velocity from 65,000 ft/sec to 44,000 ft/sec so that a conventional Apollo-type heat shield may be used. It also permits a close inspection of Venus at essentially no increased propulsion requirements.

Compared to a direct return flight from Mars, the Venus swingby increases the trip duration from 434 days to 495 days, resulting in additional life support supply requirements and a 3.5-percent increase in total vehicle weight. The anticipated life support system will recover both water and oxygen. As it has been proposed to perform carbon dioxide reduction by the Sabatier reaction, no carbon recovery may be expected unless methane formed by the primary Sabatier process is cracked to form carbon in a subsequent reaction. Solid waste (including feces and urine residues) was proposed to be frozen and stored. Normal crew size is anticipated to be six men, but may be increased to eight men

TABLE 17

MAVES PLANETARY LANDING MISSIONS PROFILE

Mission	Venus 1981	Mars 1982
Duration, days	120 + 20 + 260 = 400	190 + 30 + 200 = 420
Crew, men	8	8
ΔV for correction maneuvers, each heliocentric transfer leg, ft/sec	300	300
ΔV for capture orbit trimming, ft/sec	400	400
ΔV for perihelion brake maneuver, ft/sec	9,000 to 13,000	12,000
Earth reentry velocity, ft/sec	40,000	42,000
Crew vehicle weight, lb	1.57×10^6	2.38×10^6
2 Service vehicles, each, lb	0.56×10^6	0.84×10^6

TABLE 18

COMPARISON OF AVAILABLE AND REQUIRED ΔV FOR MAVES PLANETARY LANDING MISSIONS

Mission	Mission Phase	Duration (days)	Crew (men)	Carbon Waste Used (%)	Waste (lb)	Waste Propellant (lb)	Crew Payload Weight (lb)	ΔV Generated During the Phase (ft/sec)	Available Cumulative[(a)] ΔV (ft/sec)	Mission Phase Propulsion Task	ΔV Requirements (ft/sec)
Mars	Earth-Mars	190	8	100	2,035	4,521	150,000	226	226		
			8	68	1,733	3,851		192	192	Midcourse corrections	300
			12	100	3,055	6,789		342	342	Mars orbit capture	400
			12	68	2,599	5,756		289	289		
	Mars Orbit	30	8	100	321	714		35	261		
			8	68	274	608		30	222		
			12	100	482	1,072		53	395		
			12	68	410	912		45	334		
	Mars - Earth	200	8	100	2,142	4,759		238	499		
			8	68	1,824	4,053		202	424	Midcourse corrections	300
			12	100	3,216	7,146		360	755	Perihelion brake maneuver	12,000
			12	68	2,722	6,048		304	638		
Venus	Earth - Venus	120	8	100	1,285	2,856	150,000	142	142		
			8	68	1,094	2,432		121	121	Midcourse corrections	300
			12	100	1,930	4,287		214	214	Venus orbit capture	400
			12	68	1,633	3,629		181	181		
	Venus Orbit	20	8	100	214	476		23	165		
			8	68	182	405		20	141		
			12	100	322	715		35	249		
			12	68	272	605		30	211		
	Venus - Earth	160	8	100	1,715	3,811		190	355		
			8	68	1,459	3,243		161	302	Midcourse corrections	300
			12	100	2,573	5,717		287	536	Perihelion brake maneuver	9,000
			12	68	2,178	4,839		242	453		

(a) Assuming no prior use of waste propulsion without major changes. Waste data given in the TRW report include 0.3 pound per man-day wet urine residues and 1.3 pounds per man-day feces and other waste.

Table 19 shows that waste propulsion offers more propulsion capability than necessary for midcourse correction in a mission with an eight-man crew during the return leg from Mars. Application of waste propulsion on the outbound part of the trip does not appear promising as a sole propulsion means because the total vehicle weight is still very high. On the inbound portion, however, after the Mars excursion module, the Mars arrival heat shield, and the Mars escape stage are jettisoned, the return weight is approximately one-fourth of the initial vehicle weight. Under these conditions, the mass ratio is higher, and the same amount of waste propellant achieves a higher ΔV than during the first phase of the mission. Propulsion requirements for the return path (shown in Table 19) are slightly greater than 500 ft/sec because the Venus swingby maneuver requires slightly more propulsion accuracy than an ordinary midcourse maneuver.

The available ΔV in relation to mission requirements is shown in Figs. 5 and 6; the vertical bars represent the ΔV requirements for three correction maneuvers on each leg of the orbit. The darkened bars show which ΔV's can utilize waste propulsion provided the waste is saved for the inbound leg of the mission. Both figures show unused waste propulsion capability after the final corrective firing.

This unused capability does not yet consider the excess water carried in the Mars mission module (MMM). Of the 1,000 pounds of water in the MMM, only 150 pounds are necessary for a six-man crew after jettisoning the earth reentry module from the MMM. This leaves 850 pounds of water available for additional final entry orbit correction maneuvers and earth-entry velocity decrease. In addition to the water available, unused food, expendable activated charcoal filters, and waste accumulated since the last midcourse corrective firing would be available. It is estimated that this additional waste would total 420 pounds for a six-man crew.

Final braking capacity utilizing this additional waste is shown in Table 20. It should be noted that the available ΔV is increased markedly if the final waste propulsion firing is applied to the earth return module stage only rather than to the MMM as a whole.

2.2.6 NAA Manned Mars Landing and Return Mission Study

The Manned Mars Landing and Return Mission Study (Ref. 70), performed by the Space and Information Systems Division of North American Aviation, Inc., considered round trip missions of 12 to 18 months' duration through the cycle of oppositions from August 1971 through July 1981.

Chemical propulsion, using advanced Saturn stages, was emphasized during the early 1970's and nuclear propulsion in the later periods. The time spent at Mars varied from 6 to 60 days. Crew size was varied from three to 10 men, although six men were considered to be the smallest desirable crew for an interplanetary landing mission. For this reason, only missions with six- and

TABLE 19

COMPARISON OF REQUIRED AND AVAILABLE WASTE MANAGEMENT/ROCKET PROPULSION SYSTEM PROPULSION CAPABILITY - TRW STUDY

Phase of Mission	Duration (days)	Crew Size (men)	Vehicle Weight (lb)	Waste (lb)	Waste Propellant (lb)	Available Impulse (lb-sec)	Available ΔV (Generated During each Phase) (ft/sec)	Available Cumulative$^{(a)}$ ΔV (ft/sec)	Propulsion Task	Required ΔV (ft/sec)
Earth-Mars	190	6	474,100	2,166	4,809	1.10×10^6	75.3	75.3	Midcourse correction	500
		8	478,600	2,888	6,411	1.47×10^6	99.5	99.5	Midcourse correction	500
Mars Orbit	10	4	--	114	253.3	--	--	337		--
		6	--	152	337.8	--	--	436		--
Mars - Earth	295	6	113,200	3,363	7,466	1.71×10^6	503.7	866	Midcourse correction	≥ 500
		8	117,700	4,484	9,954	2.28×10^6	652.4	1,130	Midcourse correction	≥ 500

(a) Assuming no prior use of waste propulsion

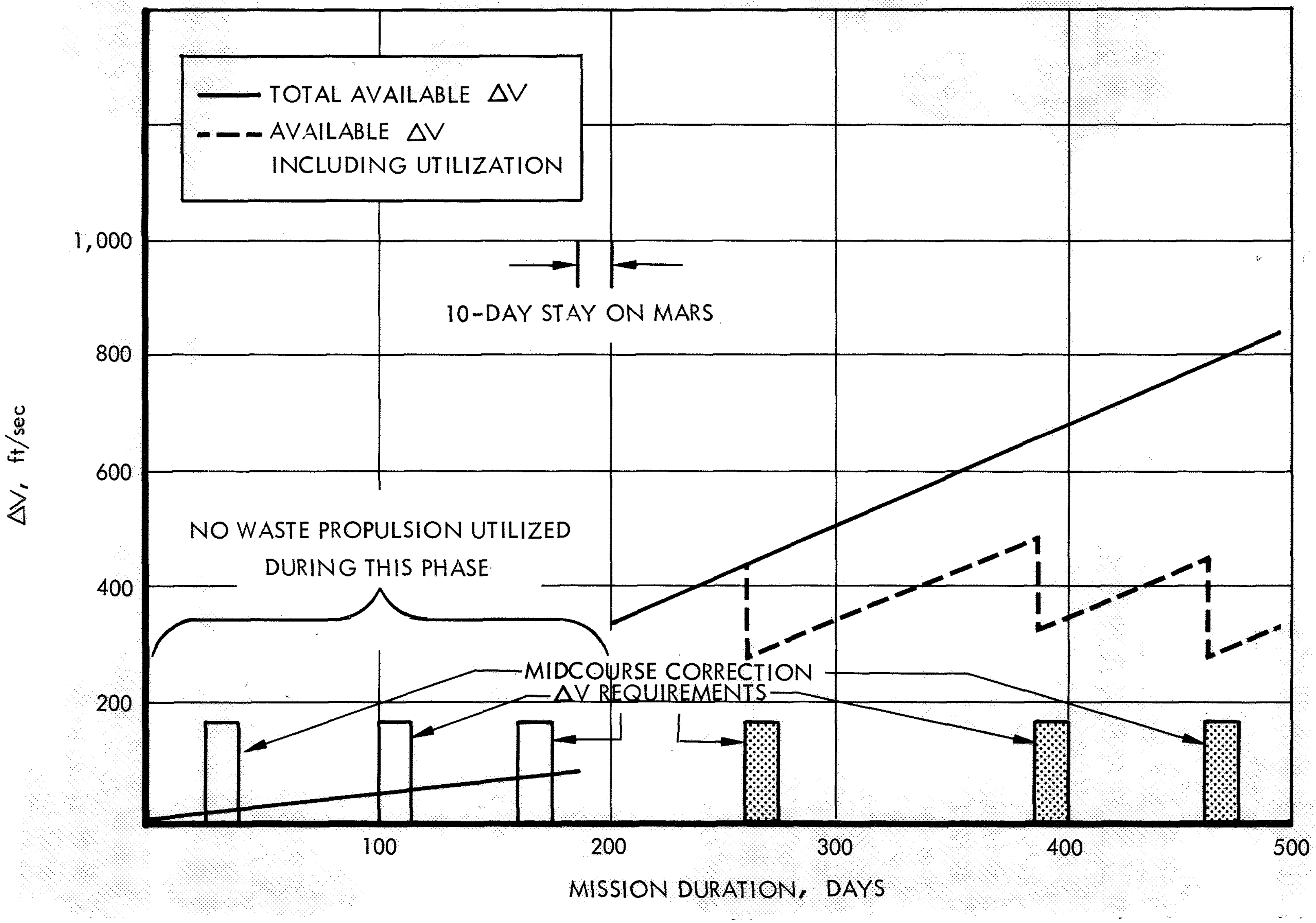

FIGURE 5. - APPLICATION OF WASTE PROPULSION TO MIDCOURSE CORRECTIONS FOR MARS LANDING MISSION (6-MAN CREW) - TRW STUDY

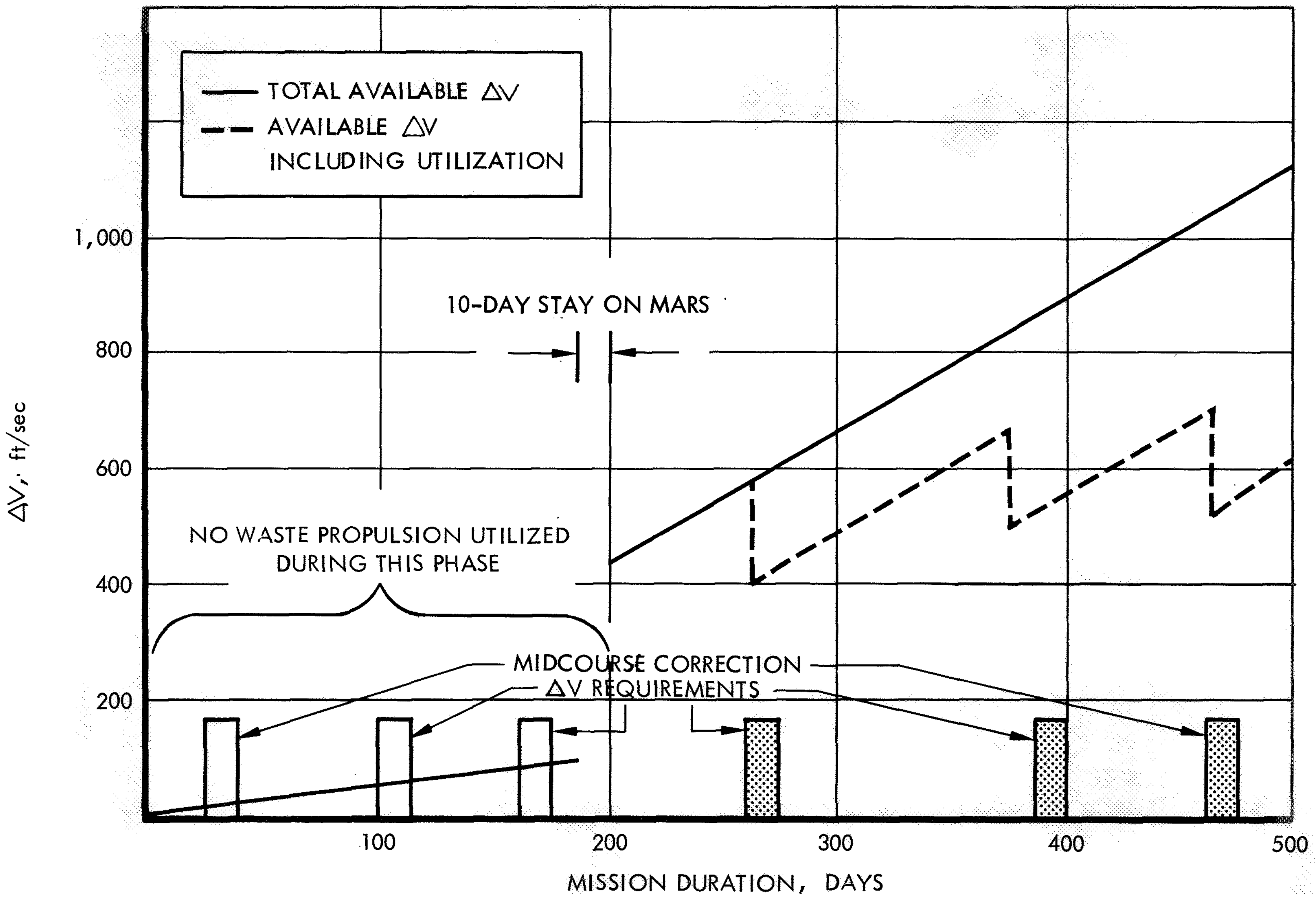

FIGURE 6. - APPLICATION OF WASTE PROPULSION TO MIDCOURSE CORRECTIONS FOR MARS LANDING MISSION (8-MAN CREW) - TRW STUDY

TABLE 20

AVAILABLE WASTE PROPULSION UPON TERMINATION(a) OF MARS MISSION - TRW STUDY

Crew Size (men)	Vehicle Weight (lb)	Final Waste(b) (lb)	Final Waste Propellant(c) (lb)	Available ΔV (ft/sec)
6	Mars Mission Module 105,734	1,270	2,819	230
6	Earth return module plus propulsion unit 24,820	1,270	2,819	1,028

(a) Re-entry velocity without braking: 65,000 ft/sec

(b) Does not include waste consumed for midcourse propulsion on return leg

(c) "Wet" waste propellant, $I_{sp\ vac}$ = 265 lbf-sec/lbm

10-man crews have been considered for applications involving the waste management propulsion system.

For this comparison, a mission with a conical Mars aerobraking concept was chosen, since this allows considerable vehicle weight savings. The referenced study estimated a gross vehicle weight of 328,580 pounds at the time of trans-Mars injection with the MMM weighing 40,350 pounds (see Table 21).

2.2.6.1 Propulsion System

The earth orbit escape propulsion system is not considered here, since no contribution can be made to this task from the waste propulsion system. The propulsion systems chosen for the 1971 Mars landing are characterized by the data compiled in Table 21. Storable chemical propellants are preferred for safety reasons, although use of cryogenic propellants results in higher specific impulses.

The NAA Mars Landing Study differs from similar studies in that the midcourse propulsion system used on the inbound leg uses different engines than used on the outbound leg of the mission. The inbound engines are also used to provide Mars escape propulsion, but are throttled down for the midcourse propulsion.

2.2.6.2 Life Support System

Seven ecological systems with various degrees of closure were studied in this report. The system appearing most practical from weight, power, and volume considerations for both Mars mission and Mars exploration requirements provides regeneration of water from urine, condensate, and wash water. Oxygen is regenerated using a Bosch reactor. The recovery of water from feces results in very little decrease in total system weight, but produces increased power requirements and system complexity. Several possibilities of waste disposal were considered, including complete storage of waste, waste burn-off or storage of waste with venting of gases to space. Basic metabolic data used in the NAA study are shown in Table 22.

2.2.6.3 Comparison of Available and Required Propulsion

A comparison of available and required ΔV for the different phases of the mission (Table 23) shows that midcourse propulsion requirements can easily be met by waste propulsion on the inbound leg of the mission. Darkened bars in Figs. 7 and 8 indicate midcourse propulsion, which is provided by the waste management/rocket propulsion system. Figures 7 and 8 also show that a considerable contribution could be possible on the outbound leg of the mission. It is assumed, however, that waste propellant would not be used on the outbound leg but saved for the return leg of the mission. A considerable propulsion capability is left over upon termination of the mission. This could be utilized for a final brake maneuver before reentering the earth's atmosphere.

TABLE 21

VEHICLE AND PROPULSION SYSTEM DATA - 1971 MARS LANDING MISSION (VENUS ENCOUNTER) - NAA STUDY

Trans-Mars Midcourse Correction	
Propellants	N_2O_4/Aerozine-50
Engines x thrust	2 x 15,000 lbf
Propellants:	
N_2O_4	24,300 lb (233 cu ft)
Aerozine-50	12,170 lb (299 cu ft)
ΔV requirements:	
Earth-Venus midcourse correction and flyby thrust	750 ft/sec
Venus-Mars midcourse correction	500 ft/sec
Mars orbit circularization	650 ft/sec
Mars Orbit Escape and Trans-Earth Midcourse Correction	
Propellants	OF_2/MMH
Engines x thrust	2 x 10,000 lbf (throttlable to 2 x 3,300 lbf)
Propellants:	
OF_2	90,700 lb (1,050 cu ft)
MMH	36,300 lb (720 cu ft)
ΔV requirements:	
Mars escape	12,750 ft/sec
Trans-Earth midcourse correction	500 ft/sec
Vehicle Weight	
Earth return module (ERM)	8,800 lbs
Mars mission module (MMM)	42,000 lbs
Mars excursion modules (MEM)	53,000 lbs
Return weight (MMM + ERM + Propulsion system) (estimated)	59,100 lbs

TABLE 22

MARS LANDING MISSION WASTE DATA (NAA STUDY)

	Waste Available For Propellant Use (lb/man-day)
Carbon output (Bosch Reactor)	0.55
Feces (67% H_2O)	0.33
Urine residues	0.21
Packaging material	0.07
Miscellaneous waste (estimated)	0.20
Total available waste	1.36

TABLE 23

COMPARISON OF AVAILABLE AND REQUIRED ΔV
(NAA MISSIONS)

Mission	Phase of Mission	Crew (men)	Duration (days)	Waste (lb)	Waste Propellant (lb)	Vehicle Weight (lb)	Available ΔV (Generated During the Phase) (ft/sec)	Available Cumulative ΔV(a) (ft/sec)	Propulsion Task	ΔV Requirements (ft/sec)
Manned Mars landing with Venus encounter	Earth - Mars	6	320	2,598	5,773	328,580	131	131	Midcourse corrections and Venus Flyby	750
		10	320	4,330	9,621	350,000	206	206	Establish Mars orbit	650
	Mars[(b)] Orbit	3	30	122	271	184,400	10.8 6 men 10 men	246 407	Mars orbit escape	12,750
	Mars - Earth	6	230	1,867	4,149	59,100	537	1,398	Midcourse corrections	500
		10	230	3,112	6,915	71,300	753	1,985		

(a) Assumes no prior use of waste management propulsion system

(b) It is assumed that waste generated by crew members on Mars surface is not carried back into orbit.

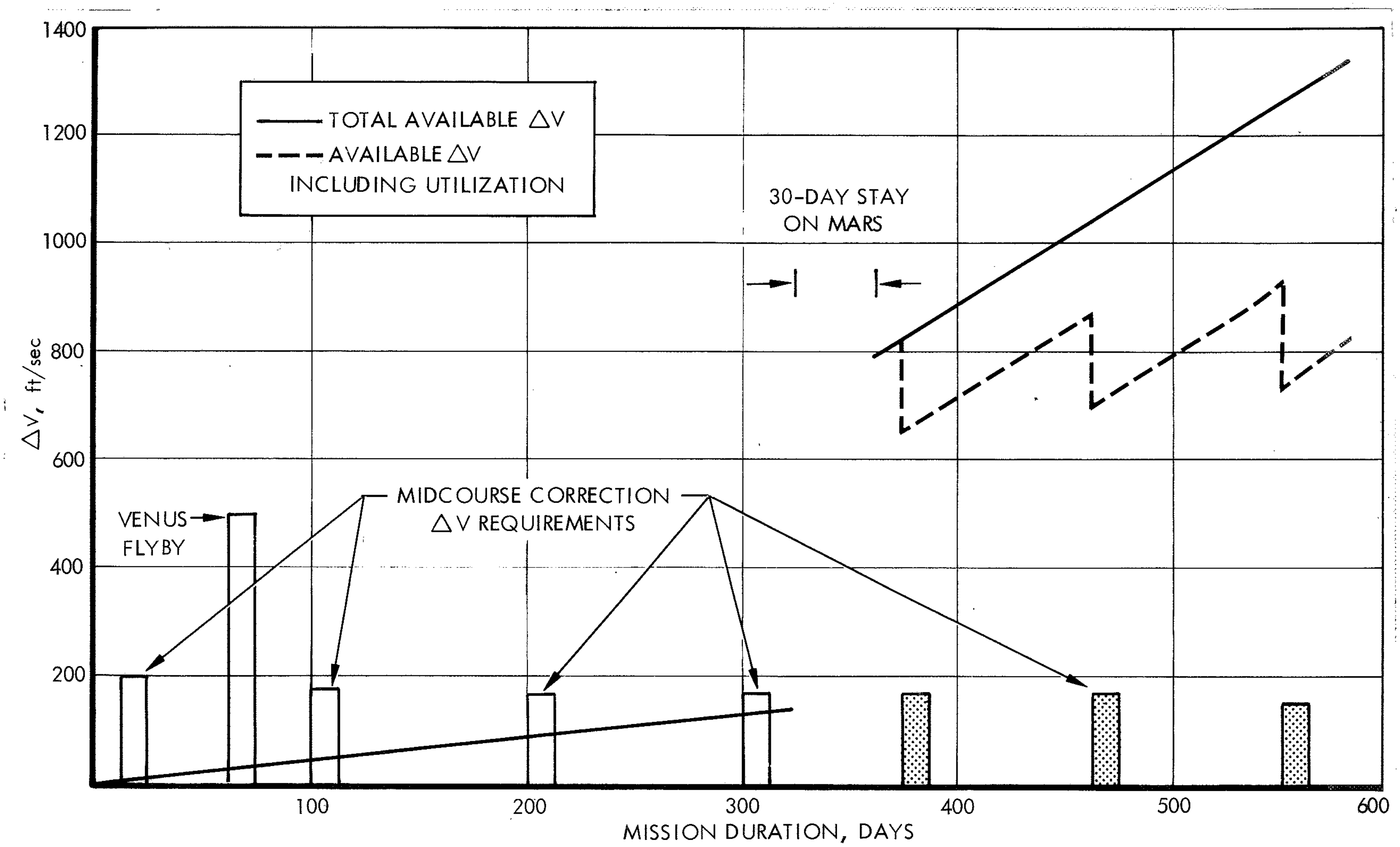

FIGURE 7. - APPLICATION OF WASTE PROPULSION TO MIDCOURSE CORRECTIONS FOR MARS LANDING MISSION (6-MAN CREW) - NAA STUDY

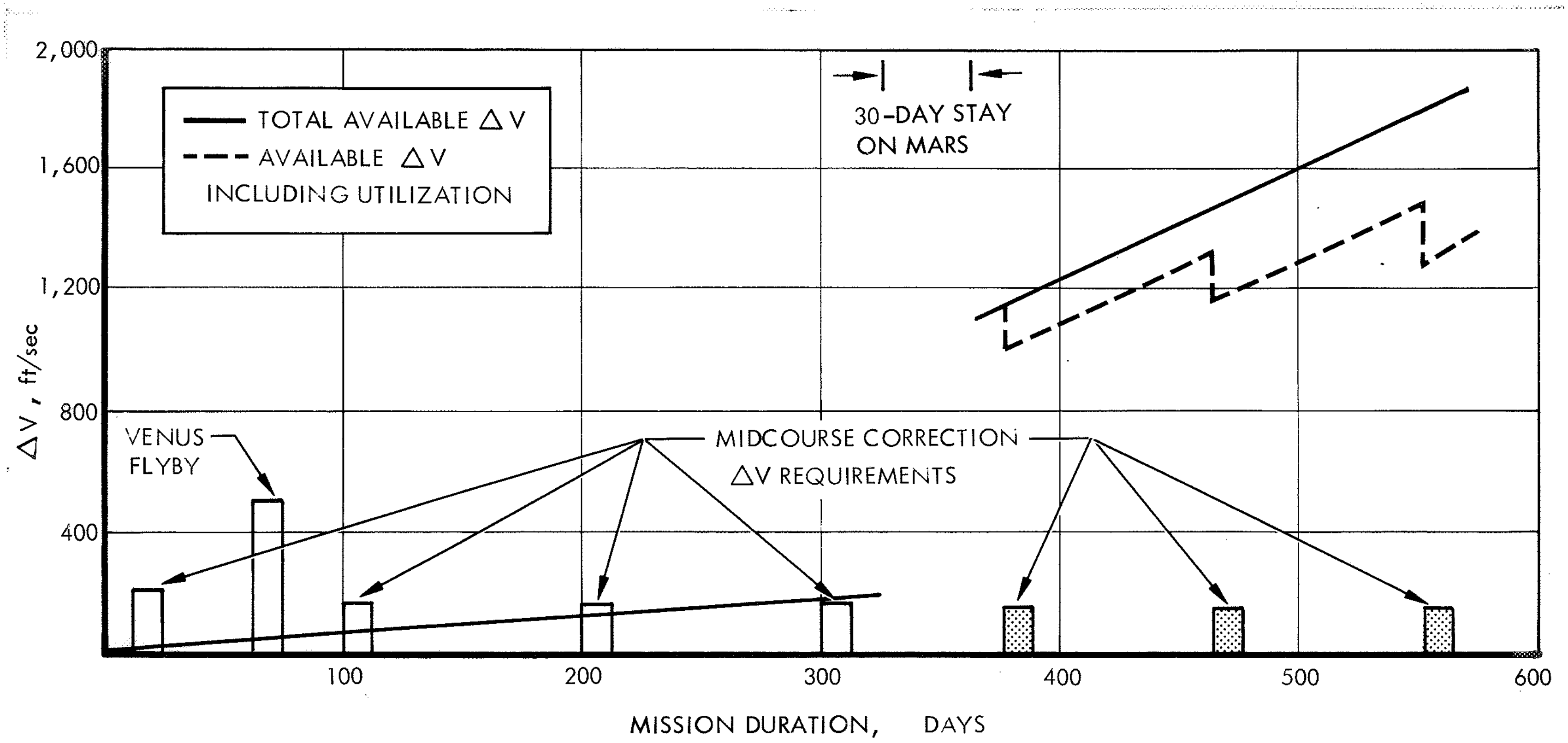

FIGURE 8. - APPLICATION OF WASTE PROPULSION TO MIDCOURSE CORRECTIONS FOR MARS LANDING MISSION (10-MAN CREW) - NAA STUDY

2.3 SUMMARY - MISSION SURVEY

A literature search was conducted to determine the available types and quantities of wastes that can be utilized in an integrated waste management propulsion system. It was discovered that available wastes vary, depending upon the type of life support system used. This led to a review of life support system plans. The results of this review are summarized in Table 24.

The greatest quantities of waste would be available in systems where water is not reclaimed from urine. These relatively "wet" systems allow a higher specific impulse waste propellant than is obtainable in systems where less water is available. Rocket Research Corporation's calculations for a "dry" formulation with 45 percent waste, 25 percent aluminum, and 30-percent ammonium nitrate have a vacuum specific impulse of 229 lbf-sec/lbm compared to 265 lbf-sec/lbm of vacuum specific impulse estimated for "wet" formulations with 45-percent waste (calculations based upon 90-percent efficiency and 50:1 area ratio). The available waste materials are also determined by the type of oxygen recovery process. The Bosch process produces carbon, which is usable in a waste propellant and is preferred to the Sabatier process, which produces methane. If water is reclaimed from fecal matter, the amount of available wastes will also be reduced. Since the process of recovering water from feces is relatively difficult, however, it is not expected to be employed in the near future.

A mission analysis was conducted to determine the relationship of available waste propulsion to propulsion requirements on advanced manned space missions. Information was obtained from discussions with NASA and reviews of several prime contractor's studies on advanced missions. The following studies were reviewed in detail:

a. Douglas Manned Orbital Research Laboratory (MORL) Mission Study

b. NAA Manned Mars and/or Venus Flyby Vehicle Systems Studies

c. Lockheed-Empire Planetary Flyby Mission Study

d. General Dynamics Manned Mars and Venus Exploration Study (MAVES)

e. TRW Manned Mars Landing Mission Study

f. NAA Manned Mars Landing and Return Mission Study

From the results of the mission survey, the following applications for an Integrated Waste Management Rocket Propulsion System appear feasible:

a. Drag makeup for MORL-type vehicles where the crew size is at least six men, the vehicle orbit is at least 164 nautical miles high, or Brayton power supply is used in place of solar panels. Application in these instances will depend on the results of engine tests indicating whether or not the MONEX W system is suitable for numerous repeated (or intermittent) firings at the required thrust level.

TABLE 24

SUMMARY OF SPACE MISSION WASTE PRODUCTS
USABLE FOR MONEX W PROPULSION

(lbs per man-day)

	MORL 6-Man Crew	NAA Flyby	EMPIRE Flyby	MAVES Landing	TRW Landing	NAA Landing
Feces	0.34	0.33	0.34	0.34	0.33	0.33
Urine residues	0.15	0.15	0.15	0.15	0.60 (wet)	0.21
Carbon	--	0.55	0.61	0.63	--	0.54
Miscellaneous waste[a]	0.25	0.65	0.20	0.20	0.97	0.27
Total net waste	0.74	1.68	1.30	1.32	1.90	1.35

[a] Estimated

b. Spin/despin operations for the MORL vehicle if the number of operations can be limited to fewer than conceived in the original studies (spin-up/despin every 150 days instead of every 90 days).

c. Midcourse corrections for the return leg of planetary landing missions. Potential cases are shown in the TRW and NAA Mars landing missions. In these instances a large weight difference occurs between the outward-bound and inward-bound vehicles, and different propulsion systems are expected to handle the midcourse correction requirements. Application of an Integrated Waste Management/Rocket Propulsion System eliminates the necessity of throttling down large engines originally used for orbit escape.

d. Spin/despin requirements during both planetary flyby and planetary landing missions. Little information concerning these requirements is available in the studies reviewed. Additional study of such applications is necessary.

e. Midcourse corrections for the return leg of planetary flyby missions. The manned space flyby missions to reconnoiter both Mars and Venus have requirements for midcourse guidance that can be achieved in many instances with an Integrated Waste Management/Rocket Propulsion System. The propulsion requirements can most effectively be met on missions where the waste propulsion is used on the return leg, utilizing wastes generated on both legs of the mission. This application would generally require a large change in vehicle weight in the vicinity of the planet in order to justify carrying the waste management propulsion system for return maneuvers only. In certain cases, the conventional propulsion system providing the outbound midcourse propulsion requirements may also be capable of performing the inbound propulsion requirements with additional propellant. In these cases, it should be determined by further systems analysis whether jettison of this system and use of a waste management propulsion on the return leg would provide an overall advantage.

f. To provide auxiliary or emergency propulsion capability for midcourse, attitude control, or spin/despin requirements.

g. To reduce the braking requirements of the return retrorocket system on earth arrival and reduce the heat shield weight requirements.

A preliminary weight analysis has been conducted to compare a waste management propulsion system with a conventional N_2O_4/Aerozine-50 bipropellant propulsion system. This system comparison shows that the waste propulsion system is lighter in weight than the conventional system over a wide variation in payload weight and ΔV requirements. A more comprehensive analysis would be desirable to more accurately define the advantages in system performance.

The mission survey reported here has revealed many potential applications of an Integrated Waste Management/Rocket Propulsion System. Integration of a life support system with a waste propulsion system is expected to alter total mission design. Therefore, some recommendations are given for the planning of future missions in order to make maximum use of the waste management propulsion system. Possibly these recommendations will give a guideline to the design of interplanetary mission vehicles that are especially tailored to include waste propulsion systems. Inclusion of a waste management propulsion system in already existing, highly integrated mission profiles would not take maximum advantage of the system. A more effective integration would be possible if integration occurs in a very early stage of mission design.

Considerations leading to the selection of crew size are usually determined by the tasks to be performed, by the capacity of the vehicle, and by life support requirements. Limitations to crew size will be considered less stringent if it can be shown that by using a waste propulsion system, it is possible to increase the crew size with fewer weight penalties as compared to a nonintegrated system. Increasing the crew size provides more waste and thus more waste propulsion capability. Total vehicle weight does not generally increase in the same ratio as crew size.

Food packaging constitutes a considerable portion of the available wastes. As no standards exist at this time for the packaging of food for long-duration space missions, the choice of packaging materials may be selected on the basis of providing maximum benefit to a waste propulsion system.

3.0 THEORETICAL PERFORMANCE OF MONEX W

3.1 THEORETICAL PERFORMANCE CALCULATIONS

Theoretical performance calculations for MONEX W were performed by the Service Bureau Corporation, San Jose, California. These calculations were obtained primarily for use in interpretation of engine test firing data.

Although feces has been extensively characterized with respect to its numerous and complex specific chemical identities, including those present in trace quantities (Refs. 71, 72), a preliminary search of the literature has revealed no reported values of overall elemental analysis, even with respect to the most common elements. It was necessary, therefore, to determine experimentally a representative value for the elemental composition of feces. This analysis is reported in Par. 4.1.3.4.

The method used to calculate the approximate heat of formation of feces and urine is described in Appendix A. Inasmuch as the majority of the propellant studies employed feces as the sole waste component, the major portion of the calculations were those of compositions containing aluminum, ammonium nitrate, feces, and the M-1 burning rate additive as ingredients. Detailed performance data for selected cases appear in Appendix B. Calculations for several wet MONEX W compositions (urine-to-feces ratio of 8:1) were computed for comparison and are also presented in Appendix B.

Theoretical specific impulse (1,000/14.7 psia) of MONEX W (only feces as waste) as a function of propellant composition is shown in Fig. 9. Contours of constant specific impulse are depicted for the region of interest (20- to 55-percent waste). In Fig. 10, theoretical chamber temperatures are also plotted as a function of propellant composition for the same conditions. Fig. 10 exhibits a significant plateau at 2,318°K, corresponding to the melting point of aluminum oxide. The width of this plateau, as expected, increases with increasing aluminum content of the composition because a larger portion of available heat is required for the melting of aluminum oxide. Although not revealed in the current calculations, similar but larger plateaus are expected at very high aluminum concentrations. Within these regions, aluminum oxide is expected to appear in both solid and liquid form in the combustion chamber.

In order for combustion of MONEX W to proceed at temperatures lower than the melting point of aluminum oxide, it would probably require the combustion of aluminum particles to proceed via a mechanism involving diffusion through a solid aluminum oxide coating, regardless of whether aluminum vapor or oxidizing gases were involved in the diffusion process. Above the melting point of aluminum oxide, oxidation may be expected to proceed by rupture of a fluid aluminum oxide coating surrounding the particle (Refs. 73 and 74). The fact that certain MONEX W formulations possess a theoretical chamber temperature less than the melting point of aluminum oxide does not necessarily imply that they cannot be fired in a monopropellant engine but rather that a major change in the combustion mechanism, including reaction rates, will probably occur. As implied by the performance calculations, certain formulations with combustion temperatures less than the melting point of aluminum oxide would be

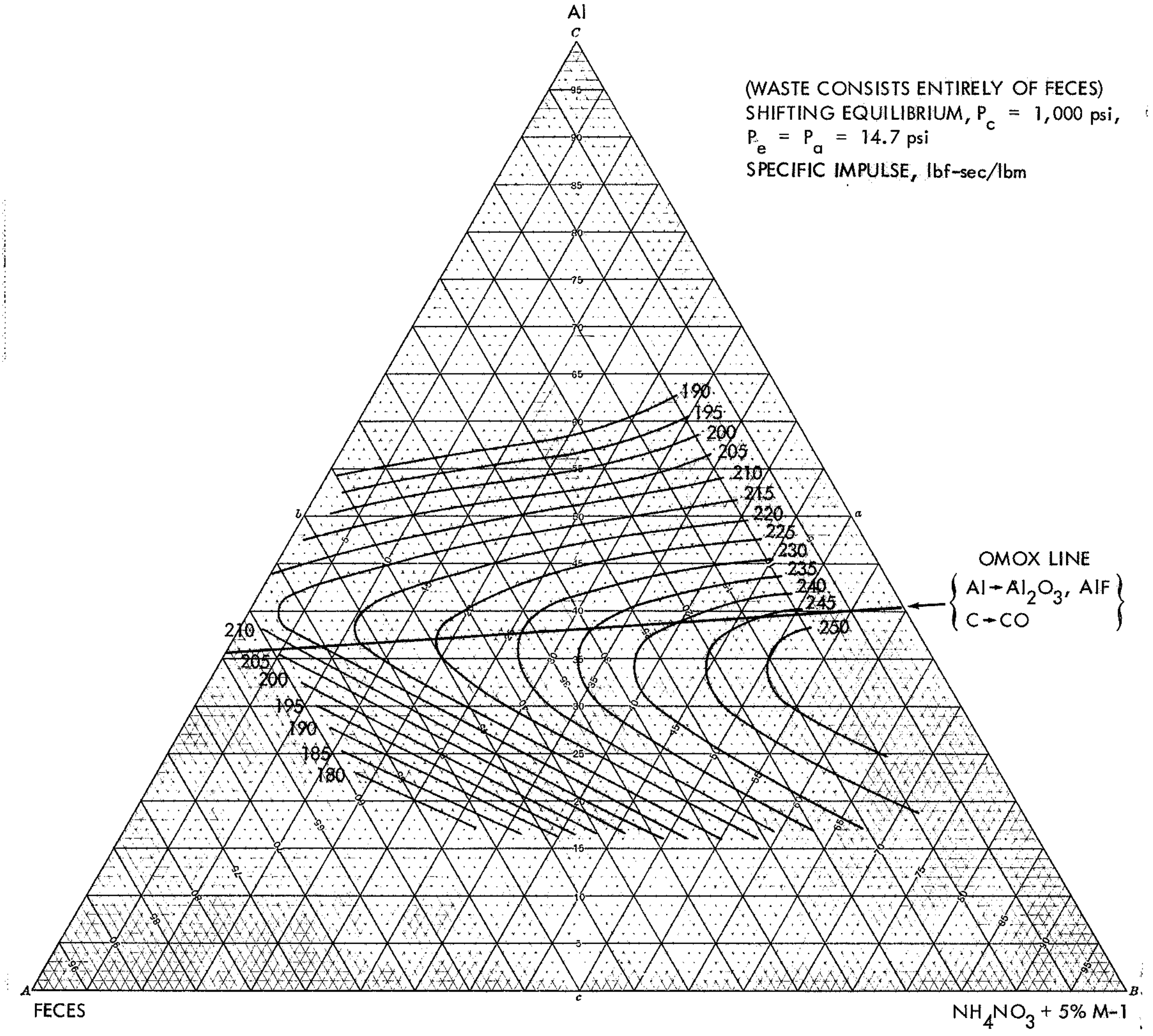

FIGURE 9. - THEORETICAL SPECIFIC IMPULSE AS A FUNCTION OF COMPOSITION MONEX W (DRY)

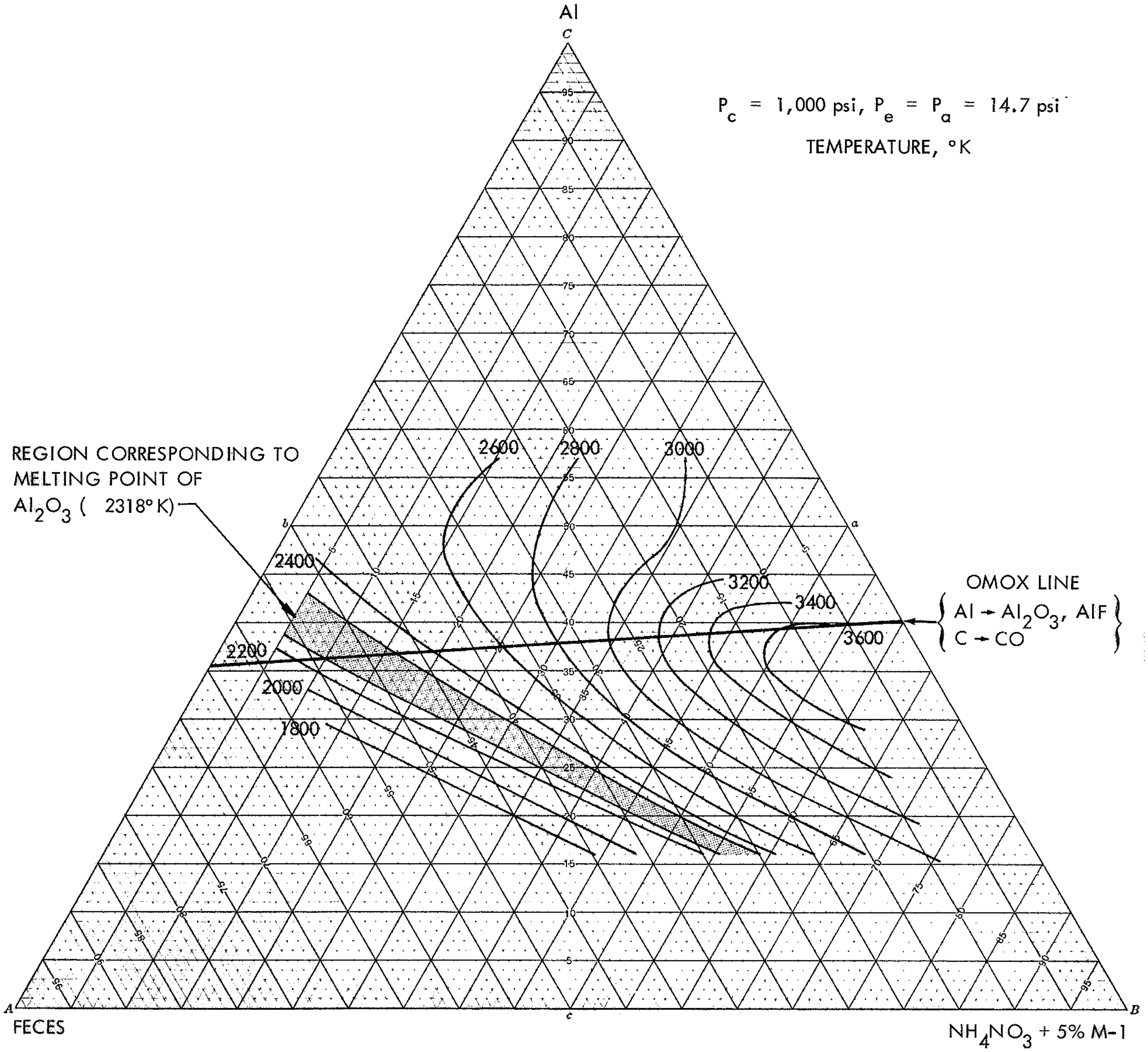

FIGURE 10. - THEORETICAL CHAMBER TEMPERATURE AS A FUNCTION OF COMPOSITION MONEX W (DRY)

attractive for use in the Integrated Waste Management/Propulsion System if they could be fired successfully.

Theoretical specific impulse of a wet MONEX W (urine-to-feces ratio of 8:1) as a function of composition appears in Fig. 11. Performance of the wet MONEX W is generally somewhat higher than that of compositions containing only feces as the waste component, presumably due to the increased carbon content of the latter. As corresponding flame temperatures are also higher (see Fig. 12), it is expected that a larger range of propellant compositions, including those of higher waste content, can be successfully fired in rocket engines. Furthermore, the formations containing urine are expected to be considerably more fluid, leading to better atomization at the injectors and subsequent improved performance (see Par. 4.2.5).

In addition to the I_{sp}, other propellant properties, e.g. the combustion properties and spray characteristics are influenced by variations in composition. If the feces content of MONEX W were too high, it would become difficult to maintain stable combustion and to ignite the propellant. Conversely, MONEX W propellants too low in feces content would be expected to exhibit poor transport characteristics and cause difficulties when being forced through injector orifices. Even though the acceptable variation is wide, definite limits with appropriate margins must be defined. In selecting a composition for practical application, a minimum variation of total impulse delivered as a function of composition is desirable. Similarly, an I_{sp} optimization of the NH_4NO_3 to Al ratio may be performed for a given fixed waste content.

The primary exhaust species from the waste management propellants are solid aluminum oxide particles and hydrogen gas. The hydrogen is formed by the reaction of aluminum with water as well as by decomposition of organic fecal matter and ammonia from the ammonium nitrate. Lesser gaseous species (presented on a mole percentage basis in Table 25) include carbon monoxide, nitrogen, water, hydrogen fluoride, aluminum fluoride, and carbon dioxide. The nitrogen arises primarily from the ammonium nitrate present in the propellant, carbon and carbon dioxide from the organic portion of the waste, and the hydrogen fluoride from the M-1 additive. At aluminum concentrations in the vicinity of stoichiometric compositions and at even higher aluminum concentrations, however, the concentration of hydrogen fluoride is minimal as the fluorine exists primarily as aluminum fluoride. It is not known presently if M-1, the source of fluorinated species in the exhaust, will actually be used. In a single test which was performed, little difference was observed in the performance of propellant with and without the M-1 burning rate additive.

3.2 VARIATION OF IMPULSE WITH WASTE CONTENT

Varying propellant composition must be expected for the waste management propulsion system. Waste production data used so far are average values that are subject to variations. Throughout the mission survey (Sec. 2.0), a propellant composition containing 45-percent waste was considered. For the purpose of this study, it will be assumed that delivered waste variations result in MONEX W compositions with ±5-percent waste, i.e. the relative

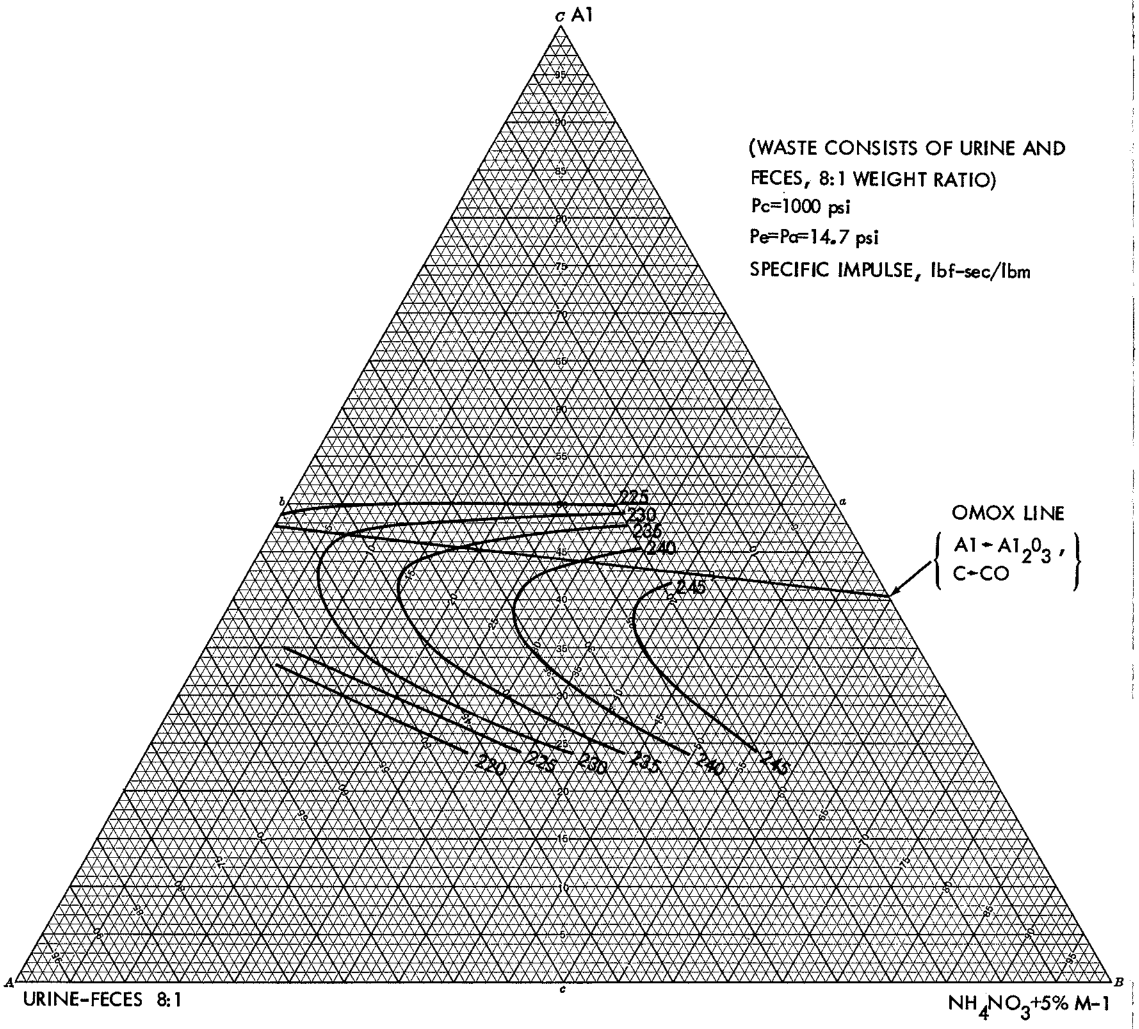

FIGURE 11.-THEORETICAL SPECIFIC IMPULSE (SHIFTING) AS A FUNCTION OF COMPOSITION

MONEX W (WET)

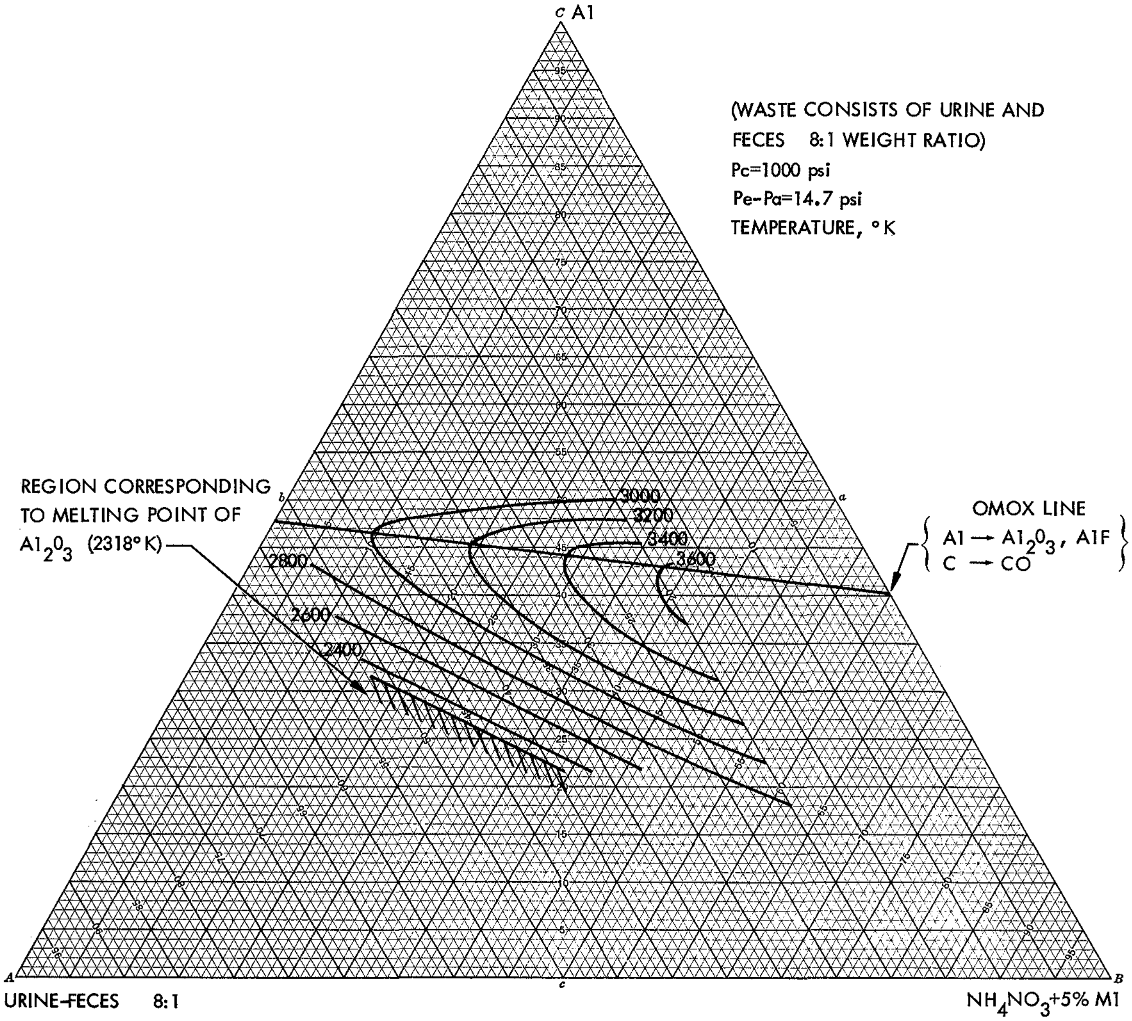

FIGURE 12.- THEORETICAL CHAMBER TEMPERATURE AS A FUNCTION OF COMPOSITION

MONEX W (WET)

TABLE 25

THEORETICAL EXHAUST SPECIES OF SELECTED "DRY" MONEX W COMPOSITIONS

Propellant Composition, % by Weight						
Case Number[(a)]	19	12	1	6	5	26
Aluminum	38.0	38.0	38.0	38.0	38.0	38.0
Ammonium Nitrate	47.5	38.0	28.5	19.0	9.5	0.0
Feces	9.5	19.0	28.5	38.0	47.5	57.0
M-1	5.0	5.0	5.0	5.0	5.0	5.0
Major Gaseous Exhaust Species	Mole % Gas					
H_2	57.5	63.1	66.3	71.7	78.8	81.8
N_2	22.4	16.8	11.8	6.6	4.5	1.1
CO	8.4	12.1	15.0	16.9	12.8	12.6
H	2.9	.8	.2	.04	.02	.002
AlF	4.0	4.7	5.7	2.2	.6	.0006
HF	3.1	1.8	.4	.8	1.1	2.9
H_2O	1.0	.15	.01	.003	.004	.02
Minor Gaseous Exhaust Species	Mole % Gas					
AlF_3	.02	.07	.06	1.0	1.5	1.1
CO_2	.02	.005	--	--	--	--
Ca	.13	.11	.06	.04	--	--
AlF_2	.07	.09	.06	.09	.05	--
HCN	.0004	.004	.12	.23	.14	--
AlOF	.22	.05	--	--	--	--
PN	.09	.18	.25	.30	.34	.24
Condensed Phases Moles/100 gm Exhaust						
Al_2O_3 (S)[(b)]	0.00	0.24	0.61	0.61	0.67	0.69
Al_2O_3 (L)[(b)]	0.65	0.39	0.00	0.00	0.00	0.00
CaO (S)	0.00	0.005	0.01	0.02	0.02	0.02
C (S)	--	--	--	0.05	0.31	0.43

(a) Case numbers refer to computer print-outs in Appendix B

(b) (S) = Solid, (L) = Liquid

deviation from nominal waste content, for example, would be ±11-percent in case of 45-percent waste and ±10-percent in case of 50-percent waste.

The ammonium nitrate:aluminum ratio is fixed by the supply of propellant ingredients stored on board the spacecraft. In some cases, it might even be predetermined by mixing ammonium nitrate and aluminum together before launch, thus saving weight for additional storage containers and metering devices.

Because exact machine data over the range of compositions considered are currently available only for the conditions of 1,000 psi chamber exhausting to 14.7 psi, the calculations have been performed for this case rather than expansion to vacuum. This is justified inasmuch as the relative variation with change in composition is essentially the same for both I_{sp} and $I_{sp\ vac}$. The relative variation also is expected to be similar for compositions containing miscellaneous waste (feces, carbon, paper) or feces only. Calculations in this section are based on utilization of feces as the only waste source, as the delivery of feces is the main variable to be expected.

For the following discussion, two compositions from extreme regions of the triangular diagram (Fig. 9) have been selected. The Composition A is situated in an area with steepest variation of I_{sp} with waste content, and Composition B is situated in an area with little variation:

Composition A	40% Feces, 26% Al, 29% NH_4NO_3, 5% M-1
Composition B	28% Feces, 38% Al, 29% NH_4NO_3, 5% M-1

Composition A yields a theoretical I_{sp} of 220 lbf-sec/lbm; Composition B yields a theoretical I_{sp} of 235 lbf-sec/lbm. Similar compositions have been successfully test fired under this program. The ammonium nitrate:aluminum ratio is kept constant throughout variation of feces content within each composition. In discussing the influence of delivered waste on performance, we have to differentiate between the effect on specific impulse and the effect on available total impulse. Data compiled in Table 26 and plotted in Fig. 13 demonstrate that specific impulse of Composition A possesses a much more pronounced dependence on feces content than Composition B.

In order to show the influence of variable waste accumulation and utilization on total achievable impulse, a nominal waste accumulation of 100 pounds with a variation from 80 to 120 pounds was assumed. The amount of AN and Al available remained constant. Results shown in Fig. 14 and Table 27 indicate that total impulse varies from -3.0 percent to +2.5 percent over the range of 80 to 120 pounds of feces available in the case of Composition A. In spite of the fact that Composition B shows a less pronounced variation of I_{sp} with percent of waste, the total impulse delivered varies more than that of Composition A, namely from -6.2 to +5.0 percent. As it is desirable to utilize a composition with the least variation of total impulse with waste input, Composition A is preferable to Composition B. Composition A also exhibits advantages in that similar compositions have proved to give good combustion

TABLE 26

VARIATION OF SPECIFIC IMPULSE WITH FECES CONTENT

Composition	Nominal (% Feces)	Relative Variation (%)	Actual (% Feces)	I_{sp} (1,000/14.7 psia) (lbf-sec/lbm)	ΔI_{sp} (%)
A	40	+20	48	194	-13.4
		+10	44	210	- 4.8
		+ 5	42	215	- 2.3
		± 0	40	220	±00
		- 5	38	225	+ 2.2
		-10	36	230	+ 4.3
		-20	32	235	+ 6.4
B	28	+20	33.6	233	- 0.85
		+10	30.8	234	- 0.43
		+ 5	29.4	234.5	- 0.21
		± 0	28.0	235	± 0.0
		- 5	26.6	234.5	- 0.21
		-10	25.2	234	- 0.43
		-20	22.4	232.5	- 1.08

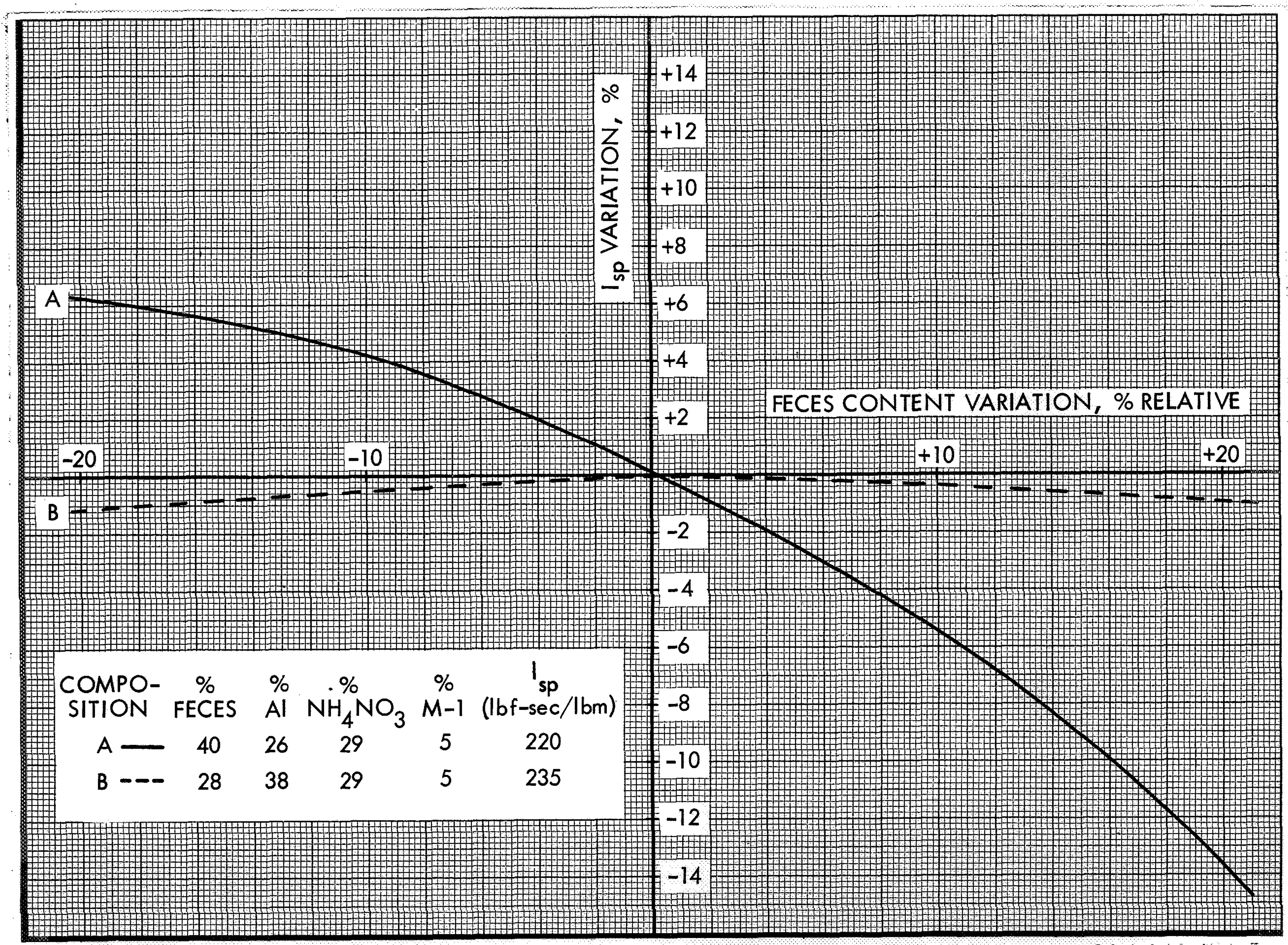

FIGURE 13. - VARIATION OF I_{sp} WITH FECES CONTENT OF MONEX W

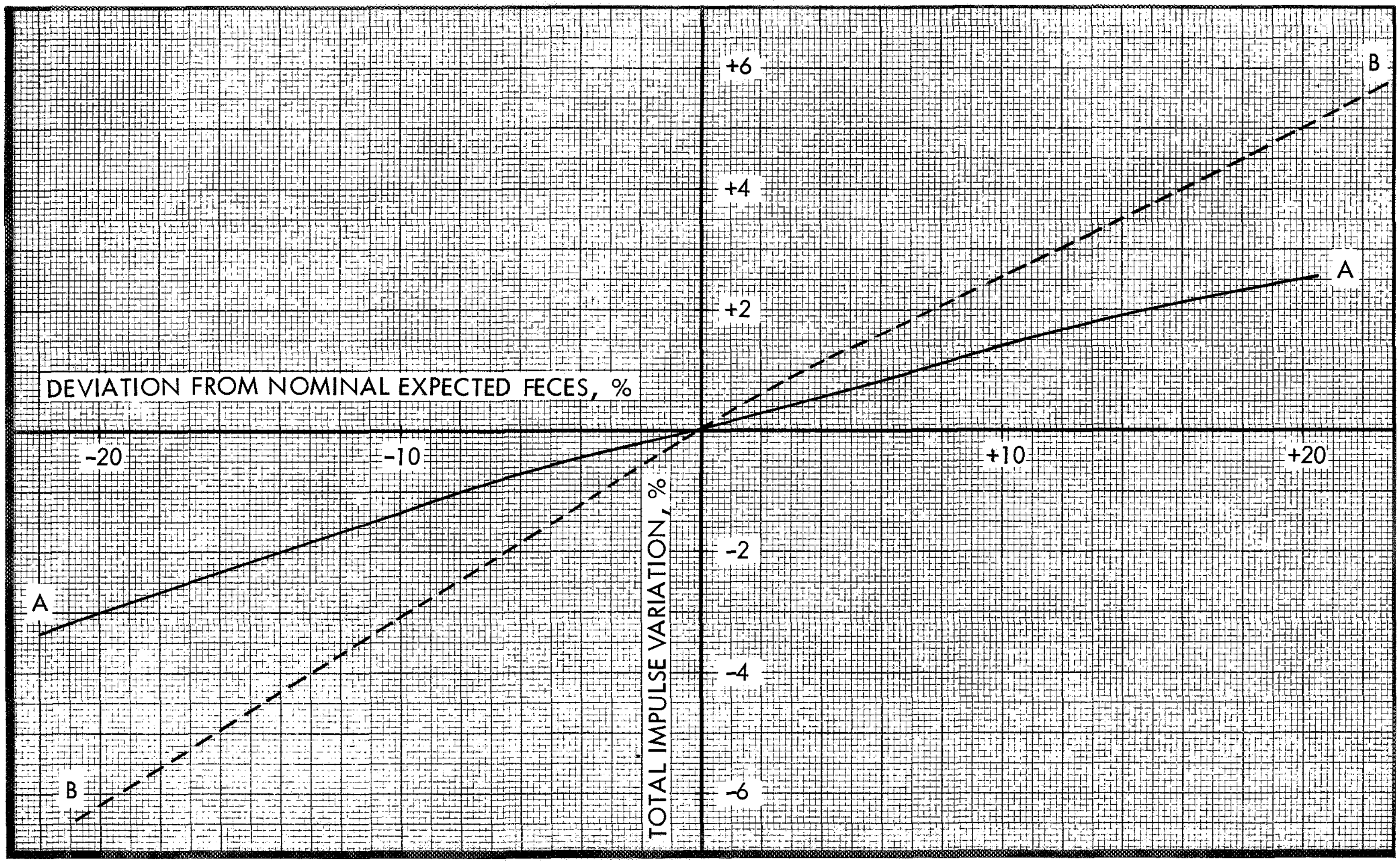

FIGURE 14. - VARIATION OF TOTAL IMPULSE WITH AVAILABLE FECES

TABLE 27

VARIATION OF TOTAL IMPULSE WITH FECES INPUT

Composition	Relative Variation in Feces Input (%)	Feces (lb)	AN + Al + M-1 (lb)	Waste (%)	Waste Propellant (lb)	I_{sp} (1,000/14.7 psia) (lbf-sec/lbm)	Total Impulse (lbf-sec)	Δ Impulse (lbf-sec)	Relative Variation (%)
A	-20	80	150	34.8	230	232.0	53,360	-1,640	-3.0
	-10	90	150	37.5	240	226.0	54,240	- 760	-1.4
	- 5	95	150	38.8	245	223.2	54,684	- 316	-0.6
	± 0	100	150	40.0	250	220.0	55,000	0.00	±0.0
	+ 5	105	150	41.2	255	217.2	55,386	+ 386	+0.7
	+10	110	150	42.3	260	214.6	55,796	+ 796	+1.4
	+20	120	150	44.4	270	208.8	56,376	+1,376	+2.5
B	-20	80	258	23.7	338	233.4	78,889	-5,241	-6.2
	-10	90	258	25.9	348	234.3	81,536	-2,594	-3.1
	- 5	95	258	26.9	353	234.6	82,814	-1,316	-1.6
	± 0	100	258	28.0	358	235.0	84,130	0.00	±0.0
	+ 5	105	258	28.9	363	234.7	85,196	+1,066	+1.3
	+10	110	258	29.9	368	234.3	86,222	+2,092	+2.5
	+20	120	258	31.7	378	233.7	88,339	+4,209	+5.0

efficiency. This may be due to the low aluminum content. High aluminum content (also in solid propellants) freqently leads to poor combustion efficiency and excessive slag formation. It is surprising to note that the total delivered impulse of Composition B increases in spite of a decrease in specific impulse. This is due to more propellant becoming available if the feces input is higher than expected.

The purpose of these calculations is to show that the waste management rocket propulsion system is very insensitive to variations in amount of waste delivered. It may easily be adapted to different waste accumulation situations on board a spacecraft (variation in crew size, metabolic rates, change in diet, etc.). The variation considered in this example is excessive compared to the actual situation, since the available waste will not vary that much. If waste production (mainly feces) drops below the nominal expected value, the corresponding amount of unused food may be used as propellant.

4.0 LABORATORY INVESTIGATION

After preliminary analytical work to develop suitable techniques for the analysis of feces, especially for water content, major emphasis was placed on developing propellant formulations suitable for use with an injection-type engine, since this appears to be the most desirable mode for utilizing MONEX W propellants. Propellant processing techniques and equipment were evaluated. Methods of propellant analysis were developed, and a suitable means of screening propellant for biological activity was determined. Numerous physiochemical and safety characteristics were determined to obtain a firm foundation for future work in this area. A three-phase test engine program demonstrated the feasibility of the waste management concept. Finally, waste from a manned spacecraft simulation experiment was characterized.

4.1 PROPELLANT PROCESSING

Similar processing techniques were used for both large and small-scale propellant preparations. The initial step was the homogenization of a suitable quantity of feces in a commercial blender. Both Waring blenders and Osterizers were used for small batches, but a 12-speed electric food mixer (Sears, Roebuck & Co.) proved to be more suitable for batches larger than 2 lbs.

The blending of feces produced a thick, homogeneous paste to which ammonium nitrate was added. Solution of the ammonium nitrate in the feces was endothermic. The thick paste of feces was also liquified by this process. Aluminum powder was then incorporated, followed by carbon black or any other additives. The mixture became more viscous as the solids loading increased. In the range of formulations tested, there was no visual observation of solids settling even after periods of greater than 500 days (W-1, W-22[a]), (Table 28).

In the large-scale batches prepared for injection spray testing or engine firings, an additional step of filtering the propellant through a 16- or 24-mesh screen was added to ensure that no large particles remained that could plug the injector orifices.

4.1.1 Propellant Ingredients

In the following paragraphs the main propellant ingredients employed in the laboratory preparation of waste management propellant are described and their functions discussed.

4.1.1.1 Aluminum Metal

Source: All aluminum metal powder employed was spherical 5-micron material (H-5 grade) obtained from the Valley Metallurgical Corporation.

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[a] W-numbers refer to MONEX W compositions listed in Table 28.

TABLE 28

MONEX W PROPELLANT FORMULATIONS

Composition (Wt. %)	W-1	W-2	W-3	W-4	W-5	W-6	W-7	W-8	W-9	W-10	W-11	W-12	W-13	W-14	W-15	W-16	W-17	W-18	W-19	W-20	W-21	W-22
Al H-5	35.0	25.0	15.0	15.0	9.99	8.84	20.0	23.6	10.0	22.5	17.0	19.8	25.0	20.0	20.0	20.0	25.0	25.0	21.2	22.0	22.1	24.0
NH_4NO_3	40.0	40.0	25.0	20.0	29.97	26.53	30.0	37.7	30.0	36.0	36.3	29.7	40.0	40.0	40.0	40.0	40.0	40.0	33.9	35.2	35.4	38.5
Feces	25.0	30.0	50.0	50.0	49.95	44.20	40.0	25.0	50.0	27.0	31.5	39.6	28.0	28.0	25.0	20.0	28.0	28.0	23.7	30.0	23.5	24.0
Carbon	--	5.0(b)	10.0(a)	15.0(a)	9.99(b)	20.34(b)	10.0(c)	10.0(c)	10.0(c)	12.2(b)	11.6(b)	9.9(c)	4.0(c)	8.0(c)	10.0(c)	15.0(c)	--	7.0(c)	4.2(c)	9.3(c)	15.5(c)	9.6(c)
Polyethylene(d)	--	--	--	--	--	--	--	--	--	--	--	--	3.0	4.0	5.0	5.0	7.0	--	17.0	--	--	--
Dowicil(e)	--	--	--	--	0.10	0.09	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
M-1(f)	--	--	--	--	--	--	--	3.7	--	--	--	--	--	--	--	--	--	--	--	3.5	3.5	3.9
Lomar D(g)	--	--	--	--	--	--	--	--	--	--	--	1.0	--	--	--	--	--	--	--	--	--	--
Polyox WSR-301(h)	--	--	--	--	--	--	--	--	--	2.3	3.6	--	--	--	--	--	--	--	--	--	--	--

Composition (Wt. %)	W-25	W-27	W-29	W-30	W-31	W-32	W-33	W-34	W-35	W-36	W-37	W-38	W-40	W-41	W-42	W-43	W-49	W-50	W-51	W-52	W-53	W-54	W-55	W-56	W-57
Al H-5	32.0	30.0	28.0	28.0	24.0	21.0	31.0	28.0	24.0	21.0	31.0	24.0	32.17	20.5	32.10	33.79	24.70	23.75	22.80	21.85	20.90	38.0	28.5	28.5	38.0
NH_4NO_3	33.0	25.0	17.0	37.0	31.0	24.0	44.0	37.0	31.0	24.0	44.0	30.0	28.85	23.4	28.53	30.03	41.80	36.10	29.45	23.75	20.90	28.5	38.0	19.0	9.5
Feces	35.0	45.0	55.0	28.0	36.0	44.0	20.0	28.0	36.0	44.0	20.0	35.0	34.77	42.9	34.37	36.18	22.69	27.98	34.03	39.32	42.35	28.5	28.5	47.5	47.5
Carbon(c)	--	--	--	7.0	9.0	11.0	5.0	--	--	--	--	6.0	--	10.7	--	--	3.88	4.78	5.81	6.72	7.24	--	--	--	--
Polyethylene(d)	--	--	--	--	--	--	--	7.0	9.0	11.0	5.0	3.0	--	--	--	--	1.93	2.39	2.91	3.36	3.61	--	--	--	--
M-1(f)	--	--	--	--	--	--	--	--	--	--	--	2.0	4.21	2.5	5.00	--	5.00	5.00	5.00	5.00	5.00	5.0	5.0	5.0	5.0

(a) Darco G-60 Carbon

(b) Carbon from Bosch reactor

(c) Norit A charcoal

(d) Formula 1914A, 50 mesh powdered polyethylene, Eastman Chemical Products

(e) Antimicrobial agent: 1-(3-chloroallyl)-3, 5, 7-triaza-1-azoniaadamantane chloride-Dow Chemical Company

(f) Burning rate additive

(g) Wetting agent for aqueous dispersions of carbon black, NOPCO Chemical Company

(h) Water soluble resin, Union Carbide Corporation

TABLE 28 (Concluded)

MONEX W PROPELLANT FORMULATIONS

Composition (Wt. %)	W-58	W-59	W-60	W-61	W-62	W-63	W-64	W-65	W-66	W-67	W-68	W-69
Al H-5	31.94	32.10	32.10	38.00	47.5	24.0	24.0	38.5	37.0	32.10	45.00	45.00
NH_4NO_3	28.39	28.53	28.53	19.00	--	30.0	30.0	33.5	15.0	28.53	12.00	19.00
Feces	34.20	3.82	3.80	38.00	47.5	35.0	35.0	23.0	43.0	27.34	38.00	31.00
Carbon(a)	--	--	--	--	--	--	--	--	--	4.69	--	--
M-1(b)	4.97	5.00	5.00	5.00	5.0	2.0	--	5.0	5.0	5.00	5.00	5.00
Polyethylene(c)	--	--	--	--	--	3.0	--	--	--	2.34	--	--
Polyox WSRN-10(d)	0.50	--	--	--	--	--	--	--	--	--	--	--
Urine	--	30.55	30.27	--	--	--	--	--	--	--	--	--
Kelzan(e)	--	--	0.30	--	--	--	--	--	--	--	--	--
Ferric carbide	--	--	--	--	--	6.0	11.0	--	--	--	--	--

(a) Norit A charcoal

(b) Burning rate additive

(c) Formula 1914A, 50-mesh powdered polyethylene, Eastman Chemical Products

(d) Water-soluble polymer of ethylene oxide, Union Carbide Corporation

(e) Gelling agent, Kelco Company

Functions:

a. The reaction of aluminum metal powder with oxygen-containing species in the propellant to form aluminum oxide provides the primary source of energy in the MONEX propellants. The high heat of formation of aluminum oxide (-384.8 Kcal/mole) constitutes the primary driving force of the combustion. In the formulations of interest (those having high waste content) the waste (e.g. feces) provided the primary oxygen source in the form of water.

b. In the case of MONEX A monopropellants ($Al/NH_4NO_3/H_2O$), the particle size of the aluminum metal powder is known to have a considerable effect on the magnitude of propellant burning rate. The burning rate in this instance increases with decreasing particle size of the aluminum powder. Use of ultrafine aluminum powder (e.g. less than one micron), however, is expected to have a detrimental effect on propellants by decreasing the storage stability. Although this effect has not been demonstrated with MONEX W, similar effects have been observed with other metal particle suspensions (Ref. 75). Since aluminum metal surfaces, on exposure to air, are always covered with a thin layer of aluminum oxide, it is expected that the high surface area presented by ultrafine aluminum powders will result in decreased propellant performance due to high oxide content of the metal.

4.1.1.2 Ammonium Nitrate

Source: All ammonium nitrate employed in formulation studies was reagent grade.

Function: Ammonium nitrate appeared to make the following contributions to the waste management propellant:

a. The presence of ammonium nitrate fluidized the semisolid feces and thus lent good flow characteristics to the propellant. The exact cause of this phenomenon is not known. It may be that the ammonium nitrate, by dissolving in the aqueous portion of the feces (approximately 68 percent by weight) increases the electrolytic strength of the medium to such a degree that the cohesive properties of the feces are destroyed. Such an effect is frequently observed with many gels when soluble ionic substances are added. In fact, only a few chemical gelling agents able to tolerate the presence of high concentrations of dissolved salts are known.

   An additional effect that may contribute to the increased fluidity of the propellant upon addition of ammonium nitrate was the increased volume of the liquid phase present brought about by the dissolution of the ammonium nitrate.

b. Ammonium nitrate also served to lower the freezing point of the waste management propellant. In the majority of waste propellant compositions considered in this program, the ammonium nitrate concentration did not exceed the saturation point at ambient temperatures.

c. The presence of ammonium nitrate also served to increase the theoretical flame temperature of the aluminum-feces system. This effect is clearly depicted in Fig. 10. Evidence from test firings of MONEX W suggested that increased combustion temperatures may contribute to increased I_{sp} efficiency.

d. High concentrations of dissolved ammonium nitrate are expected to produce a significant difference in osmotic pressure across the cell walls of bacteria present in the waste management propellant and may result in rupture of the cell walls. Although experiments have not shown that all bacteria are killed, the presence of ammonium nitrate appeared to inhibit bacterial growth in the propellant.

e. Since ammonium nitrate is the salt of a weak base and a strong acid, it behaves as a buffer to pH changes in aqueous solution. The acidity of the solution is stabilized in the vicinity of pH = 5 for moderate concentrations of ammonium nitrate. This effect is expected to contribute strongly to the storage stability of MONEX W propellants. Aluminum metal reacts rapidly with either basic or strongly acidic solutions, whereas reaction is very slow in near neutral solutions. This phenomenon appears related to the amphoteric nature of aluminum hydroxide and its solubility characteristics. Gelled mixtures of aluminum powder and pure water may be stored for only short periods of time (days), whereas similar mixtures containing dissolved ammonium nitrate have been demonstrated to be stable for many months at ambient conditions.

4.1.1.3 Feces

Source: Feces were obtained as random donations by employees of Rocket Research Corporation. No dietary controls were exercised.

Function: Feces provide the sole source of water (unless a wet formulation using urine was employed) needed to fluidize the propellant. They also impart sufficient viscosity to the propellant to keep the solids in suspension over long periods of time and against acceleration forces of several g's.

4.1.1.4 Burning Rate Additive

Source: All M-1 additive employed in this program was obtained as a free-flowing powder of particle size averaging 10 microns and a density of approximately 2.0 gm/cm^3.

Function: The additive M-1 was originally included in the waste management propellant, since it had been demonstrated conclusively that M-1 markedly accelerated the strand burning rate of the monopropellant MONEX A (Al, NH_4NO_3, H_2O), which contains some of the principal ingredients of MONEX W propellant.

Since no direct correlation has been demonstrated between the monopropellant strand burning rates and performance in liquid-injection-type engines, the question of whether or not inclusion of M-1 in MONEX W propellants is advantageous has not been answered. An initial test in which MONEX W formulations with and without added M-1 were fired in a liquid injection engine under similar conditions was not conclusive, as both tests were performed with an L* of 450 inches. The residence time under these conditions was quite long; with much shorter residence times, a significant difference in combustion efficiency might well result.

4.1.1.5 Bosch Reactor Carbon

Source: Carbon from a Bosch reactor was provided by the NASA-Langley Research Center. The material, as received, was nonhomogeneous with pea-sized nodules and smaller particles mixed with powdery material. Partial elemental analysis showed 87.04-percent carbon, 9.29-percent iron, and 0.26-percent hydrogen, with the remaining 3.41 percent unaccounted for. Presumably, much of the iron was present as iron carbide (Ref. 76). The material actually used in propellant preparation was material that passed through a 24-mesh screen.

Function: Carbon is one of the waste products anticipated during a long-duration manned spaceflight that is usable as a source of fuel for waste management propellant. Both the Bosch and Sabatier systems, which have been investigated for use in manned spacecraft to reduce carbon dioxide to reclaim the oxygen, produce carbon that is apparently not usable except in waste management propellant. The Sabatier process first produces methane, but this can be converted to carbon and hydrogen.

Carbon also acts as a thickening and suspending agent when used in propellant.

4.1.1.6 Wetting Agents

Source: Three different types of wetting (or dispersing) agents were evaluated. Lomar D, a high molecular weight sulfonated napthalene condensate was obtained from the NOPCO Chemical Company of Newark, New Jersey. Polyox WSR-301 and WSR N-10, water soluble polymers of ethylene oxide, were obtained from the Union Carbide Corporation, Chemicals Division, New York, New York.

Function: The anticipated function of the wetting agents was to lower the viscosity of the propellant, thereby aiding in the mixing process and also increasing the fluidity, which would result in a better injector spray pattern. However, both qualitative and rheological testing of propellants containing these wetting agents showed that they offered only marginal improvement. (See Par. 4.2.5.)

4.1.1.7 Urine

Source: Wet MONEX W formulations employed urine as well as feces in the preparation of waste management propellant; both of these components were provided by Rocket Research Corporation personnel. Wet MONEX W formulations proved to be too fluid to keep the solids in suspension without the aid of a gelling agent. Kelzan, a gelling agent based on algin (obtained from the KELCO Company, Clark, New Jersey) was selected on the basis of prior usage in MONEX A propellants.

Function: Urine provided a source of water, which gives the propellant additional fluidity. On long manned spaceflights, urine undoubtedly would be recycled and thus not be available for propellant use except near the terminal stage of the voyage when water recovery would no longer be needed.

4.1.2 Propellant Preparation

Sixty-nine different propellant formulations were investigated during the course of the program. Their compositions are listed in Table 28.

Numerous small scale batches (50 to 250 grams) of various propellant formulations were prepared for combustion testing, rheological testing, and development of analytical procedures. Although these batches were manually blended, their consistency appeared similar to that of the large-scale batches mixed mechanically. The large-scale batches, (2 to 15 lbs) were prepared for injector spray testing, engine firings, and storage tests.

Initially, formulations were tested which contained carbon black and powdered polyethylene to simulate the dry wastes expected to be generated on board a manned spacecraft (formulations W-2 through W-19, W-13 through W-19). Because the supply of carbon from a Bosch reactor was inadequate, Norit A charcoal was used as a substitute. However, as described in Par. 4.2.10.1, Bosch reactor carbon, as currently produced, appears to be incompatible with waste management propellant and may require pretreatment prior to use. Further improvements in the operation of Bosch reactors are expected to result in recovery of carbon of higher purity.

The effect of wetting agents was tested using formulations W-10, W-11, W-12 and W-58. As described previously in Par. 4.1.1.6, these agents were not effective.

Formulations W-5 and W-6 were used to evaluate the use of Dowicil, an antimicrobial agent. A series of formulations was used to evaluate strand burning rates (Par. 5.1), while another series was used for testing to evaluate spray nozzles (Par. 4.2.5.1). Table 42 lists those formulations used in test engine firings.

4.1.3 Fecal Analysis

Satisfactory methods for the analysis of feces for water content, total nitrogen, and ash content were demonstrated. Methods of blending feces in order to obtain a uniform sample with little danger of aerosol infection to laboratory personnel were adopted. For small batches, a commercial blender, the Osterizer (John Oster Company, Milwaukee, Wisconsin), in which the sample was thoroughly blended in a tightly sealed unit, was used. By using the Osterizer in conjunction with a fume hood, the danger of aerosol contamination was minimized. The reproducibility of results from several analytical determinations on duplicate fecal samples (Tables 29 and 30) indicate that uniform blending was attained. Feces samples used for chemical analysis or propellant preparation are identified by numbers preceded by a capital F, e.g. F-42-3-22.

4.1.3.1 Water Content of Feces

Of the four methods investigated for determining the water content of feces, azeotropic distillation with benzene was selected as the preferred method, since it requires little labor, produces consistently accurate determinations and also reduces odor to a minimum. Azeotropic distillation, using a modified Dean-Stark trap, required from 4 to 6 hours for complete separation of water from feces but only a few minutes of setup time. The collected distillate possessed an offensive amine-type odor. Karl Fischer titration of an aliquot of a single distillate indicated the sample to be 99.8-percent water. Determinations of several distillates indicated variable pH even for duplicate samples (Table 29).

Oven drying of a thin film sample to constant weight was found to give good reproducibility, but the method required more working time than azeotropic distillation and also created an offensive odor.

Vacuum drying of feces with retention of the volatiles in a cold trap was rejected after a single test as being too time consuming.

An attempt was made to employ Karl Fischer titration for water determination in fecal samples, but satisfactory results were not obtained. Direct determination was not attempted, since feces did not dissolve or disperse readily in the Karl Fischer solutions. Instead, samples of feces were dispersed in absolute methanol by use of an Osterizer blender. It was anticipated that the water in the samples could be extracted quantitatively by use of a large excess of methanol or dispersed to such a degree that the water would be able to react readily with the reagent. Titrations with Karl Fischer reagent failed to give reproducible results. The end point was not sharp and faded gradually, an indication of possible side reactions with other fecal components. Titration of centrifuged methanol extracts also gave poor results.

4.1.3.2 Nitrogen Content of Feces

Total nitrogen in feces was determined by either the standard Kjeldahl method or by using a Coleman Nitrogen Analyzer. The latter is considerably more rapid when analyzing a large number of samples at one time. Nitrogen content of three lots of blended feces analyzed by the Kjeldahl method were quite similar, as shown in Table 30.

4.1.3.3 Ash Content of Feces

The ash content of duplicate fecal samples ashed in a muffle furnace showed good reproducibility. The ash content of three individual blends of feces varied by only 0.5 percent (Table 30).

4.1.3.4 Elemental Analysis

To obtain data suitable for use in theoretical performance calculations of MONEX W propellants (see App. B), it was necessary to determine values of what might be expected for the average overall composition of feces, as produced over a period of several days, based on normal nutritional intake.

TABLE 29

COMPARISON OF METHODS OF MOISTURE ANALYSIS OF FECES

Sample	Oven Drying Wt % H_2O[a]	Azeotropic Distillation Wt % H_2O	Azeotropic Distillation pH of Distillate
F-11-8-1	65.6	64.4	9.0
	66.2	64.9	8.5
	70.6		
F-11-16-1	69.1	69.5	8.1
	69.5		
F-11-16-2	64.8	66.8	8.6
	65.0	66.9	8.4
F-11-16-3	66.5	66.5	8.4
	66.7	66.6	9.0

(a)Loss in weight assumed to be water

TABLE 30

NITROGEN AND ASH ANALYSIS OF FECES

Sample	% Nitrogen	
	Coleman Analyzer	Kjeldahl
F-11-8-1	1.99	2.02
	2.25	2.02
F-11-16-1		2.08
		2.17
F-12-14-1		2.05
		2.13

Sample	Wt % Ash
F-11-16-1	3.73
	3.67
F-11-16-2	3.93
	3.98
F-11-16-3	4.27
	4.27

The fecal samples taken for analysis were obtained from two large batches of blended feces. Each batch consisted of about 5,000 grams and represented 33 individual samples. Each sample of blended feces was dried to constant weight at 110°C. Following this dehydration step, each residue was powdered and again dried to constant weight at 110°C. The samples were then transferred and weighed in an atmosphere of dry nitrogen prior to analysis in order to prevent adsorption of moisture. Dried, powdered feces are known to be quite hygroscopic. Both samples were analyzed for carbon, hydrogen, and nitrogen (see Table 31). No direct determination of oxygen was performed, and its concentration was assumed by difference.

The pH of an aqueous suspension of the dried residues was approximately 6.0. Calculations of the overall average composition of feces and its heat of formation are presented in App. A.

4.1.4 Propellant Analysis

Propellant analysis methods were tested and developed for applicability to MONEX W formulations. Table 32 shows the results of these analyses. The analytical data compared well with the theoretical content. The percentages of theoretical components do not add exactly to 100 percent, because miscellaneous other components (approximately 8.8 percent) of the feces were not included in the analysis.

Detailed procedures for the analysis of MONEX W propellant for ammonia, nitrate, aluminum, M-1, and water are presented in the following paragraphs.

4.1.4.1 Ammonia

The ammonia present as ammonium nitrate is determined by a Kjeldahl distillation method. Interference may be expected from urea and amino compounds in feces, which decompose upon boiling with caustic. The results indicate, however, that only minor amounts of ammonia are added by these reactions.

4.1.4.1.1 Preparation of Samples

As aluminum and nitrate contained in MONEX W will react upon addition of caustic according to equation

$$3\ NaNO_3 + 8\ Al + 21\ NaOH \rightarrow 8\ Al(O\ Na)_3 + 3\ NH_3 + 6\ H_2O,$$

the aluminum must be removed before the sample is placed into the Kjeldahl flask. A comparative analysis performed without prior removal of aluminum gave high and erratic results of ammonia content (Table 32). An attempt to dissolve the aluminum with acid also led to high ammonia determinations.

Therefore, the aluminum was filtered from the propellant sample as follows: A weighed sample (about 5 grams) of MONEX W was dispersed in 100 milliliters of distilled water. A Buchner funnel with a Whatman No. 2 filter paper was prepared by covering the filter paper with a 2mm layer of Celite Filter Aid and rinsing with water. One or two tablespoons of Celite were also dispersed

TABLE 31

ELEMENTAL ANALYSIS OF DRIED FECES[a]

Component	Percent by Weight Batch F-42-3-22	Batch F-42-3-28B	Average
Carbon	48.66	49.28	48.97
Hydrogen	6.67	6.16	6.41
Nitrogen	5.72	5.89	5.81
Residue	14.60	13.80	14.20
Oxygen (by difference)	24.35	24.87	24.61

(a)Dried to constant weight at 110°C

TABLE 32

RESULTS OF MONEX W COMPOSITION ANALYSIS

Batch No.	Sample Weight (milligrams)	Component	Component Weight Found (milligrams)	Found (%)	Theoretical (%)
W 54-4-24	4,837.9	NH_3	292.9	6.05	6.06
		NH_3	293.4	6.06	6.06
W 54-4-24	619.9	NH_3	53.63	8.65(a)	6.06
	612.7	NH_3	55.25	9.02(a)	6.06
W 54-6-23	7,125.4	NO_3	1,512.9	21.1	21.3
		NO_3	1,513.9	21.2	21.3
W 54-4-24	4,988.3(b)	Al	1,829.0	36.7	37.4(c)
		Al	1,833.9	36.8	37.4(c)
W 54-4-24	12,351	M-1	611.8	4.9	5.0
	12,981	M-1	602.8	4.6	5.0
W-38	2,889.8	Al	688.7	23.8	23.9(c)
		Al	691.5	23.9	23.9(c)
W 54-4-24	89,400	H_2O	19,300	21.6	21.5
	10,100	H_2O	22,000	21.8	21.5
F 54-4-24	21,800	H_2O	16,400	75.2	--
	28,950	H_2O	21,800	75.3	--

(a) Sample not filtered before addition of caustic, demonstrates effect of NO_3 reduction

(b) 10 ml aliquot used of 250 ml total

(c) Corrected for 98.36-percent assay of aluminum H-5 used in the sample to speed up the filtering process. (The use of Celite is required to prevent the 5 micron aluminum from passing through the filter.) The prepared sample was then forced through the filter with suction. The residue on the filter was washed with 100 milliliters of distilled water in 20-milliliter fractions. The filtrate was transferred quantitatively into a 250-milliliter volumetric flask which was then filled with 6 N hydrochloric acid.

Unless acid is used to stabilize the solution, the filtrate is not stable, due to bacterial deterioration. In several cases it has been observed that clear filtrates became turbid overnight due to bacteria growth. This again demonstrates that the ingredients of MONEX W inhibit bacteria growth but do not prevent all bacterial activity. Some of these bacteria may possibly consume or produce ammonia and/or nitrate.

4.1.4.1.2 Apparatus

A Precision Scientific Company Kjeldahl distilling apparatus, Model 11-X-4 (55128) with 300 milliliter Kjeldahl flasks, was used for performing the analysis. This apparatus allows the processing of two samples simultaneously.

4.1.4.1.3 Reagents

a. NaOH solution, 10 N
b. NaOH solution, 0.1 N
c. HCl, 0.1 N
d. Methyl red indicator, 0.2 percent in 90-percent ethanol

4.1.4.1.4 Ammonia Analysis Procedure

A 50-milliliter aliquot of the previously prepared sample was transferred to a 300-milliliter long-necked Kjeldahl flask containing several ceramic boiling stones. The neck of the flask was then rinsed with approximately 70 milliliters of water.

A wide-necked 250-milliliter Erlenmeyer flask, containing 50 milliliters of 0.1 N HCl and three drops of methyl red indicator solution, was placed under the Kjeldahl condenser. The drip tube of the condenser was below the fluid surface in the Erlenmeyer flask.

Immediately after adding 15 milliliters of 10 N NaOH to the sample, the Kjeldahl flask was closed and connected to the condenser. When 50 milliliters of distillate had accumulated in the Erlenmeyer flask, the flask was lowered and the internal surface of the condenser was rinsed by continuing distillation for an additional 5 minutes. The tube exterior was rinsed with water.

The contents of the Erlenmeyer flask were then back-titrated with 0.1 N NaOH solution, and the quantity of NaOH required to reach the methyl red end point was noted.

4.1.4.1.5 Calculations

The percent by weight of NH_3 was computed by the following equation:

$$\% NH_3 = \frac{(50 - X)\ (1.7032)\ (5)\ (100)}{\text{Weight of original sample (mg)}}$$

$$X = \text{ml of NaOH (0.1 N) required}$$

4.1.4.2 Nitrate

For MONEX A, the nitron procedure has been successfully used for the determination of nitrate. In the case of MONEX W, however, unidentified constituents of the feces interfere with the precipitation of nitron nitrate.

A redox titration using Fe^{++} to reduce the nitrate, as described by Kolthoff (Ref. 77), was preferred for the determination of nitrate in MONEX W.

$$2\ HNO_3 + 8\ FeSO_4 + 3\ H_2SO_4 \rightarrow 2\ Fe(NO)\ SO_4 + 3\ Fe_2(SO_4)_3 + 4\ H_2O$$

The excess Fe^{++} was back-titrated with dichromate solution, using ferroin as an indicator:

$$6\ FeSO_4 + K_2Cr_2O_7 + 7\ H_2SO_4 \rightarrow 3\ Fe_2(SO_4)_3 + K_2SO_4 + Cr_2(SO_4)_3 + 7\ H_2O$$

4.1.4.2.1 Preparation of the Sample

The analysis sample was prepared by removing the aluminum by filtration, according to the procedure described in Par. 4.1.4.1.1. Sample weight is selected to yield about 1 gram of nitrate ion in 500 milliliters.

4.1.4.2.2 Reagents

a. Ferrous sulfate solution, approximately 0.2 N, prepared as follows: 55g of pure $FeSO_4 \cdot 7H_2O$ are dissolved in 100 milliliters of water containing one drop of 50-percent sulfuric acid and diluted to one liter with 50-percent sulfuric acid.

b. Ferroin solution, 0.025M in water

c. Potassium dichromate solution, 0.1 N

4.1.4.2.3 Analysis Procedure

A blank titration was performed prior to each analysis, to determine the normality of the $FeSO_4$ solution used. This step was necessary because the ferrous content of the solution may change by autoxidation. The blank is titrated according to the same procedure, except that 25 milliliters of distilled water is used instead of the sample solution.

A 25-milliliter aliquot of the sample was transferred to a wide-necked 25-milliliter Erlenmeyer flask that contained exactly 25 milliliters of the ferrous solution, after which 25 milliliters of concentrated sulfuric acid were added. After inserting several small boiling stones the solution was boiled gently for 3 minutes until the color changed from brown to clear yellow. The solution was cooled with tap water and mixed with 3 to 5 milliliters of 70- to 80-percent phosphoric acid and 50 milliliters of distilled water; it was then cooled to 30°C. Finally, the solution was titrated with 0.1 N dichromate to the end point from brown to blue-green, using two drops of 0.025 M ferroin solution as an indicator. A correction factor for the $K_2Cr_2O_7$ solution was determined by titrating a standard nitrate solution of known concentration.

4.1.4.2.4 Calculation

The percent by weight of NO_3 was determined from the following equation:

$$\% \, NO_3 = \frac{(X-Y) \times F \times 2.067 \times 20 \times 100}{\text{Weight of sample (mg)}}$$

X = ml 0.1 N $K_2Cr_2O_7$ used for blank

Y = ml 0.1 N $K_2Cr_2O_7$ used for sample

F = Factor $K_2Cr_2O_7$

4.1.4.3 Aluminum

A modified JANAF-recommended method (Ref. 78) has been applied to the analysis of aluminum in MONEX W. The method is normally applicable to iron-free and chromium-free propellants only. Minor amounts of iron were introduced into the propellant with the feces but did not lead to erratic results.

The aluminum was complexed with excess complexone at pH 5. Excess reagent was back-titrated with ferric ammonium sulfate solution.

4.1.4.3.1 Preparation of Sample

About 5 grams of MONEX W were dispersed in 100 milliliters of water. The aluminum was dissolved by adding concentrated hydrochloric acid, one drop at a time. After all the aluminum had been dissolved, the solution was filtered to remove undissolved feces and M-1. The filter was thoroughly washed. The filtrate was then quantitatively transferred to a 500-milliliter volumetric flask and filled to the mark with distilled water.

4.1.4.3.2 Reagents

a. Ethylenediaminetetraacetic acid, disodium salt, dihydrate (= EDTA), 0.1 M solution was prepared as follows: 37.27 grams of EDTA reagent and 500 milligrams of sodium hydroxide were dissolved in a one-liter volumetric flask with distilled water and stored in a plastic bottle

b. Ferric ammonium sulfate, approximately 0.1 M, prepared as follows: 50 grams of $Fe(NH_4)(SO_4)_2 \cdot 12\ H_2O$ were dissolved in water containing 2.5 milliliters acetic acid, diluted with water to one liter. The concentration was adjusted to require 45 to 50 milliliters of Fe solution for 50 milliliters of EDTA

c. Sodium salicylate indicator solution was prepared as follows: 5 grams of sodium salicylate were dissolved in 100 milliliters of distilled water

d. Bromcresol green indicator solution, 0.1 percent in water

e. Ammonium acetate, reagent grade

4.1.4.3.3 Analysis Procedure

Three drops of bromcresol green indicator solution and 60 milliliters of water were added to a 20-milliliter aliquot part of the sample (containing about 50 to 100 milligrams of aluminum). The excess acid was neutralized by adding solid ammonium acetate until the color changed from yellow to green. An excess of 15 grams of ammonium acetate was added to buffer the solution to pH 5. Then 50 milliliters of 0.1 M EDTA reagent were added to the sample. After gently boiling the treated sample for 10 minutes, it was cooled, and 5 milliliters of sodium salicylate indicator solution were added. The sample and a corresponding blank were titrated with 0.1 M ferric ammonium sulfate solution to a brown color.

4.1.4.3.4 Calculation

The percent by weight of aluminum was computed with the following equation:

$$\%\ Al = \frac{(X - Y)\ (F)\ (25)\ (100)\ (2.698)}{\text{Weight of sample (mg)}}$$

X = ml of $Fe(NH_4)(SO_4)_2$ used for blank

Y = ml of $Fe(NH_4)(SO_4)_2$ used for sample

F = Correction factor for $Fe(NH_4)(SO_4)_2$ solution

4.1.4.4 M-1 Burning Rate Additive

The method used for M-1 extraction is applicable only to MONEX W compositions that do not contain carbon black, polyethylene, or other acid-insoluble waste ingredients.

4.1.4.4.1 Reagents

a. Concentrated hydrochloric acid
b. Concentrated nitric acid
c. Potassium dichromate (not always required)
d. Sulphuric acid (not always required)

4.1.4.4.2 Analysis Procedure

A 5-gram propellant sample was dispersed in 50 milliliters of water contained in a wide-necked 250-milliliter Erlenmeyer flask. The aluminum was dissolved with a drop-by-drop addition of concentrated hydrochloric acid. Then an additional 20 milliliters of concentrated hydrochloric acid and 20 milliliters of concentrated nitric acid were added. The solution was gently boiled under an exhaust hood. When the quantity of liquid sample fell below 50 milliliters, concentrated nitric and hydrochloric acid were added in 50-milliliter portions until most of the organic substance had been destroyed (approximately 10 hours). If this procedure did not result in a white residue, an additional treatment with 5-percent potassium dichromate in 60-percent sulphuric acid (130°C for 10 hours) removed residual organic contaminants.

The dispersion was then filtered through a preweighed filter crucible with a glass paper filter disk. The residue was dried at 110°C for a minimum of 4 hours and weighed.

4.1.4.4.3 Calculation

Percent by weight of M-1 was computed as follows:

$$\% \text{ M-1} = \frac{\text{Weight of Residue } (100)}{\text{Weight of original sample}}$$

4.1.4.5 Water

Water was determined by azeotropic distillation with benzene, using a modified Dean Stark receiver to collect and measure the water distilled from the sample. Both feces and propellant were analyzed for water by this procedure.

4.1.4.5.1 Apparatus

A 25-milliliter round-bottomed flask fitted with a 25-milliliter modified Dean-Stark distilling receiver (graduated from zero to one milliliter with 1/10 milliliter divisions, and one to 25 milliliters with 2/10 milliliter divisions) and a water-cooled condenser fitted with a drying tube containing Drierite were used. A steam bath was satisfactory for refluxing the benzene.

4.1.4.5.2 Reagents

a. Dry benzene
b. Drierite

4.1.4.5.3 Analysis Procedure

The procedure used was similar to ASTME 123. The sample of feces or propellant (approximately 20 to 30 grams of feces, 50 to 100 grams of propellant) was added to a tared 250-milliliter round-bottomed flask through a powder funnel (to prevent material from being deposited on the standard taper fitting). The flask was reweighed to obtain the sample weight. Dry benzene was added until the flask was from one-half to two-thirds full. The joints were lightly greased, and ~~the~~ apparatus was assembled. Heat was applied at a rate sufficient to cause moderate refluxing of the benzene. Refluxing was continued until the water collected in the Dean-Stark receiver reached a constant level. This took from 4 to 6 hours. A hazy upper water layer sometimes resulted, especially in propellant samples.

If the assembly were allowed to stand overnight (with the heat turned off), the water-benzene interface became clearly discernible. The volume of water collected in the graduated receiver was recorded after the water had cooled to room temperature.

4.1.4.5.4 Calculation

The volume of water collected was used as the weight of water, since the correction for density variation with temperature is insignificant. Percent by weight of water was computed as follows:

$$\% \, H_2O = \frac{\text{Volume (Weight) of Water Collected (ml)} \times 100}{\text{Weight of Sample (g)}}$$

4.2 PROPELLANT CHARACTERISTICS

Propellant properties and characteristics necessary to perform a preliminary evaluation of MONEX W propellants were determined. The following subsections, describing in detail some significant properties and characteristics, demonstrate that MONEX W propellants are indeed feasible for use on spacecraft. Properties of a representative waste management propellant are described in Table 33.

4.2.1 Biological Activity

Initially, there was concern that MONEX W propellants, unless sterilized, would provide a suitable environment for significant biological growth resulting in propellant degradation. However, subsequent long-term storage tests demonstrated that MONEX W propellants possessed excellent long-term storage stability and that biological growth was effectively inhibited even though the propellants were not sterilized.

Testing of propellant formulations for biological activity was limited to aerobic culturing of various propellant samples in trypticase soy broth at 37°C (98.6°F) and was conducted according to recommendations made by the Washington State Health Department.

4.2.1.1 Propellant Tests

Initial testing of propellant formulations containing 40 percent of ammonium nitrate and 25 to 30 percent feces (by weight) indicated that biological activity was definitely inhibited, however, all viable species were not killed.

TABLE 33

PROPERTIES OF A REPRESENTATIVE WASTE MANAGEMENT PROPELLANT

Density, @ 77°F	97 lb/ft^3
Freezing point	8.6°F
Vapor pressure, @ 77°F	8.2 mm Hg
Autodecomposition	485°F
Detonability (JANAF card gap test)	Nondetonable - zero attenuation
Impact sensitivity	Negative/120 Kg-cm
Mechanical stability (phase separation under acceleration)	No separation - 5g's/5 min Minor separation - 26g's/5 min

4.2.1.1 Propellant Tests

Initial testing of propellant formulations containing 40 percent of ammonium nitrate and 25 to 30 percent feces (by weight) indicated that biological activity was definitely inhibited, however, all viable species were not killed.

Propellant W-1 cultured after 55 days of storage in a sealed glass container showed vigorous growth within 12 hours of incubation at 37°C using a trypticase soy broth. It also showed growth after both 10 and 18 months of storage. Although this propellant was not sterilized, there was no outward sign of decomposition of the propellant. Propellant W-1 was saturated with respect to ammonium nitrate and also contained some undissolved ammonium nitrate and therefore represented the highest osmotic pressure to be found in any of the propellant formulations used in this program.

Before long term storage results demonstrated the stability of MONEX W propellants, several attempts were made to chemically sterilize the propellant by the use of Dowicil, an antimicrobial made by the Dow Chemical Company. (The active ingredient of Dowicil is 1-(3-chloroallyl)-3,5,7-triaza-1-azonia-adamantane chloride.)

Results of these tests, in which 0.1-0.5 percent Dowicil was added, either as a powder or dissolved in water, showed that Dowicil may inhibit bacterial growth initially but it does not sterilize MONEX W propellants.

Further attempts to chemically sterilize the propellants were not made since initial storage data showed no signs of propellant degradation. Table 34 shows that five different MONEX W propellants, stored for varying lengths of time up to 335 days, were not sterile since cultures made of them exhibited signs of growth after 24 hours. Yet, visual examination of the propellant samples disclosed no sign of decomposition. They appeared homogeneous, exhibited no gas bubbles or pressure buildup and still had a slightly acidic pH (5 to 6).

A microscopic examination of one of the propellant cultures using gram stain showed gram positive cocci and gram positive rods to be present. Some of the rods contained spores. Whether or not these spores originated in the feces or were a contaminant is not known. Surprisingly, no gram negative rods were observed, some of which are indicator organisms for fecal contamination. These tests were performed on a courtesy basis by the Washington State Department of Health, whose report noted that examination of a single culture should not be used as proof that no fecal bacteria were present. The identification of the various forms of biological life in the propellant is not pertinent to this program, so no further attempts were made to identify the organisms cultured in the test media.

4.2.1.2 Propellant Exhaust Gas Tests

Samples of exhaust gases from engine firings of both fresh and stored MONEX W propellant displayed no signs of biological activity when cultured in trypticase soy broth at 37°C.

TABLE 34

CULTURE TESTS OF MONEX W PROPELLANTS[a]

Propellant	Days of Storage	24 Hours After Culturing	48 Hours After Culturing
W-1	302	Slight bottom growth	Heavier bottom growth
W-7	232	Hazy, white surface growth	No change
W-38	178	Hazy, white surface growth	No change
W-38	335	Hazy, white surface growth	No change
W-42	162	Hazy, white surface growth	No change
W-60	47	Very slight bottom growth	Slight bottom growth

[a] Cultures were made in trypticase soy broth and incubated at 98.6°F

The propellant tested was a MONEX W-38 composition that had been modified prior to test firing. During the fourth month of this program, propellant formulation W-38 was selected for test firing after long-term storage for the purpose of examining the biological activity in the exhaust products. The selection of W-38 was made before engine test firings had been initiated. During the engine test firing program to evaluate various propellant formulations, it was determined that the composition of W-38 lay in a region where unsatisfactory engine performance was to be expected. Therefore, with concurrence from the NASA-Langley contract monitor, the composition of MONEX W-38 was altered by the inclusion of additional aluminum and ammonium nitrate prior to engine testing. The resultant composition, redesignated W-67, closely approximated formulation W-42, which had previously been successfully fired.

Cultures made of the stored MONEX W-38 immediately prior to modification were positive. Cultures made two days after the composition was altered (to W-67) were also positive. This was to be expected, since samples of MONEX W-42 stored for 8 months also yielded positive results when cultured. Freshly prepared W-67 also gave positive cultures.

Two samples of exhaust gases were obtained from each firing of W-67. One sample was obtained during the midcourse of the firing, while the second sample was obtained during shutdown of the engine, the period when biological contamination of the exhaust gases was most likely to occur.

Gas samples were obtained by means of a probe of stainless steel tubing connected to two evacuated gas sampling bottles. To sterilize the gas sampler, the open end of the probe was sealed with polyethylene film, the system was evacuated and then refilled with a gaseous sterilizing mixture consisting of 12-percent ethylene oxide and 88-percent Freon-12. The sterilizing mixture was left in the sealed system from 16 to 24 hours. Several hours prior to use, the gas sampling apparatus was again evacuated. To collect samples, the end of the probe was positioned 6 feet downstream from the nozzle in the middle of the exhaust plume. The polyethylene film covering the end of the probe was consumed by the hot exhaust gases during the firing and the gas samples were obtained by actuation of solenoid valves connecting the gas sampling bottles to the probe. Cultures were made by bubbling the gas samples through test tubes containing sterile trypticase soy broth and then incubating the samples at 37°C for a week. In a control test, air samples were obtained from directly above a Waring blender during mixing of a sample of fresh MONEX W-67 propellant. Cultures of this test were positive, demonstrating that the sterilization technique employed was valid.

The results of these tests demonstrated that at least the biological species in the propellant that reproduce readily in trypticase soy broth were sterilized during the course of the firing.

Obviously, a much more extensive series of tests would have to be performed using a wide range of culturing media and conditions and testing of exhaust gases from numerous engine firings before it can be reliably concluded that the exhaust gases from MONEX W engine firings are completely sterile.

4.2.2 Freezing Point

Freezing points of MONEX W-38, MONEX W-42 and MONEX W-60 (incorporating feces only and feces and urine, respectively, as the waste components) were determined by slowly cooling a small tube of propellant while stirring slowly. A gradual thickening of the propellant, followed by the appearance of small solid particles, was observed. Continued cooling increased the number of solid particles until almost complete solidification of the propellant made stirring impossible. This point was selected as the freezing point, since MONEX W is a complex mixture and does not exhibit a sharply defined freezing point. MONEX W-38 showed a freezing point of -21°C and -23°C (-5.8°F and -9.4°F), respectively, with two batches made with different lots of feces. For W-42, the freezing point was -13°C (8.6°F), while for W-60 it was -10.5°C (13.1°F). This is not the trend expected, since W-38 has a higher concentration of dissolved ammonium nitrate. The freezing points of NH_4NO_3/ water mixtures and MONEX W propellants are shown on Fig. 15.

4.2.3 Vapor Pressure-Temperature Relationship

The vapor pressure of MONEX-W propellants was expected to be determined mainly by the ratio of ammonium nitrate to water in the propellant. The other components are either insoluble (aluminum, carbon, M-1 additive) or contribute only little to the overall vapor pressure (minor feces constituents, e.g. skatol and amino acids).

The vapor pressure-temperature relationship was established for MONEX W-38 containing feces, carbon, and polyethylene and for MONEX W-42 containing only feces as waste components. Figure 16 is a semilogarithmic plot of vapor pressure versus the reciprocal of the absolute temperature (log p vs 1/T). The difference in vapor pressure between W-38 and W-42 is somewhat surprising, since one would expect them to be quite similar on the basis of their composition. The same lot of feces was used in both propellant batches, and the ratio of feces water to ammonium nitrate was approximately the same.

4.2.4 Density-Temperature Measurements

The density-temperature relationships for three MONEX W propellants (W-38, W-42, and W-30, were determined over the range of 38° to 122°F. The linear relationships obtained for all three propellants are graphically illustrated in Fig. 17. Densities were determined by the liquid displacement method using silicone oil as the displacement medium. The densities of individual batches of propellant of the same formulation are expected to vary somewhat, depending on the composition of the feces incorporated in them. However, the temperature coefficient of density for these formulations should remain approximately the same.

Bulk density values were determined by weighing a known volume of propellant. This value was generally lower than the absolute density, since the propellant contained trapped air. These values are presented with the engine firing data (Par. 5.5).

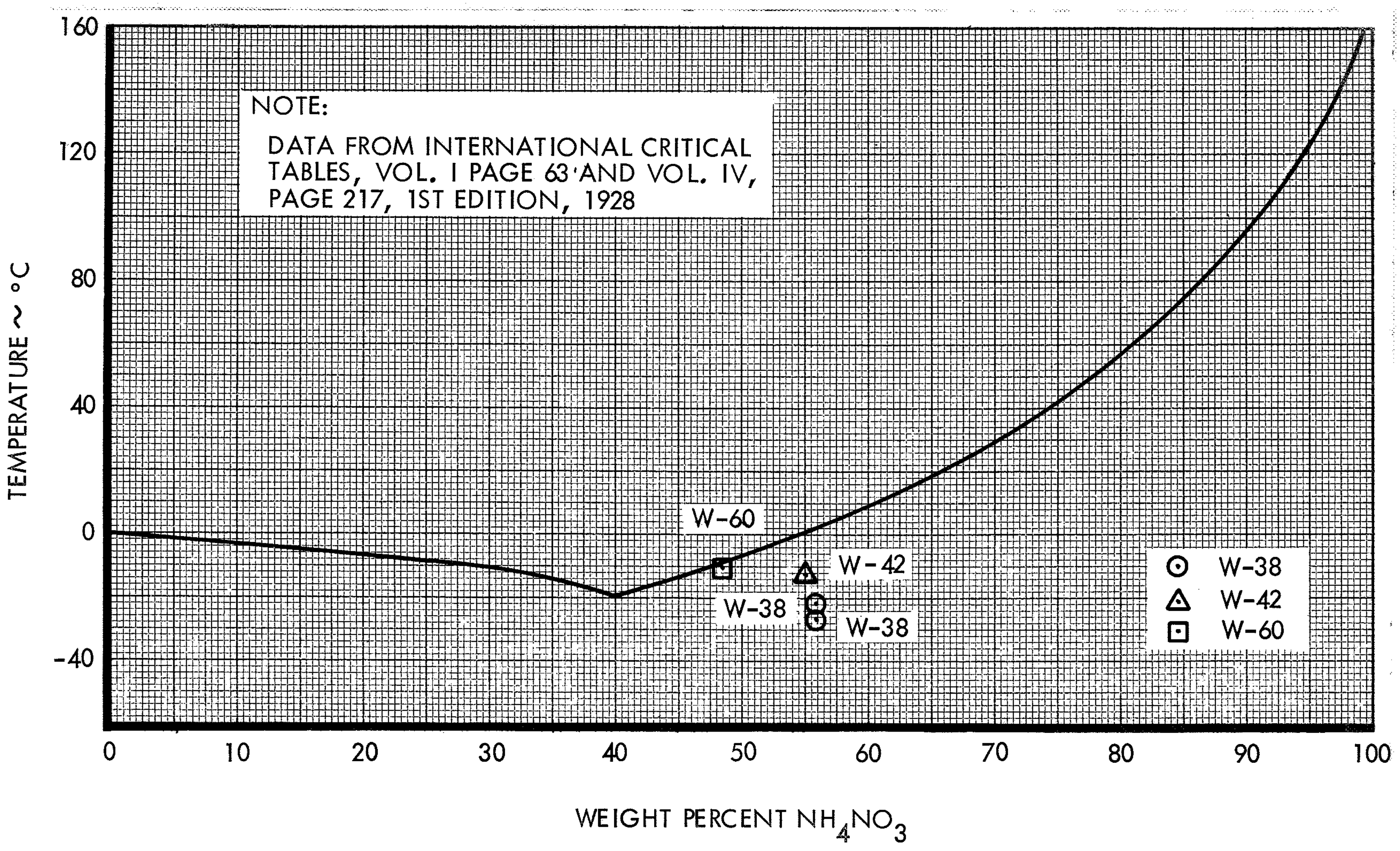

FIGURE 15. - EXPERIMENTAL FREEZING POINT OF AMMONIUM NITRATE/WATER MIXTURES AND MONEX W PROPELLANT FORMULATIONS(a)

(a) PERCENT NH_4NO_3 BASED ON RELATIVE NH_4NO_3 AND H_2O CONTENT OF THE FORMULATIONS

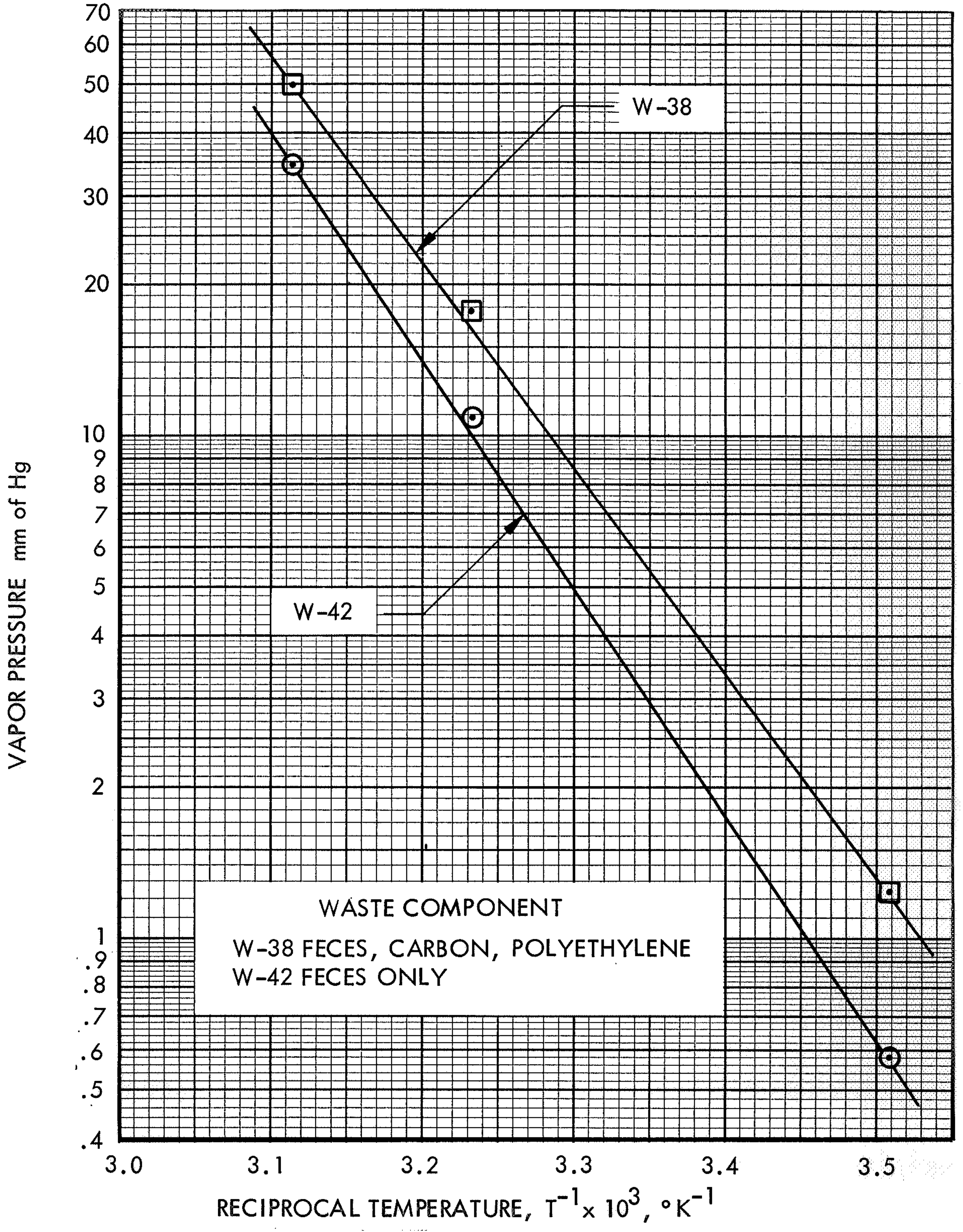

FIGURE 16. - MONEX W PROPELLANT VAPOR PRESSURE VERSUS RECIPROCAL TEMPERATURE

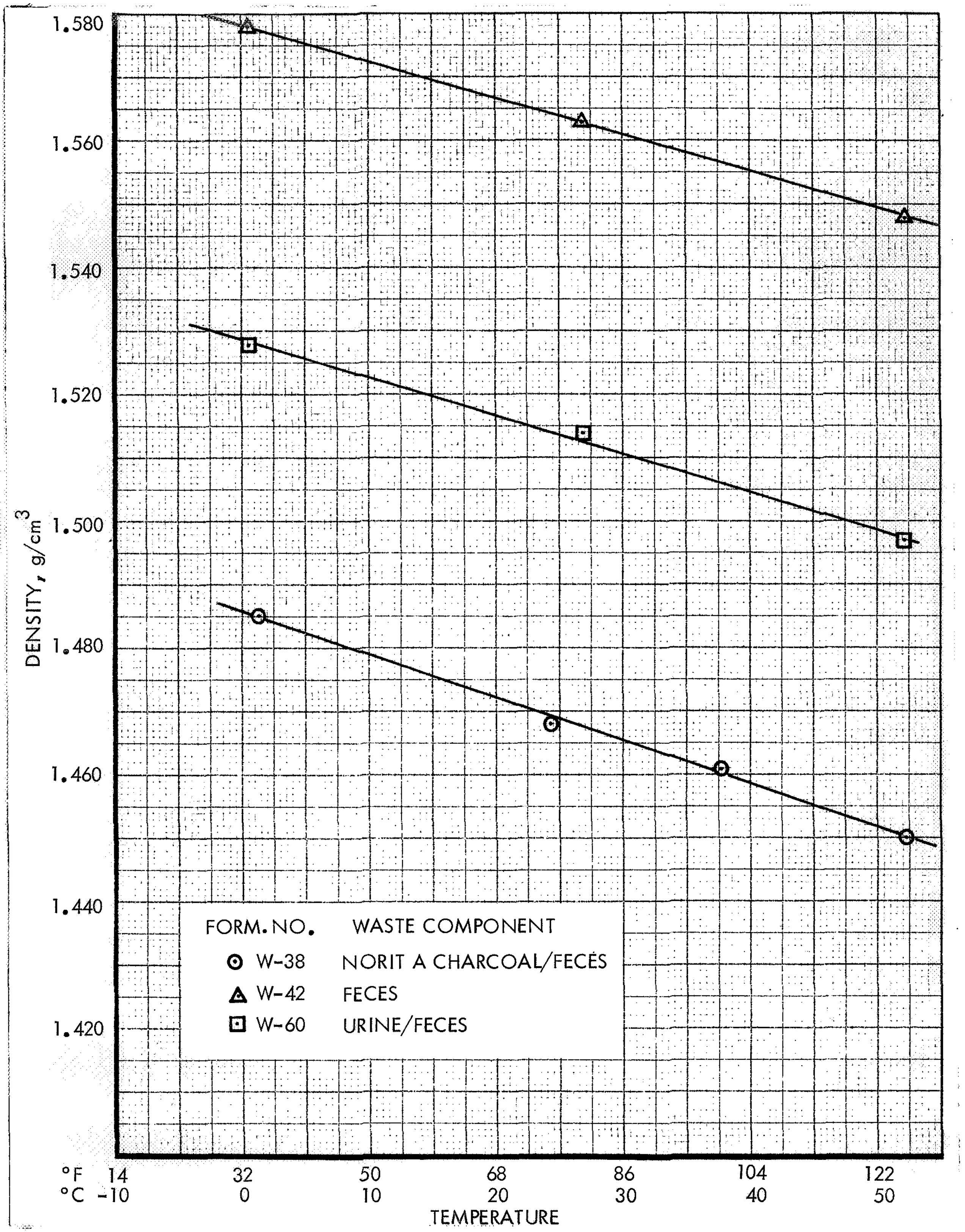

FIGURE 17. - DENSITY VS TEMPERATURE MONEX W PROPELLANTS

4.2.5 Rheological Properties

A capillary extrusion rheometer was used to measure the flow properties of MONEX W propellants. The propellant tank employed had a 4-inch internal diameter and was 16 inches long. Interchangeable capillary tubes of various L/D ratios (length/internal diameter) can be used with the rheometer, but a single capillary tube (6.25 inches long by 0.06-inch inside diameter) was used for all tests reported here, since a direct comparison of the flow properties was desired. By using the same capillary tube for each series of tests, no new parameters were introduced. Pressure was applied to the piston by compressed nitrogen and monitored by two calibrated Helicord gauges for the ranges of zero to 500 psig and zero to 1,000 psig. Electrically actuated valves were used to control pressure on the piston. Propellant flow was timed by an electric timer actuated by a switch on the propellant flow control valve.

Figure 18 illustrates the effect of storage for both 2 and 9-1/2 months on flow properties of MONEX W-38. The propellant was stored in a polyethylene container at ambient temperature (70° to 75°F). The propellant became slightly more fluid during storage, but exhibited no gross signs of separation, decomposition, or agglomeration. The increase in fluidity of the propellant may possibly be due to the slow degradation of some of the fibrous material normally found in feces, either by the highly concentrated ammonium nitrate solution or biological degradation.

Figure 19 is a comparison of the flow properties of three different types of freshly prepared MONEX W propellants. W-38 contains carbon and feces; W-42 contains only feces; and W-60 contains urine and feces as waste ingredients. Two batches of W-38 were made, one containing carbon from a Bosch reactor and the other containing Norit A charcoal. The difference in viscosity between the two W-38 formulations may be due to the difference in carbon particle size or to the iron carbide and other impurities in the Bosch reactor carbon.

Formulation W-60, containing over 30-percent urine, has the highest water content as well as the lowest solids content of the three formulations tested which accounted for its markedly more fluid characteristics. Formulation W-42, when made from feces provided by Rocket Research Corporation personnel, was somewhat more fluid than W-38. This is probably due to the fact that W-38 contained finely divided carbon which increases viscosity. W-42 utilizing feces from a 60-day manned spacecraft simulation experiment (four-man crew on an anticipated Apollo diet) was much more viscous than any of the other propellant batches tested (formulations W-38, W-42, and W-60). Since the water content of the feces for this batch of W-42 propellant was only slightly less than that of other batches of W-42 (see Fig. 20), the viscosity increase cannot be attributed solely to the water content. The low bulk nature of the Apollo type diet may be responsible for much of the viscosity increase noted.

An attempt was made to lower the viscosity of MONEX W propellants by incorporating small amounts of water-soluble polymers of ethylene oxide (Polyox WSR resin made by Union Carbide Corporation). These materials have friction reduction properties in aqueous systems, but their effectiveness in highly

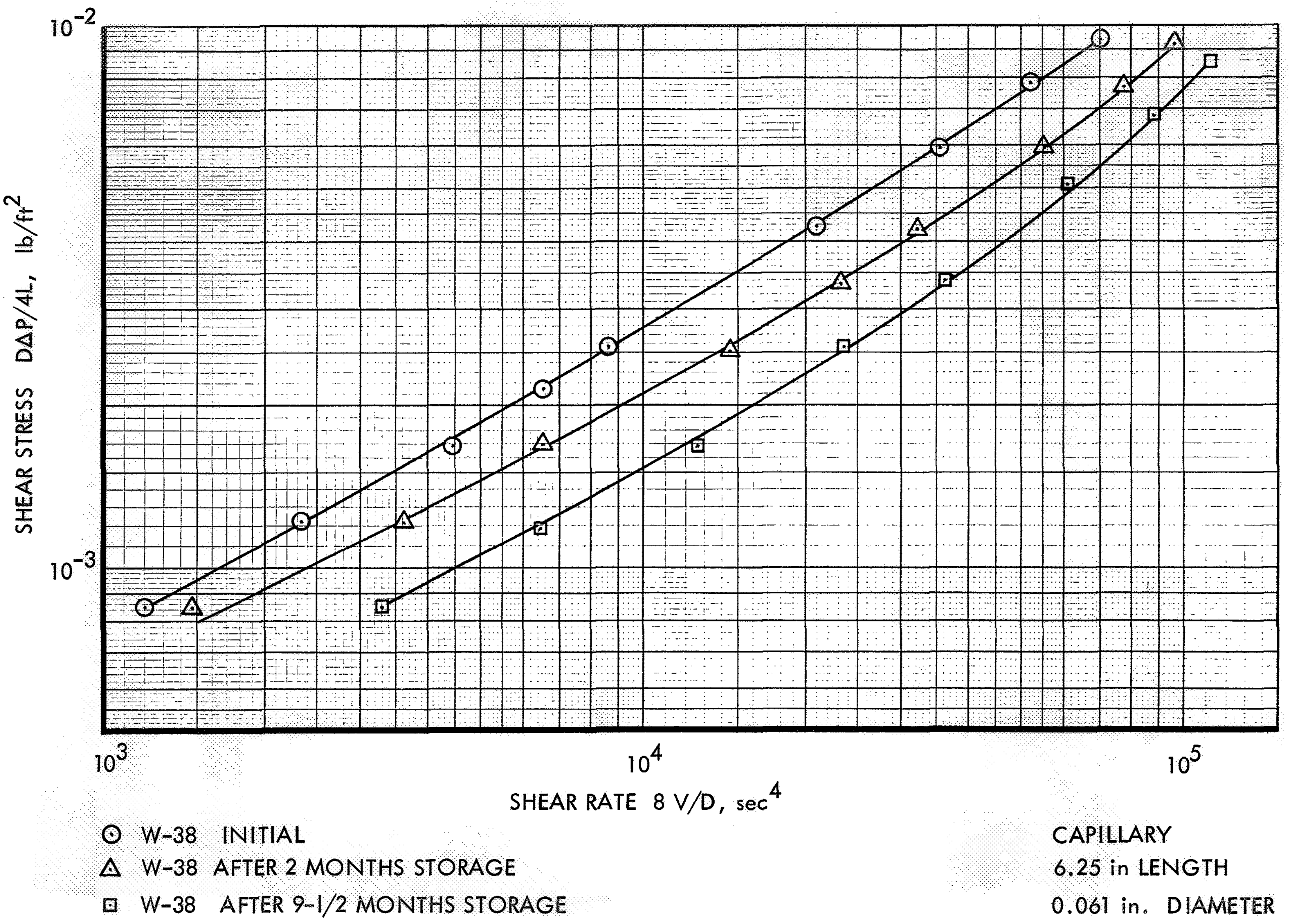

FIGURE 18. - EFFECT OF AMBIENT STORAGE ON THE FLOW PROPERTIES OF MONEX W-38 CAPILLARY EXTRUSION RHEOMETER DATA, 73°F

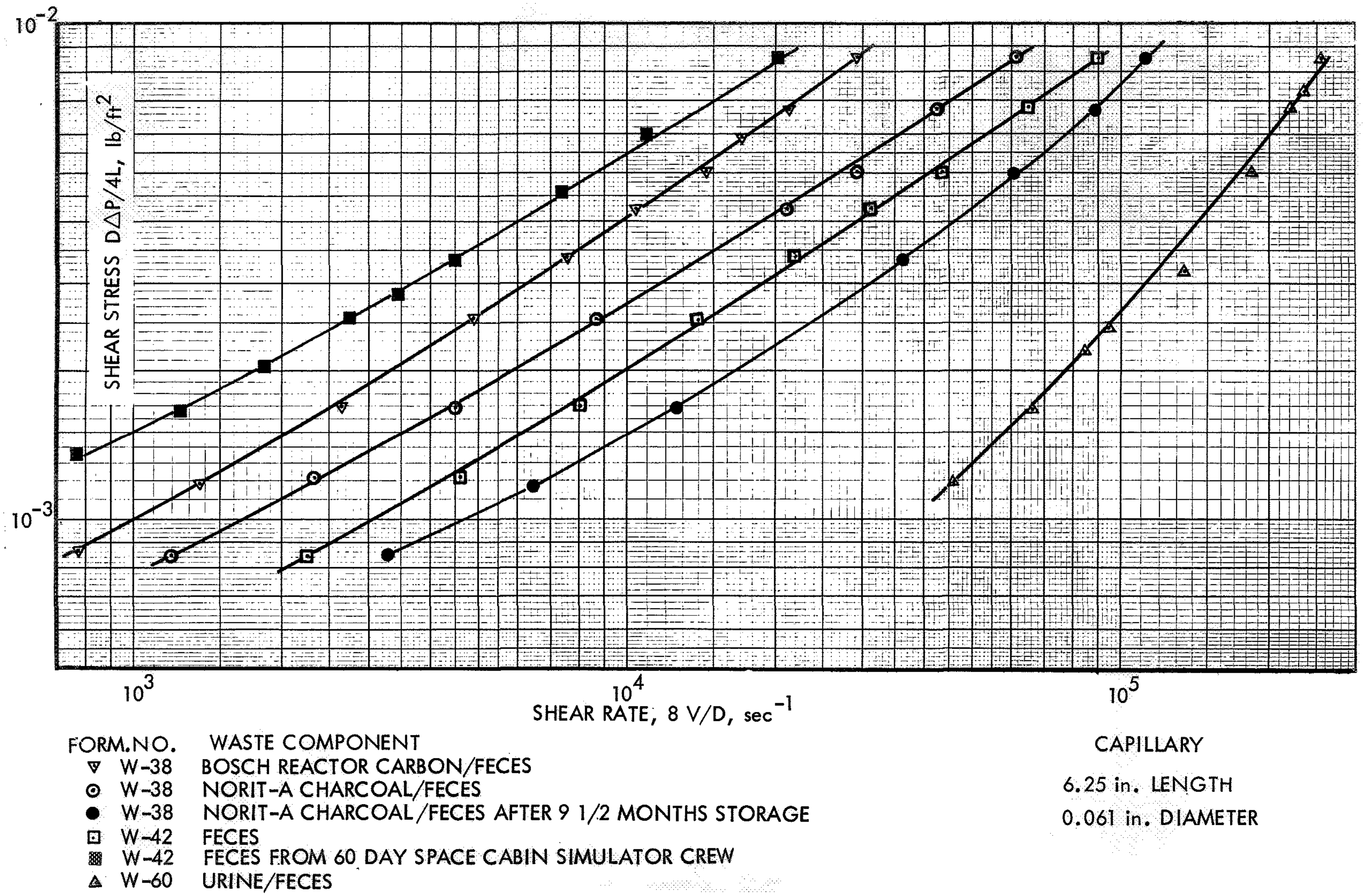

FIGURE 19. - COMPARISON OF FLOW PROPERTIES OF MONEX W FORMULATIONS CAPILLARY EXTRUSION RHEOMETER DATA, 73° F

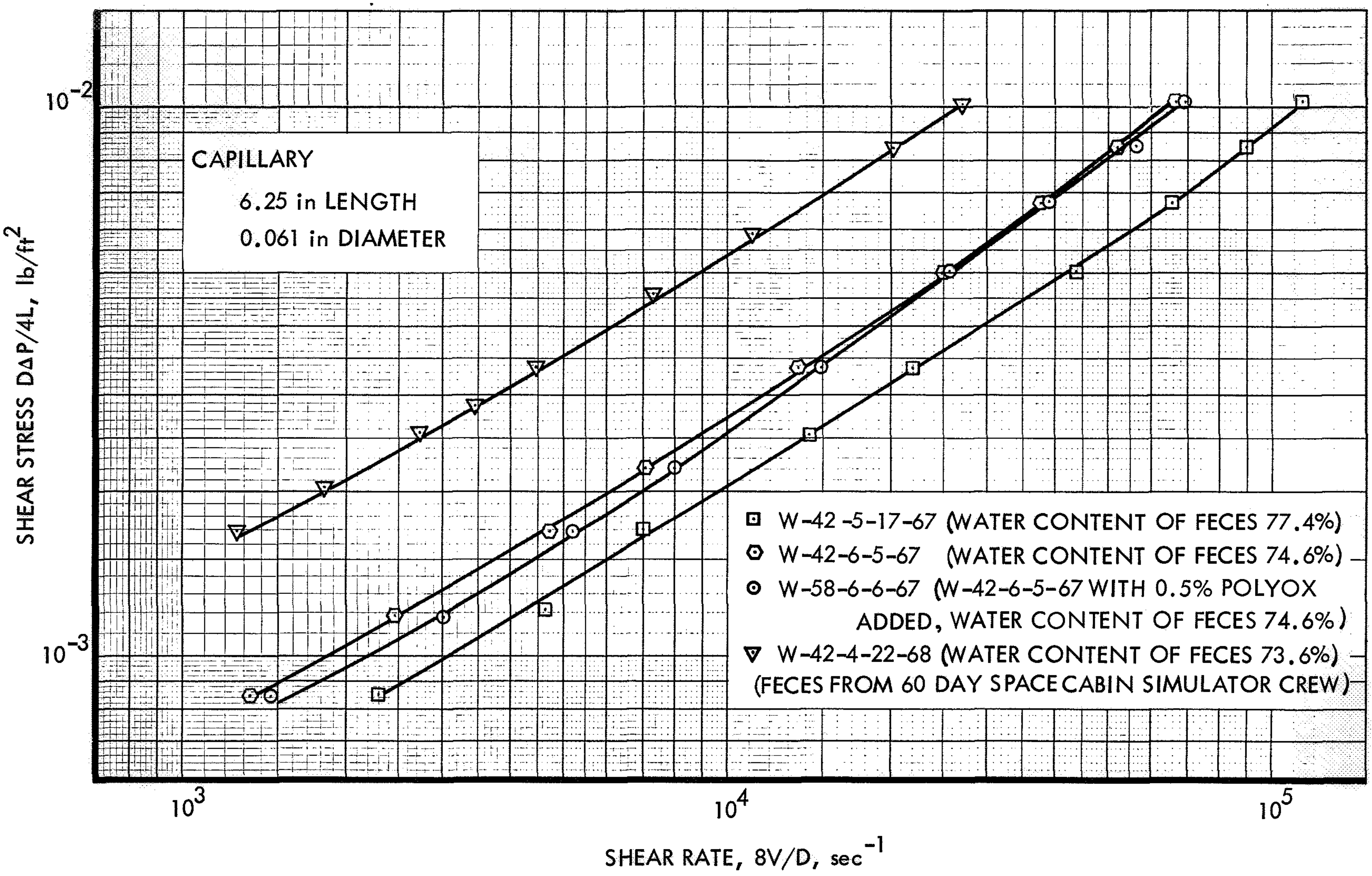

FIGURE 20. - COMPARISON OF FLOW PROPERTIES OF MONEX W-42 BATCHES CAPILLARY EXTRUSION RHEOMETER DATA, 73°F

concentrated systems (such as MONEX W) is not known. To test the effect of Polyox WSR N-10 on MONEX W propellants, formulation W-58 was made. It is identical to W-42, except for the addition of 0.5-percent-by-weight Polyox resin. As Fig. 20 illustrates, the Polyox is marginally effective in increasing propellant shear rate at stresses below 5 x 10^{-3} lb/ft^2, but above that level the two curves representing W-42 and W-58 tend to merge.

Figure 20 also illustrates the effect of varying moisture content of feces on propellant flow properties. Propellant W-42, made from feces containing 77.4-percent water, is more fluid than that made from feces containing 74.6-percent water. While this represents a difference of one percent in water content between the two propellant batches, water content of the numerous feces samples analyzed has ranges from 66 to 77 percent. A greater variation in flow properties than that exhibited by the two batches of W-42 would be anticipated when processing identical formulations with different batches of feces.

4.2.5.1 Spray Testing

Qualitative spray tests were performed with a series of waste management propellant compositions to aid in the selection of formulations with characteristics suitable for use in liquid injection engine firings.

Spray tests of each MONEX W composition were performed with solid cone spray nozzles (Spraying Systems Company, Bellwood, Illinois) of 0.067- and 0.125-inch discharge orifice diameter at pressure drops of 300 and 500 psi. The propellant was sprayed into a large glass vessel, which permitted viewing of the spray while protecting the operator from aerosol contamination. The results of these tests are presented in Table 35.

Formulation W-22 was selected on the basis of its high viscosity as a propellant likely to possess only marginal spray characteristics. Formulations W-25, -27, and -29 contained only feces as waste and were formulated so that the oxygen present was just sufficient to convert all of the aluminum to aluminum oxide and the carbon (present in the feces) to carbon monoxide.

Formulations W-30, -31, -32, and -33 were formulated to contain a feces-to-carbon ratio of 4:1 while also maintaining a balanced fuel-to-oxidizer ratio. In formulations W-34, -35, -36, and -37, carbon was replaced with powdered polyethylene. Formulation W-38 was tested since it was selected for low term storage testing and engine firings. W-40 represented formulations containing the M-1 burning rate additive and only feces as waste.

The results of the spray tests are summarized as follows:

a. In all tests, the 0.125-inch-diameter discharge orifice yielded a better spray pattern than the 0.067-inch-diameter orifice.

b. None of the formulations containing only feces as the waste component produced sprays under the conditions tested.

TABLE 35

NOZZLE SPRAY TESTS

Formulation	ΔP (psi)	Discharge Orifice(a) Diameter (inches)	Remarks
W-22	300	0.067	No spray
W-22	500	0.067	No spray
W-22	300	0.125	Coarse spray - fair
W-22	500	0.125	Coarse spray - fair
W-25	500	0.067	No spray) Contains only
W-25	500	0.125	No spray) feces as waste
W-27	300	0.067	No spray) Contains only
W-27	300	0.125	No spray) feces as waste
W-29	300	0.067	No spray) Contains only
W-29	300	0.125	No spray) feces as waste
W-30	300	0.067	Good spray
W-30	300	0.125	Good spray
W-30	500	0.125	Good spray
W-31	300	0.067	No spray
W-31	500	0.067	Fair - good spray
W-31	300	0.125	Very coarse spray - poor
W-31	500	0.125	Good spray
W-32	300	0.067	No spray
W-32	500	0.067	No spray
W-32	300	0.125	Coarse spray - fair
W-32	500	0.125	Fair - good spray
W-33	300	0.067	No spray
W-33	500	0.067	Coarse spray - fair
W-33	300	0.125	Coarse spray - fair
W-33	500	0.125	Fair - good spray

(a) Solid cone spray nozzles, Spraying Systems Co., Bellwood, Illinois

TABLE 35 (Concluded)

NOZZLE SPRAY TESTS

Formulation	ΔP (psi)	Discharge Orifice[a] Diameter (inches)	Remarks
W-34	300	0.067	Coarse spray - fair
W-34	500	0.067	Coarse spray - fair
W-34	300	0.125	Good spray
W-34	500	0.125	Good spray
W-35	300	0.067	No spray
W-35	500	0.067	Fair - good spray
W-35	300	0.125	Good spray
W-35	500	0.125	Good spray
W-36	300	0.067	No spray
W-36	500	0.067	No spray
W-36	300	0.125	Fair - good spray
W-36	500	0.125	Good spray
W-37	300	0.067	No spray
W-37	500	0.067	No spray
W-37	300	0.125	Fair - good
W-37	500	0.125	Good
W-38	300	0.067	Very coarse spray - poor
W-38	500	0.067	Very coarse spray - poor
W-38	300	0.125	Fair - good
W-38	500	0.125	Good
W-40	300	0.067	Fair - good
W-40	500	0.067	Good
W-40	300	0.125	Good
W-40	500	0.125	Good

(a) Solid cone spray nozzles, Spraying Systems Co., Bellwood, Illinois

c. No major differences between spray patterns of those formulations containing carbon and those containing an equal amount of polyethylene substituted for carbon were observed.

d. A ΔP of 500 psi generally produced a better spray pattern than a ΔP of 300 psi with the same formulation.

Although many of the laboratory spray tests included propellant compositions containing carbon and polyethylene, the majority of subsequent engine test firings were performed with only feces as the propellant waste component in order to more clearly define the effect of the three major propellant components (aluminum, ammonium nitrate, and feces) on performance.

Engine test firings demonstrated that some formulations producing poor spray patterns in the spray testing apparatus still gave satisfactory engine performance. This is probably due to the fact that the propellant spray pattern is strongly influenced by other factors such as the density of the medium into which it is injected, the intense sonic field (pressure oscillations), and flash vaporization in an intense thermal radiation environment.

4.2.6 Autodecomposition

Autodecomposition tests were performed using formulation W-65, a propellant of low waste content, selected as being representative of compositions most likely to be hazardous.

Tests were conducted using the thermal stability procedure developed by G. A. Mead of Air Reduction Company, Inc., Murray Hill, New Jersey. This procedure was developed with support of the Space Systems Division, Air Force Systems Command, USAF, Edwards, California, under Contract AF 04(611)-7413. It is similar to the standard JANAF Thermal Stability Test.

To conduct a thermal stability determination, a sample of propellant was placed in a small stainless steel bomb which was then sealed with a burst diaphragm. The loaded bomb was immersed into a molten metal bath at initially 225°F and heated at a rate of 15°F/minute. Thermocouples were used to measure the temperature of the heating bath and also the differential temperature between the propellant sample and the heating bath. A sample of n-propyl nitrate was used as a control. A self-heating rate of 5°F/minute was used as the criterion for determining the occurrence of an exotherm.

As shown in Fig. 21, the n-propyl nitrate showed an exotherm beginning at 360°F, somewhat above the 330°F value reported in the procedure described by Mead. This possibly may be due to the use of n-propyl nitrate of higher purity (99.8 percent) than that used by Mead (purity not reported).

The test propellant (W-65, Fig. 21) displayed a broad endothermic reaction starting at approximately 230°F and exhibiting a minimum at 325°F. A sharp endothermic reaction occurred at 495°F, causing the sample temperature to drop to 485°F. Following this, a vigorous exothermic reaction occurred, causing the temperature of the sample to rise to 555°F, at which point the

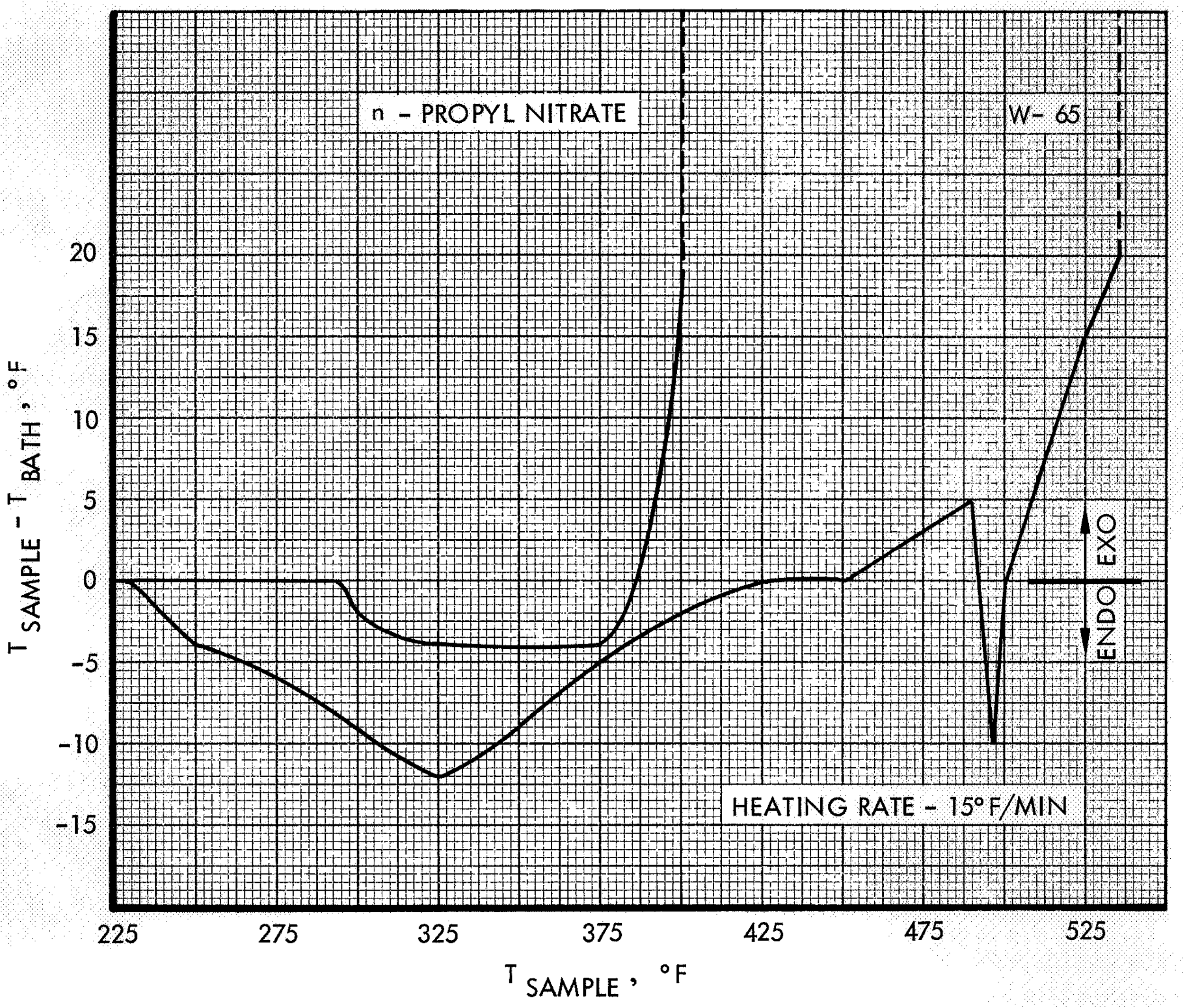

FIGURE 21. - THERMOGRAM OF MONEX W-65

pressure diaphragm burst. This exotherm (485°F) is quite near that of crystalline ammonium nitrate, which displays several sharp transition endotherms at and below its melting point with an exotherm at 464°F. (This data is from a brochure describing the du Pont 900 Differential Thermal Analyzer[a].)

Since the MONEX W propellant is not expected to be subjected to temperatures close to 485°F during preparation or storage, it appears to possess satisfactory thermal stability.

4.2.7 Detonability

Card gap tests for shock sensitivity of three MONEX W propellant formulations were conducted in accordance with the procedures recommended by the JANAF Panel on Liquid Propellant Test Methods (Ref. 79). In the tests, a 50 gram tetryl booster was placed in immediate contact with the propellant to be tested without any attenuation cards inserted, and was initiated by an Engineer Corps Special electric blasting cap.

MONEX W-38 after 9-1/2 months of storage and MONEX W-42 after 8 months of storage were nondetonable under the test conditions. MONEX W-65, the formulation selected as being potentially the most hazardous since it contained only 23 percent feces, was also nondetonable; however, the witness plates were bulged in all three tests of W-65, indicating a low-velocity propagation or incompletely developed detonation. The initiating energy input (as expressed by Joule/cm^2-sec) required to produce the observed effect with W-65 is not directly known. In the card gap test, the energy required to detonate a propellant sample is only characterized by the amount of booster explosive and the number of attenuating cards inserted. Since MONEX W propellant containing as much feces as possible offers the greatest advantage for spacecraft use, the use of propellants such as W-65, containing low amounts of feces and large quantities of ammonium nitrate, would not likely be considered.

4.2.8 Impact Sensitivity

Impact sensitivity tests, using a Model 7 Olin Mathieson Drop-Weight Tester, were performed on six MONEX W propellant formulations. The results listed in Table 36 show that all samples were negative at 120 Kg-cm (the upper limit of the test apparatus).

Propellant W-38, containing feces, carbon, and polyethylene, and propellant W-42, containing only feces as the waste component, both exhibited negative impact sensitivities both after preparation and after 9-1/2 and 8 months of storage, respectively.

Propellant formulation W-6 contained carbon from a Bosch reactor. The carbon had a gritty nature, due to contamination with iron carbide. As gritty substances are known to greatly increase the impact sensitivity of many materials, this formulation was most likely to show a positive result if the propellant

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[a] E. I. duPont de Nemours & Co., Inc. - Brochure No. A33247

TABLE 36

IMPACT SENSITIVITY OF MONEX W PROPELLANTS

Propellant	No. of Drops	Kg-cm	Results
W-38-4767 initial	10	120	Negative
W-38-4767 1-month storage	10	120	Negative
W-38-4767 2-month storage	10	120	Negative
W-38 After 9-1/2-month storage	10	120	Negative
W-42-5767 initial	10	120	Negative
W-42 After 8-month storage	10	120	Negative
W-6 Carbon from Bosch reactor with ferric carbide	10	120	Negative
W-63 Contains ferric carbide	10	120	Negative
W-64 Contains ferric carbide	10	120	Negative
W-65 Contains ferric carbide	10	120	Negative
Dry Al H-5/NH_4NO_3 (32/28.5)	10	300	Negative

were at all impact sensitive. Ten consecutive drop-weight tests of formulation W-6 with 120 Kg-cm yielded negative results.

Pure ferric carbide was used to replace part of the waste and all of the waste, (formulations W-63 and W-64, respectively) other than feces used in formulation W-38 to determine its effect in large quantities on impact sensitivity of waste management propellant. Test results were negative at 120 Kg-cm on freshly prepared propellant.

Before studying the feasibility of using a preblended dry mixture of aluminum and ammonium nitrate in propellant preparation, drop-weight impact sensitivity tests were performed. A ratio of aluminum to ammonium nitrate of 32:28.5 was selected as being typical of that used in the propellants. The impact sensitivity was determined as greater than 300 Kg-cm, the upper limit of the test apparatus. On the basis of impact sensitivity, the blended ammonium nitrate and aluminum mixture is safe; but additional tests, including detonability tests, friction tests, and spark sensitivity tests, will be required to fully demonstrate the safety of these mixtures.

4.2.9 Material Compatibility

Compatibility tests of commonly used structural materials with waste management propellant (formulation W-42) were conducted in three series of tests. Weighed samples of thoroughly cleaned materials were partially immersed in propellant and sealed in individual glass containers.

Of 18 commonly used structural materials tested, only copper displayed gross incompatibility. Brass and a molybdenum alloy (TZM) showed some slight reaction after several weeks. One aluminum sample displayed only a slight surface darkening after 261 days.

The materials tested and test results are contained in Tables 37, 38, and 39. The results show that MONEX W propellants are compatible with a large number of commonly used structural materials.

4.2.10 Storage Stability

Storage stability was measured both qualitatively and quantitatively. Qualitative results were obtained by examining propellant samples contained in sealed glass jars or polyethylene bottles that were stored in the laboratory (70^{o} to 80^{o}F). Quantitative results were obtained by determining the amount of gas evolved from propellant samples stored in constant temperature baths.

4.2.10.1 Qualitative Results

Samples of MONEX W propellants stored for up to 18 months at 70^{o} to 80^{o}F have shown no visual signs of decomposition except those containing carbon from a Bosch reactor, or those containing ferric carbide.

A sample of Bosch reactor carbon was supplied by NASA-Langley for incorporation in formulations of MONEX W. Partial analysis of this sample yielded

TABLE 37

MATERIALS STORAGE COMPATIBILITY TESTS[a] - SERIES I

	Results[b]					
Materials	24 Hours	60 Days	140 Days	210 Days	261 Days	326 Days
Aluminum 1100	NC	NC	NC	NC	Sl. surface darkening	NFC
Aluminum 6061-T6	NC	NC	NC	NC	NC	NC
Titanium 6Al-4V	NC	NC	NC	NC	NC	NC
Stainless steel 347	NC	NC	NC	NC	NC	NC
Stainless steel AM-355	NC	NC	NC	NC	NC	NC
Brass	NC	Dark crust	RC	NFC	Dull, spotted	NFC
Copper	Blue crust	RC	RC	RC	Gross corrosion	RC
Rubber, EPR-132	NC	NC	NC	NC	NC	NC

(a) Samples stored at room temperature (70° to $75^{\circ}F$) in sealed glass jars

(b) NC = No change
RC = Reaction continues
NFC = No further change

TABLE 38

MATERIALS STORAGE COMPATIBILITY TESTS[a] - SERIES II

Materials	Results[b]			
	24 Hours	30 Days	120 Days	194 Days
Nickel screen	NC	NC	NC	NC
Stainless steel 304	NC	NC	NC	NC
Stainless steel 321	NC	NC	NC	NC
Aluminum bar 6061-T6 (half submerged)	NC	NC	NC	NC
Aluminum bar 6061-T6 (completely submerged)	NC	NC	NC	NC
Rubber O-ring, 3-8E515	NC	NC	NC	NC

[a] Samples stored at room temperature (70° to 75°F) in sealed glass jars

[b] NC = No change

TABLE 39

MATERIALS STORAGE COMPATIBILITY TESTS(a) - SERIES III

Materials	Results(b) 24 Hours	25 Days	50 Days	114 Days
Haynes alloy 25 (L-605)	NC	NC	NC	NC
Haynes alloy 25 - Rigimesh	NC	NC	NC	NC
Haynes cast alloy 31	NC	NC	NC	NC
Stainless steel 17-4 P-H	NC	NC	NC	NC
Molybdenum alloy TZM	NC	Discolored	Discolored	Corroded(c)
Inconel 600	NC	NC	NC	NC

(a) Samples stored at room temperature (70° to 75°F) in sealed glass jars

(b) NC = No change

(c) Thin surface layer corroded

9.29-percent iron and 87.04-percent carbon. The iron compound present was most likely iron carbide (Ref. 50 lists iron carbide as the iron compound present in carbon from a Bosch reactor).

Six small samples of propellant made with Bosch reactor carbon showed signs of decomposition after 5 months of storage at ambient conditions. All the samples had a strong odor of ammonia and had become very hard; two of the samples had a reddish-brown powder dispersed in them. Although not identified by chemical tests, this material was presumably an iron oxide, formed from iron containing contaminants known to be present in the Bosch reactor carbon.

Addition of 5-percent-by-weight ferric carbide to propellant formulations W-38, W-42, and W-60 caused the evolution of ammonia from all three samples within three days. Samples of these propellants without ferric carbide have remained slightly acidic and have shown no signs of decomposition. The pH of the propellant is normally stabilized at approximately 5 by the buffering action of the dissolved ammonium nitrate. Under either strongly acidic or basic conditions the propellant is known to decompose, presumably due to reactions involving the aluminum metal which loses its protective coating of oxide under these conditions. Propellant formulations W-63 and W-64, containing 6- and 11-percent ferric carbide, respectively, were acidic immediately after preparation. Within 24 hours the vapor above these propellant samples became basic, and the odor of ammonia was evident. A brown crust formed over the surface of both propellants. After six days of storage, W-64 had a thick, hard brown crust. During the course of the seventh day, a vigorous exothermic reaction occurred, accompanied by copious gas evolution. The sample was immersed in cold water to quench the reaction. Sample W-63, containing less ferric carbide, did not undergo such a violent reaction. However, at the end of 25 days, the propellant had turned to a hard, brownish solid, demonstrating again the incompatibility of ferric carbide with MONEX W propellant.

Analysis of the gases evolved during storage of a sample of MONEX W-38 containing Bosch reactor carbon was made by gas chromatography. These gases consisted of air, carbon dioxide, ammonia, water, and several unknowns (occurring under one broad peak). After five days of storage at ambient temperature, the propellant had a pH of 10. After a 26-day interval, the carbon dioxide content of the gases had increased, while the ammonia content had decreased. Two new peaks occurring between the carbon dioxide and ammonia peaks were noted but not identified. During this time the propellant had thickened to a semisolid state. A Varian Aerograph gas chromatograph, Model 202B, employing a 4-foot, 9-inch by 1/4-inch diameter column packed with 50/80 mesh Porapak T was used for the analyses.

4.2.10.2 Gas Evolution at 77° and 100°F

MONEX W propellants, in common with many other propellants, exhibit a small degree of gas evolution. If the rate of gas evolution is too rapid, the propellant will be unsatisfactory for long term usage since excessive pressure will develop in the propellant storage tank even though very little change has occurred in the overall composition of the propellant.

Gas evolution from a sample of MONEX W-38 (containing carbon, polyethylene, and feces), stored in a sealed glass vessel immersed in a 25°C (77°F) constant temperature bath, exhibited a decline in rate with storage time. After an initial 8-day period characterized by a relatively high rate of gas evolution, the rate decreased continuously up to 280 days. From 280 days through 474 days there was little further gas evolution. A malfunction in the thermoregulator of the constant temperature bath after the 474th day caused an exposure of the sample to temperatures well in excess of 100°F for several hours. This resulted in resumption of a slow rate of gas evolution, as shown by the stepwise increase of the pressure curve in Fig. 22.

A sample of MONEX W-42, utilizing feces obtained from a four-man crew in a 60-day space cabin simulator test at McDonnell-Douglas (Santa Monica), displayed a lower initial rate of gas evolution during the first 64 days of testing at 77°F than did the MONEX W-38 sample. On the 65th day of testing, propellant W-42 experienced the same uncontrolled temperature environment as W-38 on its 474th day. The rate of gas evolution following this event appears abnormal and is probably a result of the exposure to elevated temperatures. In Fig. 22, a comparison of gas evolution of MONEX W-38 and W-42 at 77° and 100°F, the curves show only the amount of gas evolved in excess of that due to the equilibrium vapor pressure of the propellant.

Gas evolution was also determined from samples of MONEX W-38 (containing feces, carbon, polyethylene) and W-42 (containing only feces) stored in sealed glass vessels immersed in a 100°F constant temperature bath (Fig. 22). The sample of W-38 propellant stored at 100°F exhibited a more rapid initial rate of gas evolution than did the sample of W-42 propellant. After 80 days, a nearly constant rate of gas evolution began and continued for the following 60 days. The rate of gas evolution for W-38 during this 60-day period was 4.5×10^{-4} cm^3 (STP)/g/day. The rate of gas evolution for the same 60-day period for MONEX W-42 was 4.7×10^{-4} cm^3 (STP)/g/day. The difference in the initial rates of gas evolution may be due to some variation in the incorporated feces, as it appears unlikely that the presence of carbon black or polyethylene could account for the large variation in gas evolution rates. In comparison, the rate of gas evolution for the sample of MONEX W-38 stored at 77°F was 1.36×10^{-4} cm^3 (STP)/g/day for the period from the 45th to the 75th day. The data points for both samples stored at 100°F display somewhat more scatter than the samples stored at 77°F, probably because precise temperature control was more difficult at 100°F than at 77°F.

4.2.10.3 Storage Effect On Physiochemical Properties

Storage of MONEX W propellants at 70° to 80°F in glass or polyethylene had little or no effect on physiochemical properties. Rheological testing showed the propellant (W-38) became slightly more fluid with increased storage time (Par. 4.2.5). Impact sensitivity remained unchanged. Gas evolution decreased with length of storage time, eventually ceasing in one case (Par. 4.2.10.2).

Qualitative analysis by gas chromatography of the gases evolved from a sample of MONEX W-38 stored for 50 days at 70° to 80°F showed no sign of

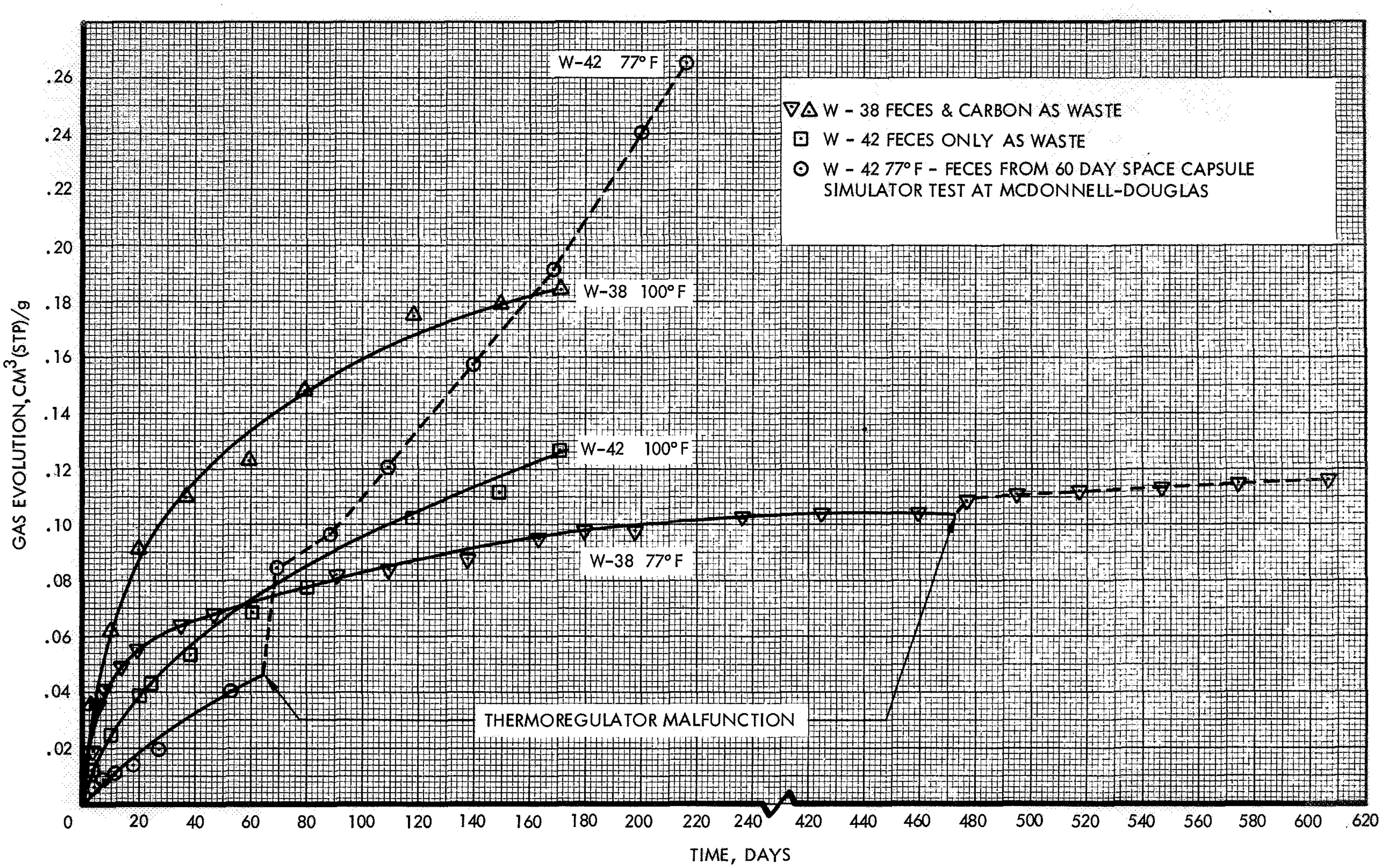


FIGURE 22. - GAS EVOLUTION$^{(a)}$ OF MONEX W PROPELLANTS

(a) CORRECTED FOR VAPOR PRESSURE OF THE PROPELLANTS hydrogen gas evolution. In addition to nitrogen, oxygen, and water vapor, there were five unknown peaks in the chromatogram, but they all appeared at higher retention times than the identified peaks and were probably more complex chemical species.

Examination of the stored propellant samples disclosed no sign of gross separation except for sample W-58, containing a Polyox water soluble resin, where a liquid and a solid phase separated. A thin liquid surface layer, common to most gelled propellant systems, was noted in all cases, but this was only a minor change. Transfer of some propellant samples to new containers revealed no sign of agglomeration or sedimentation. In general, the propellant samples appeared to have remained essentially unchanged during storage.

4.2.10.4 Storage Effect On Combustion Properties

Liquid injection test engine firings disclosed no change in the combustion properties of waste management propellant stored for 9-1/2 months. A detailed discussion of the firings is made in Par. 5.5.

4.2.11 Mechanical Stability

Qualitatively, the waste management propellants made and stored for periods of 6 to 18 months appeared to have good mechanical stability. Except for MONEX W-58, containing Polyox resin, no signs of gross separation were observed.

On a semiquantitative basis, three representative propellant formulations displayed very good mechanical stability.

Samples of MONEX W propellants were centrifuged to determine the acceleration level required to cause phase separation. MONEX W-38, W-42, and W-60, whose waste components consist of feces, carbon, and polyethylene; feces only; and feces and urine, respectively, were tested.

A model CL International Chemical centrifuge was used for these tests. Since this centrifuge operates only at seven incremental power settings, a precise separation point was not established. The following data were obtained at laboratory ambient temperature.

Propellant W-38

50 g's for 30 minutes - no separation
82 g's for 5 minutes - produced minor separation

Propellant W-42

5 g's for 5 minutes - no separation
26 g's for 5 minutes - produced minor separation

Propellant W-60

20 g's for 5 minutes - no separation
53 g's for 5 minutes - produced minor separation

4.2.12 Handling Characteristics

MONEX W propellants appear to present no unusual requirements for handling and storage. The main area of concern is in the blending of feces and mixing of propellant, which should be done in a hood to safeguard against possible biological contamination of the operator. This is especially important if a high-speed blender, such as a Waring blender, is used that can create an aerosol. Once the propellant has been made, it may be handled routinely as a safe propellant.

Spilled propellant should be wiped up and disposed of by burning or flushing with water. Since the propellant is not sterile, hypochlorite solutions, such as bleach, should be used to decontaminate contaminated areas.

Compatibility is generally not a problem with MONEX W propellants, since out of 17 structural materials only copper was shown to be grossly affected. The propellant is also difficult to ignite by pyrotechnic means unless an intense heat source is involved. No unusual cleaning procedures are needed to prepare storage containers for the propellant, since it appears to be quite inert to most contaminants ordinarily found in working areas such as grease, oil, solvents, etc.

4.3 CHARACTERIZATION OF WASTE FROM A MANNED SPACECRAFT SIMULATION EXPERIMENT

The objective of this phase of the program was to evaluate propellant produced from human waste generated during a 60-day manned spaceflight simulation study conducted for NASA by the Missile & Space Systems Division of McDonnell-Douglas Corporation at Santa Monica, California.

4.3.1 Feces Collection

Feces were collected from the four-man crew during the last 72 hours of the simulation study. A total of 648.5 grams of feces were obtained, only slightly more than a third of the 1,800-gram total anticipated on the basis of 150 grams per man-day which is the average amount excreted while on a normal diet. Individual output varied from 22.1 grams to 293.3 grams per donation. Samples were collected in the space cabin simulator in standard, waxed cardboard containers. The sealed containers were stored in a refrigerator after being passed through an airlock in the simulator.

After weighing, the individual fecal samples were combined and blended in the usual manner before being incorporated into propellant. The feces were much thicker than feces obtained from persons on a regular diet, making them difficult to blend.

4.3.2 Analysis of Feces

Samples of the blended feces were analyzed for water, elemental carbon, elemental nitrogen, and ash content. The results of these analyses were strikingly similar to results obtained previously on a blended batch of feces (approximately 66 individual samples) from persons on a regular diet. (The latter samples were obtained from personnel at Rocket Research Corporation.)

The results of the analyses on the two blended lots of feces are compared in Table 40.

A culture of the blended feces from the space cabin simulator study showed vigorous growth in 24 hours using trypticase soy broth at 37°C.

4.3.3 Propellant Characterization

A batch of MONEX W-42 propellant was prepared from the remaining feces. There was a very evident increase in viscosity as compared to previous batches of W-42. Rheological properties determined with a capillary extrusion rheometer are illustrated in Fig. 19. Propellant density at 25°C (77°F) was 1.492 g/ml, not significantly different from other batches of W-42 containing feces produced under normal conditions.

Storage stability of this propellant was determined by quantitative measurement of the gas evolved over a 7-month storage period at 77°F. Results for the first 67 days indicated that this propellant will probably evolve less gas than MONEX W-38 propellant. A more detailed account of this test is presented in Par. 4.2.10.2.

A test firing using this batch of MONEX W-42 was not successful, as the propellant failed to sustain combustion in the monopropellant mode. Paragraph 5.5.21 contains a discussion of this firing.

4.3.4 Evaluation of Additional Sources of Waste

A secondary task of this phase of the program was to evaluate additional waste (other than feces) generated in significant quantities during the manned spacecraft simulation experiment to determine its suitability for incorporation in waste management propellant.

The Space Cabin Simulator "equipment provides support for a four-man crew under conditions that are comparable to those encountered by an earth-orbiting laboratory operating on a one-year mission with 60- to 90-day resupply periods" (Ref. 3). The prime objectives of the 60-day study were to test the equipment in the subsystem concerned with a closed oxygen and water cycle. No attempt was made to have a fully integrated waste management system, so no significant quantities of waste (other than feces) suitable for waste management propellant were generated.

There were areas of operation, however, in which waste was generated that has potential application in an integrated waste management system. The most obvious area is that of food packaging and food remnants. The present study used specially prepared foods (obtained from Epicure Foods, Inc., S. Hackensack, New Jersey) packaged in vacuum-sealed metal cans. The ratio of container weight to food content would prohibit its usage for extended spaceflights. However, development of packaging material also suitable for use in waste management propellant would provide a source for propellant ingredients. The quantity of food remnants would probably be a small and predictable source of waste.

TABLE 40

FECES AND PROPELLANT ANALYSES - SPACE CABIN SIMULATOR STUDY

Raw Feces	Weight (%)	
Component	SCS Blend(a)	RRC Blend(b)
H_2O	73.70	73.58
N	1.92	1.54
C	12.63	12.94
Ash	3.58	3.75

(a) From 4-man crew of space cabin simulator study

(b) From Rocket Research Corporation Personnel

Propellant W-42(c)		
Component	Found	Theoretical
NH_3	6.20	6.07(d)
NO_3	22.13	22.10(d)
Al	31.58	31.57(e)
H_2O	25.2	24.3(f)
C	4.68	4.34(g)

(c) Using feces from crew of space cabin simulator

(d) Based on NH_4NO_3

(e) Based on 98.36% purity of Al H-5 used

(f) Based on water content of feces used

(g) Based on carbon content of feces used

The felt wick evaporator units used in the water recovery subsystem were sealed units not available for use in waste management propellant. With modifications, some of these units could possibly be a source of propellant ingredients if these units were selected for use on long space voyages. The charcoal filters used in purification of water and the cabin atmosphere also would be usable in waste management propellant when no longer usable otherwise. The useful life of these filters is not known.

The Sabatier unit used in oxygen regeneration for this study produced methane, which was vented overboard. If an extended Sabatier cycle were used in an integrated waste management system, the methane could be reacted further to produce carbon as a waste material which would be usable in propellant.

Various filters employed in the subsystems of the space cabin simulator also represent a small source of potential propellant ingredients.

Thus, the 60-day manned space cabin simulator study provided only potential sources of ingredients for waste management propellant. Since the subsystem units employed in the study were mainly breadboard units to demonstrate the feasibility of the subsystems, even semiquantitative data regarding the amount of waste available for propellant use were not obtainable.

5.0 COMBUSTION CHARACTERISTICS OF MONEX W

The combustion characteristics of MONEX W were investigated by both strand burning rate tests and liquid injection rocket engine firings. Strand burning rate tests using a high pressure combustion bomb were performed for compositions containing feces, carbon, and polyethylene as waste, whereas the majority of engine firings were performed with propellants containing only feces as waste. A total of 22 engine firings were conducted in support of the MONEX W feasibility program. The test program was divided into three data acquisition phases, Series I through III.

Series I tests were intended to check out the engine design, test setup and data acquisition systems. This series included firings No. 1 through No. 6 A MONEX A propellant (water substituted for feces) formulation of known characteristics was fired to verify the test setup. Firings No. 5 and No. 6 were conducted with identical formulations and identical hardware. Since results were very repeatable the engine configuration was frozen and propellant formulation was the sole variable.

Series II tests were preliminary tests to determine the effect of propellant formulation upon performance. They were divided into two phases; the first phase consisted of tests No. 7 through No. 11 which served to define a rather broad area of propellant composition which could be fired successfully in injection engines. Tests No. 12 through No. 16, No. 19, and No. 22 were included in the second phase of Series II tests. They were performed after analysis of the data obtained in firings No. 7 through No. 11 to further define practical propellant formulation limits. Except for firing No. 20, engine variables were held constant to obtain comparable propellant data. Firing No. 20 was conducted with a small engine (L* = 150 in.) with a propellant known to produce good performance in the larger engine.

Series III tests were performance tests in support of long term storage stability tests and included a test firing of a propellant formulated with feces obtained from a manned spacecraft simulation experiment. These firings included No. 16, No. 17, No. 18, and No. 21.

5.1 STRAND BURNING RATE TESTS

A high pressure combustion bomb was used for the determination of strand burning rates (see Fig. 23). The vessel was constructed from a 3/4-inch thick, high pressure steel cylinder and hydro-tested at 3,000 psia to insure structural integrity. A 3,000-psia burst diaphragm provided an added margin of safety in the event of a pressure surge during firing (no pressure surges were evident in any firings made). A removable hollow core contained the ignition and instrumentation leads and served as a mount for the propellant sample. The bomb was pressurized to the desired operating pressure with compressed nitrogen. Pressure in the bomb was monitored during firing by means of a 0 - 3,000 psia transducer. Strand burning rate samples, loaded in soda straws or cardboard tubes, were pierced with circuit wires at accurately spaced intervals, mounted on the core, and fired in a vertical position.

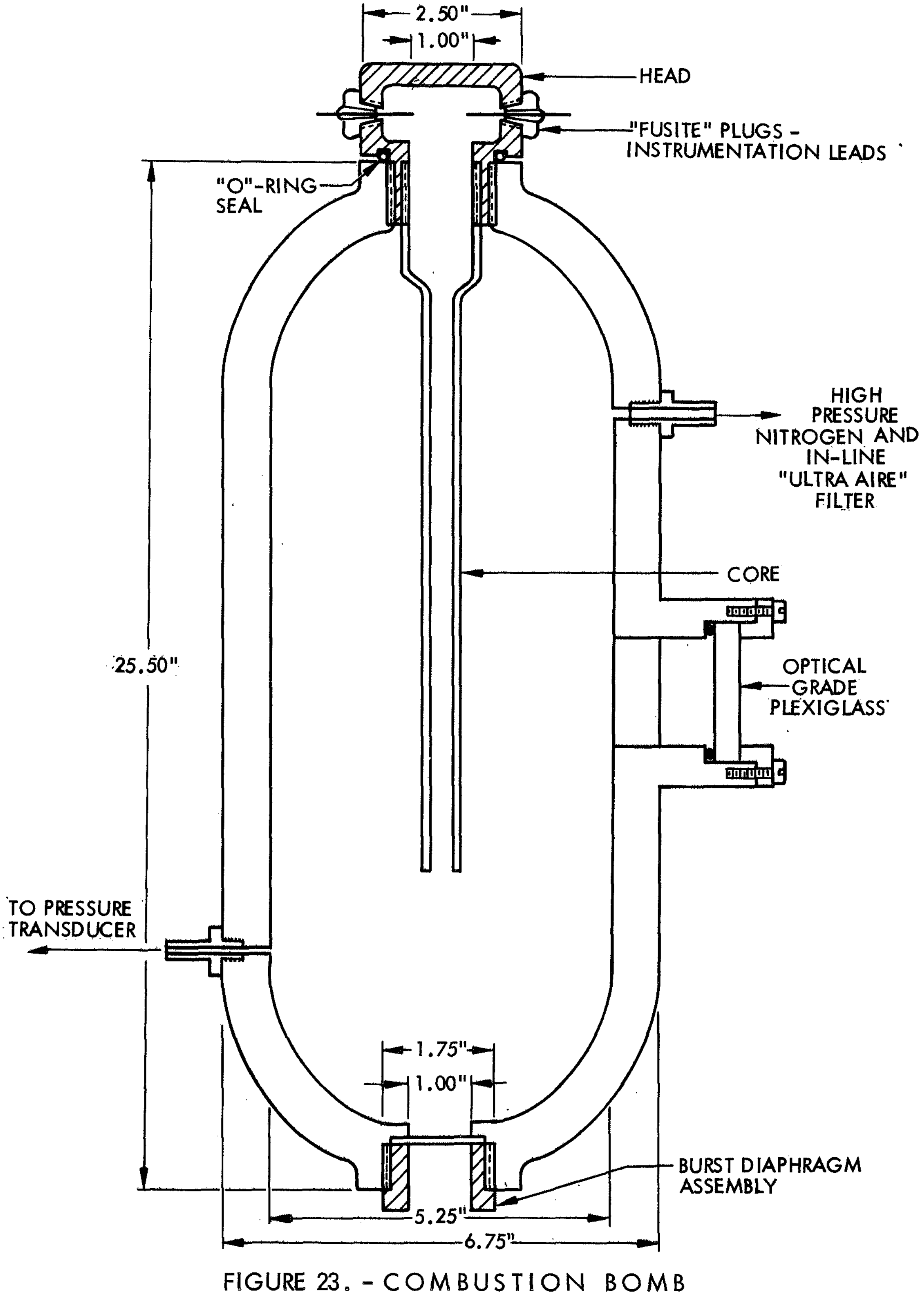


FIGURE 23. - COMBUSTION BOMB

Burning rate was determined by measurement of the time lapse between burn-through of the circuit wires. Increase in resistance of the overall circuit at each burn-through was monitored on the same strip chart recorder as the pressure, thereby facilitating data reduction.

Initially, strand burning tests were conducted using 0.266-inch I.D. soda straws. Some propellant formulations, however, failed to ignite, while others which did ignite failed to maintain combustion. The effect was probably due to the low burning rates of these propellants and associated high heat losses. By using 0.50-inch I.D. cardboard tubes, better results were obtained. Nevertheless, sustained combustion generally was obtained repeatedly only when the M-1 burning rate additive was included in the formulation. Strand burning rates are reported in Table 41.

Tests were performed with formulations W-49 through W-53. The waste component of these compositions consisted in each case of 79.6% feces, 13.6% carbon, and 6.8% polyethylene powder. Total waste content was varied from 28% to 53%, as shown in Fig. 24. Although no theoretical calculations were actually performed for this system, performance should be lower than that represented in Fig. 9. It is expected that these compositions should range from those possessing relatively high specific inpulse (low waste content) to those possessing low specific impulse (high waste content).

Strand burning rates as a function of pressure are presented in Fig. 25. Although there is considerable data scatter, it does appear that the burning rates and pressure exponents decrease with increasing waste content of the propellant (see also Fig. 26). It is not certain whether or not these effects are due wholly to the waste content of the propellant, since in the formulations tested here there was a slight decrease in aluminum content with increasing waste.

Further efforts to determine more accurately the burning rate and pressure exponents of the above propellant system containing carbon and polyethylene were not made since program emphasis centered on liquid injection engine tests of MONEX W formulations containing only feces. As no burning rate data was obtained for the latter formulations, no direct correlation between liquid injection engine performance and liquid strand burning rate data for MONEX type propellants could be obtained. The strand burning rate data, however, would be of value in connection with end-burning motor applications.

5.2 TEST ENGINE HARDWARE

The monopropellant test engine and test system employed during the Series I checkout tests are shown in Figs. 27 and 28.

The nominal design parameters of the thrust chamber were:

Thrust	200 lbs
Operating Pressure	1,000 psia
Chamber Diameter	2.66 in.
Chamber Length	10 in.
Nozzle Diameter	.40 in.

TABLE 41

STRAND BURNING RATE DATA - MONEX W

Formulation	Run No.	Inches Burned	Seconds	In/sec	Psia
W-49	1	0-2	22.80	0.0877	565
W-49	1	2-3	13.80	0.0725	615
W-49	1	3-4	12.60	0.0794	645
W-49	2	0-2	15.90	0.1260	1410
W-49	2	2-3	7.70	0.1300	1515
W-49	2	3-4	8.70	0.1150	1585
W-49	3	0-2	17.20	0.1160	1755
W-49	3	2-3	8.80	0.1140	1755
W-49	3	3-4	-	-	-
W-50	1	0-2	-	-	-
W-50	1	2-3	15.40	0.0649	630
W-50	1	3-4	15.00	0.0667	655
W-50	2	0-2	24.20	0.0826	1055
W-50	2	2-3	12.60	0.0794	1070
W-50	2	3-4	11.70	0.0855	1085
W-50	3	0-2	21.90	0.0913	1185
W-50	3	2-3	10.80	0.0926	1255
W-50	3	3-4	11.70	0.0855	1290
W-50	4	0-2	22.10	0.0905	1285
W-50	4	2-3	11.40	0.0877	1340
W-50	4	3-4	10.70	0.0935	1380
W-50	5	0-2	18.70	0.1070	1975
W-50	5	2-3	8.70	0.1150	2095
W-50	5	3-4	8.20	0.1120	2160
W-51	1	0-2	36.70	0.0545	655
W-51	1	2-3	16.80	0.0595	705
W-51	1	3-4	15.50	0.0645	730
W-51	2	0-2	33.50	0.0597	1185
W-51	2	2-3	17.40	0.0575	1215
W-51	2	3-4	16.70	0.0599	1235
W-51	3	0-2	31.70	0.0631	1890
W-51	3	2-3	14.90	0.0671	1915
W-51	3	3-4	15.50	0.0645	1915

TABLE 41 (Concluded)

STRAND BURNING RATE DATA - MONEX W

Formulation	Run No.	Inches Burned	Seconds	In/sec	Psia
W-51	4	0-2	-	-	-
W-51	4	2-3	-	-	-
W-51	4	3-4	18.30	0.0546	630
W-52	1	0-2	42.70	0.0468	1130
W-52	1	2-3	20.70	0.0483	1160
W-52	1	3-4	22.30	0.0448	1190
W-52	2	0-2	43.30	0.0462	1785
W-52	2	2-4	42.40	0.0472	1800
W-52	3	0-2	41.50	0.0482	1980
W-52	3	2-3	21.30	0.0469	2005
W-52	3	3-4	18.30	0.0546	2020
W-53	1	0-2	59.30	0.0337	1095
W-53	1	2-3	30.20	0.0331	1095
W-53	1	3-4	30.60	0.0327	1110
W-53	2	0-2	66.80	0.0299	615
W-53	2	2-3	34.90	0.0287	615

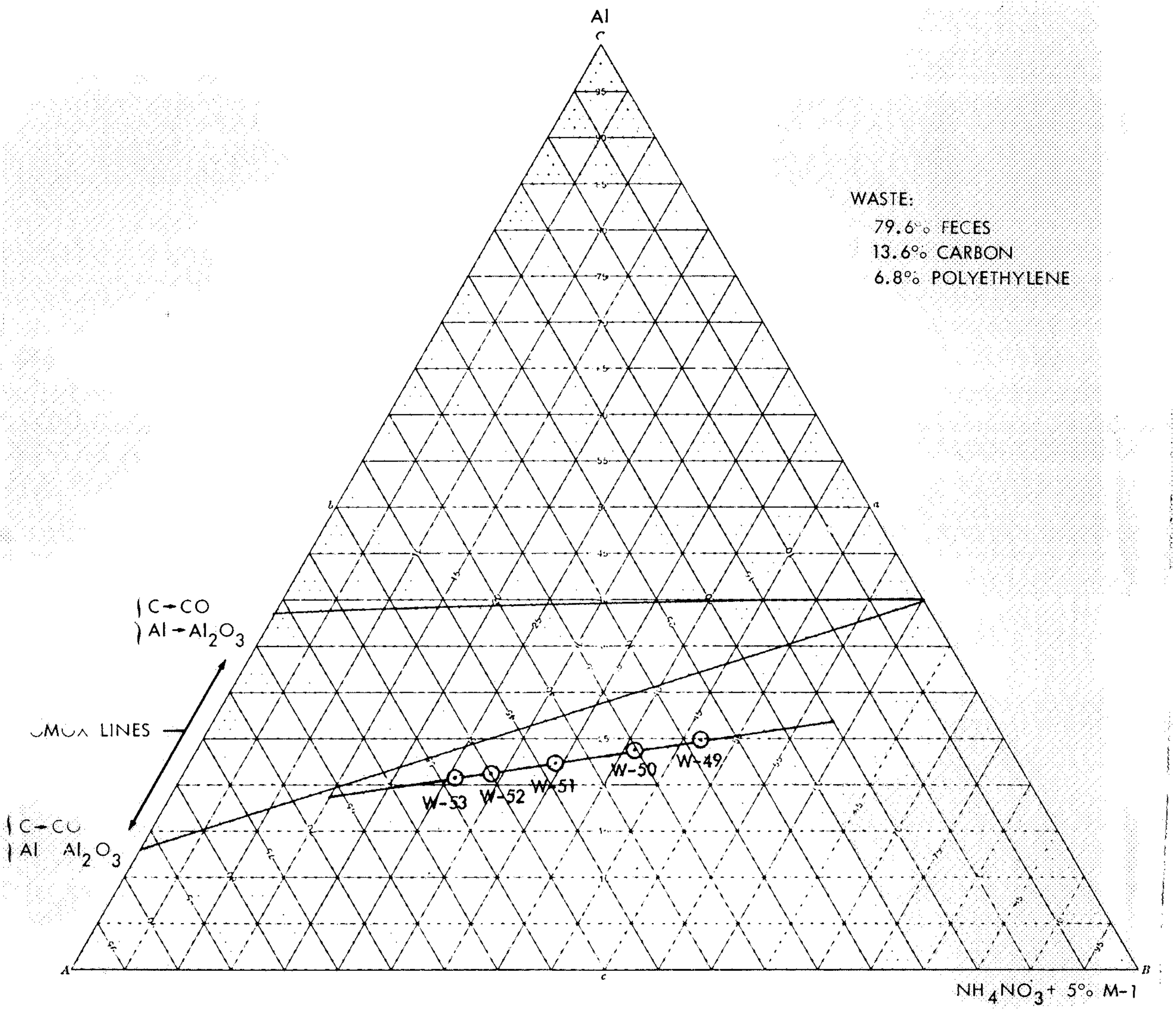
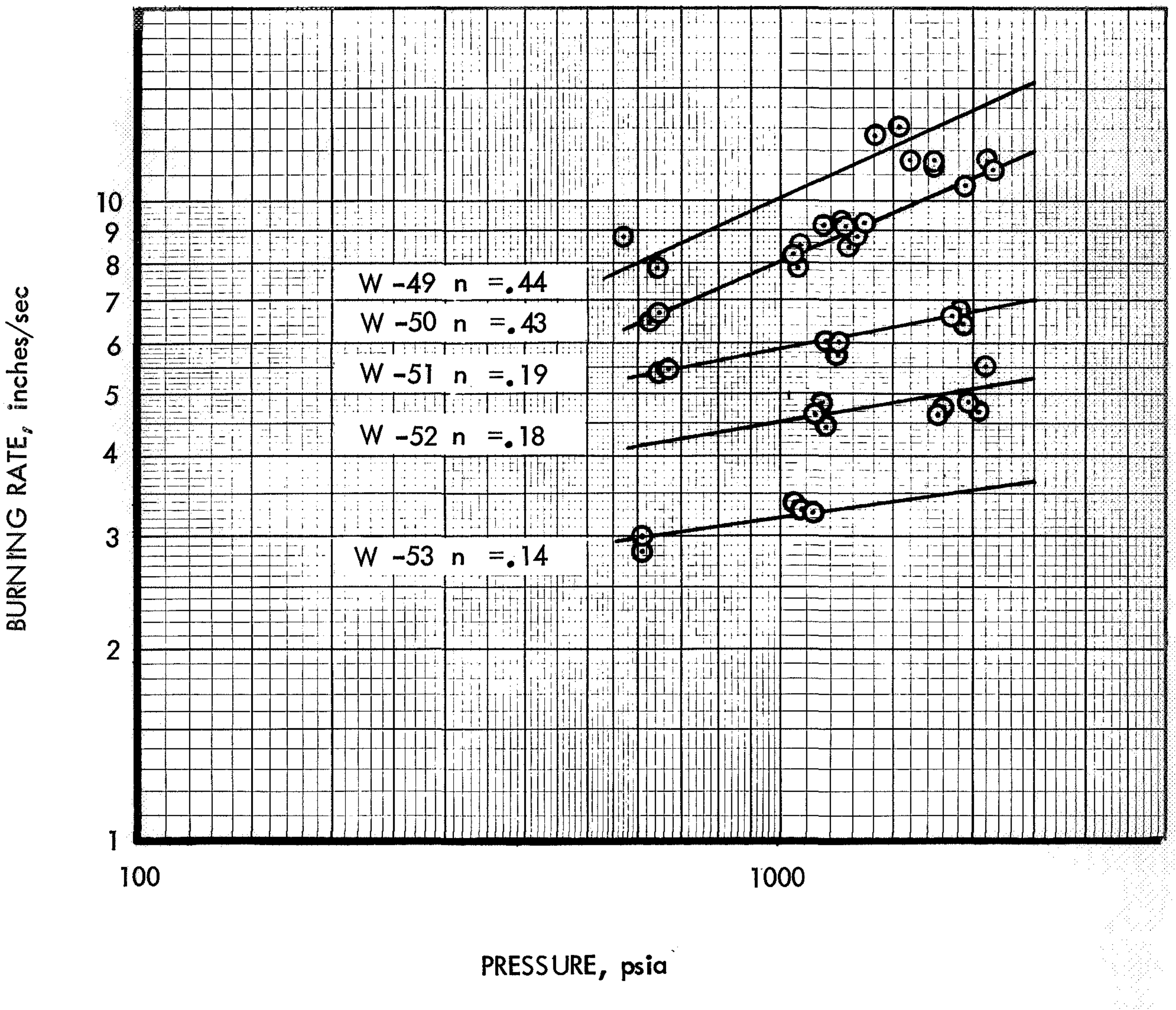


FIGURE 24. - STRAND BURNING RATE TESTS OF MONEX W COMPOSITIONS



n = PRESSURE EXPONENT

FIGURE 25. - STRAND BURNING RATES AS A FUNCTION OF PRESSURE MONEX W

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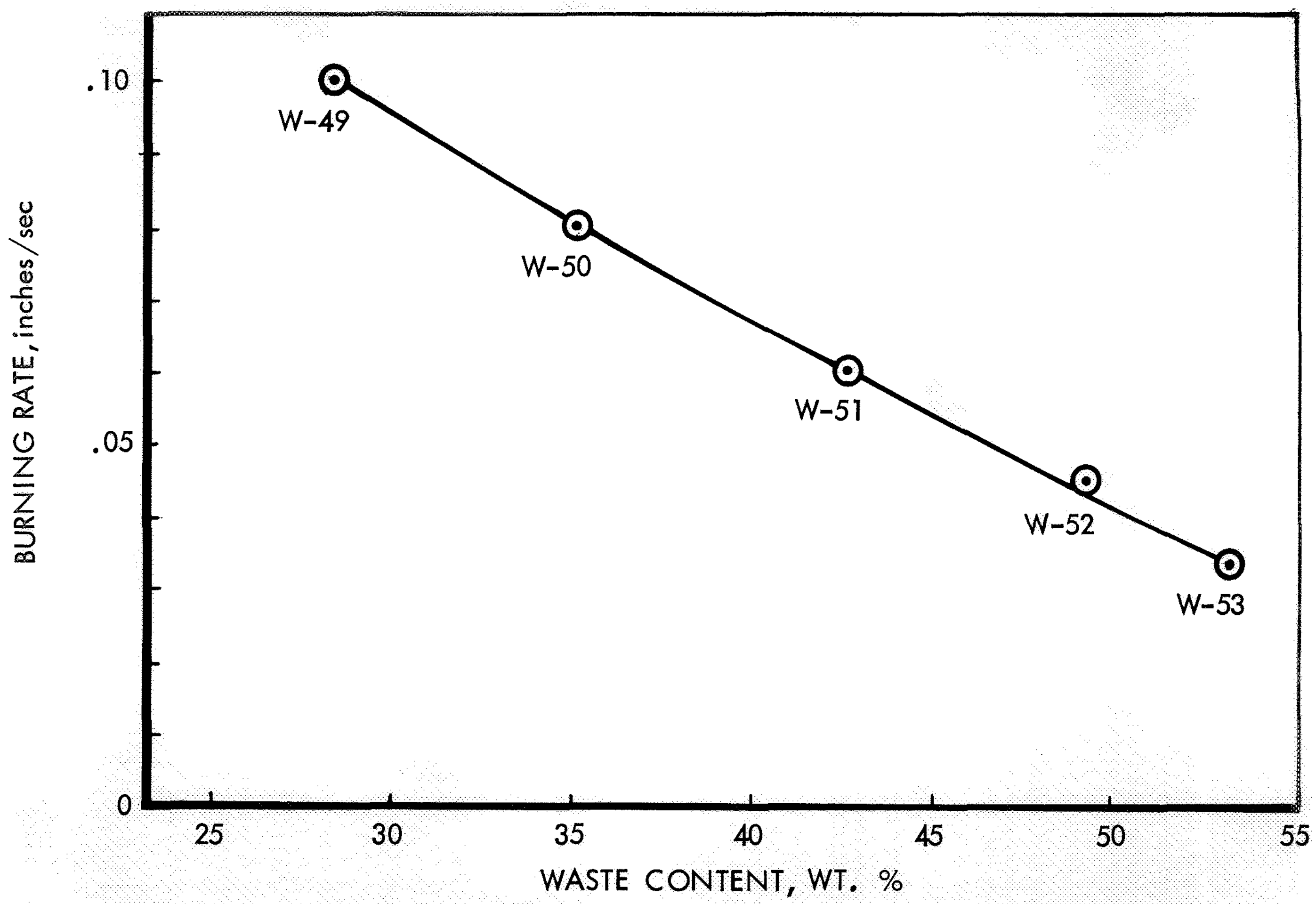

FIGURE 26. - STRAND BURNING RATES OF MONEX W AS A FUNCTION OF WASTE CONTENT

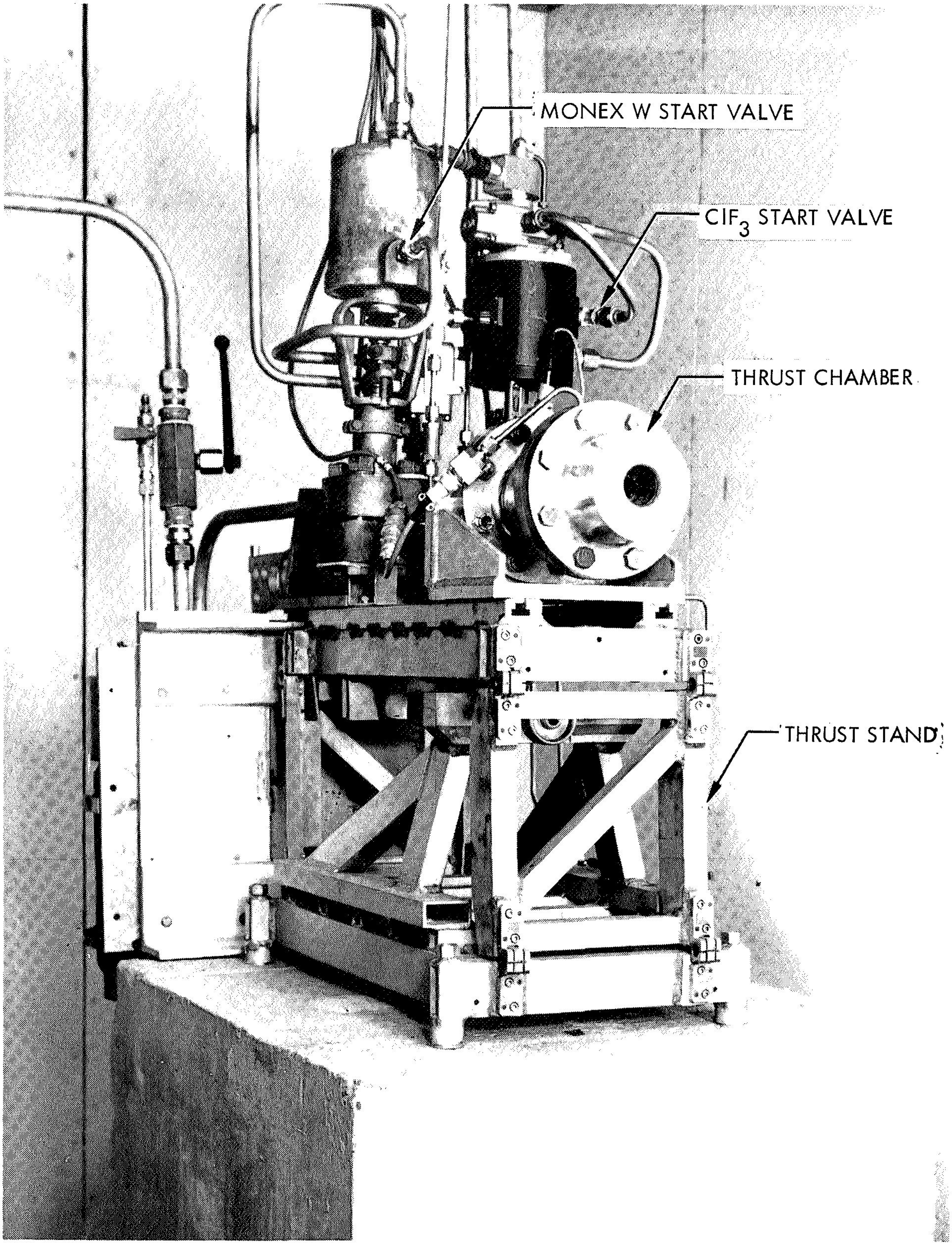

FIGURE 27. TEST INSTALLATION WASTE MANAGEMENT PROGRAM

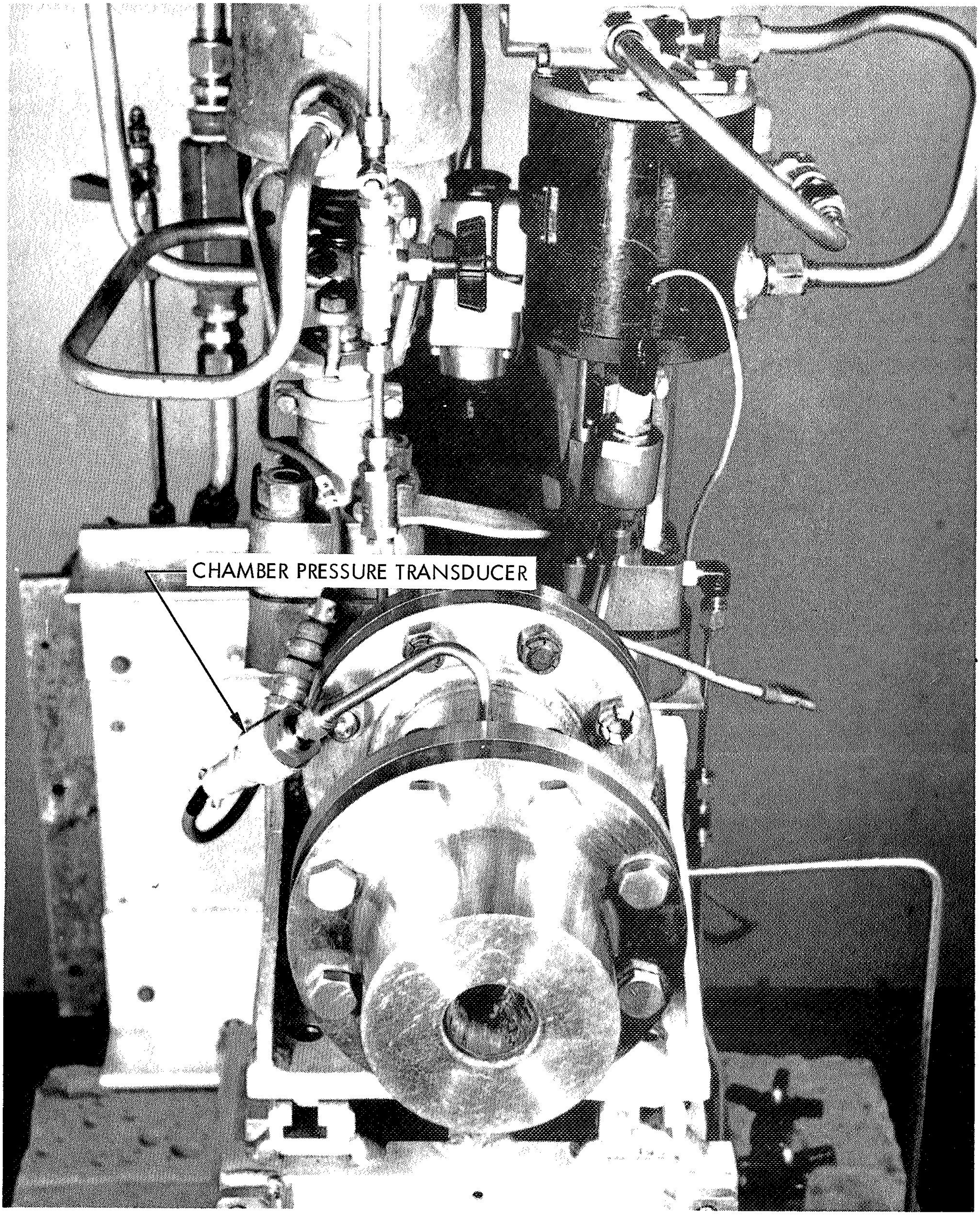

FIGURE 28. TEST INSTALLATION WASTE MANAGEMENT PROGRAM (CLOSEUP)

This basic thrust chamber design was employed throughout the program. A brief description of each of the thrust chamber components is presented in the following paragraphs.

5.2.1 Injector Design

The injector heads were fabricated of Type 321 stainless steel and were in four basic patterns.

a. A single element injector

b. A dished face, two element injector

c. A dished face, four element injector

d. A flat face, four element injector

Injectors are identified in this report by a three part hyphenated number designating the number of MONEX injector elements, the discharge orifice diameter, and the type of injector face (either flat or dished) as in the following example.

1 - 0.109 - D
Type of Injector Face: D = Dished Face
Diameter of Discharge Orifice
Number of MONEX Injector Elements

The above designation indicates a single element injector with a 0.109 inch diameter discharge orifice and a dished face.

Solid cone spray nozzles were used as the MONEX injector elements for all firings. This type of injector element was selected on the basis of spray tests with both MONEX A and MONEX W. A uniform spray pattern was produced at injector pressure drops above 200 psi. Each injector head also employed a single spray nozzle for hypergolic ignition by injecting chlorine trifluoride (ClF_3).

All tests except initial setup trials were conducted with a single element dished face injector containing a central MONEX spray nozzle and an outer ClF_3 spray nozzle.

The two element dished face injector head contained two outer MONEX spray nozzles and a central ClF_3 spray nozzle. The MONEX spray nozzles were located at 0.8 inch from the chamber centerline at an angle of 30 degrees to the chamber axis. All dished face injector heads incorporated in conical face with a 120-degree included angle.

The dished face, four element injector head incorporated four MONEX spray nozzles 90 degrees apart and a central ClF_3 spray nozzle. The MONEX spray nozzles were located 0.8 inch from the chamber centerline at an angle of

30 degrees to the chamber axis. The flat face four element injector head contained four MONEX spray nozzles 90 degrees apart, located 0.85 inch from the centrally located ClF_3 spray nozzle and parallel to the chamber axis.

5.2.2 Thrust Chamber Design

The thrust chamber was constructed of a stainless steel case, an ATJ graphite chamber liner, an ATJ graphite nozzle insert, and a stainless steel aft closure incorporating the 15-degree nozzle expansion cone.

A 450-inch L* chamber was employed during MONEX W checkout tests. This size chamber was maintained throughout the test program with the exception of test No. 20. Test No. 20 utilized a chamber L* of 150 inches.

The nominal chamber pressure level was adjusted by small changes in the nozzle throat diameter to achieve a chamber pressure of approximately 1,000 psia.

5.3 TEST FACILITIES

Two test bays were employed during the program, a test bay for unconfined firings and a special test bay for confined firings where the exhaust was sampled for biological activity.

5.3.1 Test Facility for Unconfined Firings

A schematic diagram of the checkout test setup is presented in Fig. 29. The test installation consisted of two basic systems: A MONEX pressurization and feed system, and a ClF_3 start system.

MONEX propellant flow was controlled by a pneumatically operated start valve (Model 3620 Annin valve) to obtain a limited degree of flow throttling during the start transient.

The propellant tank contained a movable piston for positive MONEX feed. Pressurization was accomplished by feeding water under pressure into the propellant tank above the piston. Water was stored in a separate tank which was pressurized by regulated gaseous nitrogen. Two Cox AN-20, turbine type flowmeters were installed in the line connecting the water and MONEX tanks. These redundant flowmeters measured the water volumetric flow rate which was exactly equal to the MONEX volumetric flow rate.

The ClF_3 system, with the exception of Teflon seated solenoid valve components, was fabricated of 300 series stainless steel. The start valve for the ClF_3 was a Model 9420 Annin valve. All hand valves in the ClF_3 system were Hoke HY 441 bellows seal valves. The ClF_3 tank (75 ml capacity) was pressurized by charging a larger pressurization tank to a preselected value with gaseous nitrogen. The pressurization valve was closed after charging the pressurization tanks and the ClF_3 system operates in the blowdown mode. ClF_3 venting and disposal was through a charcoal burner. Prior to loading the ClF_3 system, all components were passivated with ClF_3 vapor.

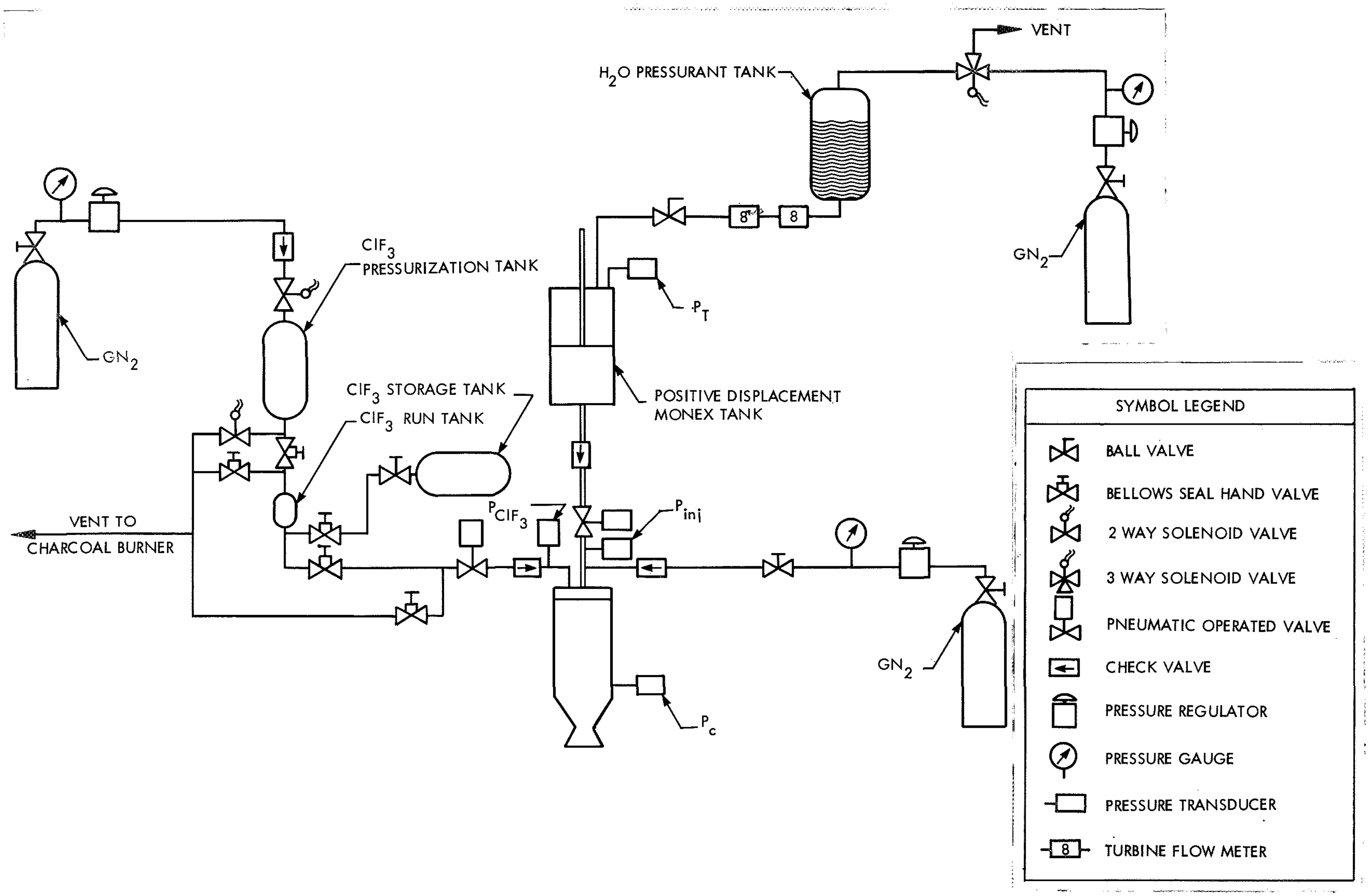

FIGURE 29. SCHEMATIC DIAGRAM MONEX W CHECKOUT TEST SYSTEM

The thrust stand utilized was a parallelogram type with Bendix Flexural Pivots as flexures. The stand was calibrated by applying known weights, acting over a 5:1 pulley through the centerline of thrust. The load cell (Schaevitz-Bytrex) had a range of 0-500 lbs.

5.3.2 Engine Test Setup Improvements

During the course of the engine-firing program, additions and modifications were made to improve the safety and performance of the test setup. After firing No. 10, significant additions to the setup were permanently installed. Original components were refurbished or replaced. Figure 30 is a schematic diagram of the final engine test setup. Principal modifications to the initial installations and modification purposes are listed below:

	Modification	Purpose
a.	A ClF_3 purge system was added	Safety
b.	An additional air-actuated MONEX enable valve was installed	Safety
c.	A fill valve and sight glass were added to the water pressurant tank	Improve operation
d.	A pressure transducer was located in the engine forward closure	Added data acquisition
e.	A ClF_3 drain system was added	Reduce ClF_3 venting

5.3.3 Test Facility for Confined Firings

This test facility was originally constructed for use with propellants producing toxic exhaust elements. The thrust chamber was directly exhausted into a 54-inch diameter by 40-feet length firing chamber which was equipped with Ultra Aire filters (Mine Safety Appliances Company) certified to remove a minimum of 99.97 percent of the solid particles having a diameter of 0.3 microns or larger, from exhaust gases. With the exception of the exhaust containment system, both the confined and unconfined test systems were essentially identical.

5.4 TEST PROCEDURE

5.4.1 Firing Procedure

In order to obtain comparable data each firing was conducted in conformance with a standard testing procedure. Significant procedural steps are described in chronological order.

a. The test engine was cleaned and the components examined for detrimental wear. Injectors, engine nozzle inserts, chamber liner and the aft closure ablative material were replaced as required. The engine was assembled using new gaskets, and throat measurements were taken.

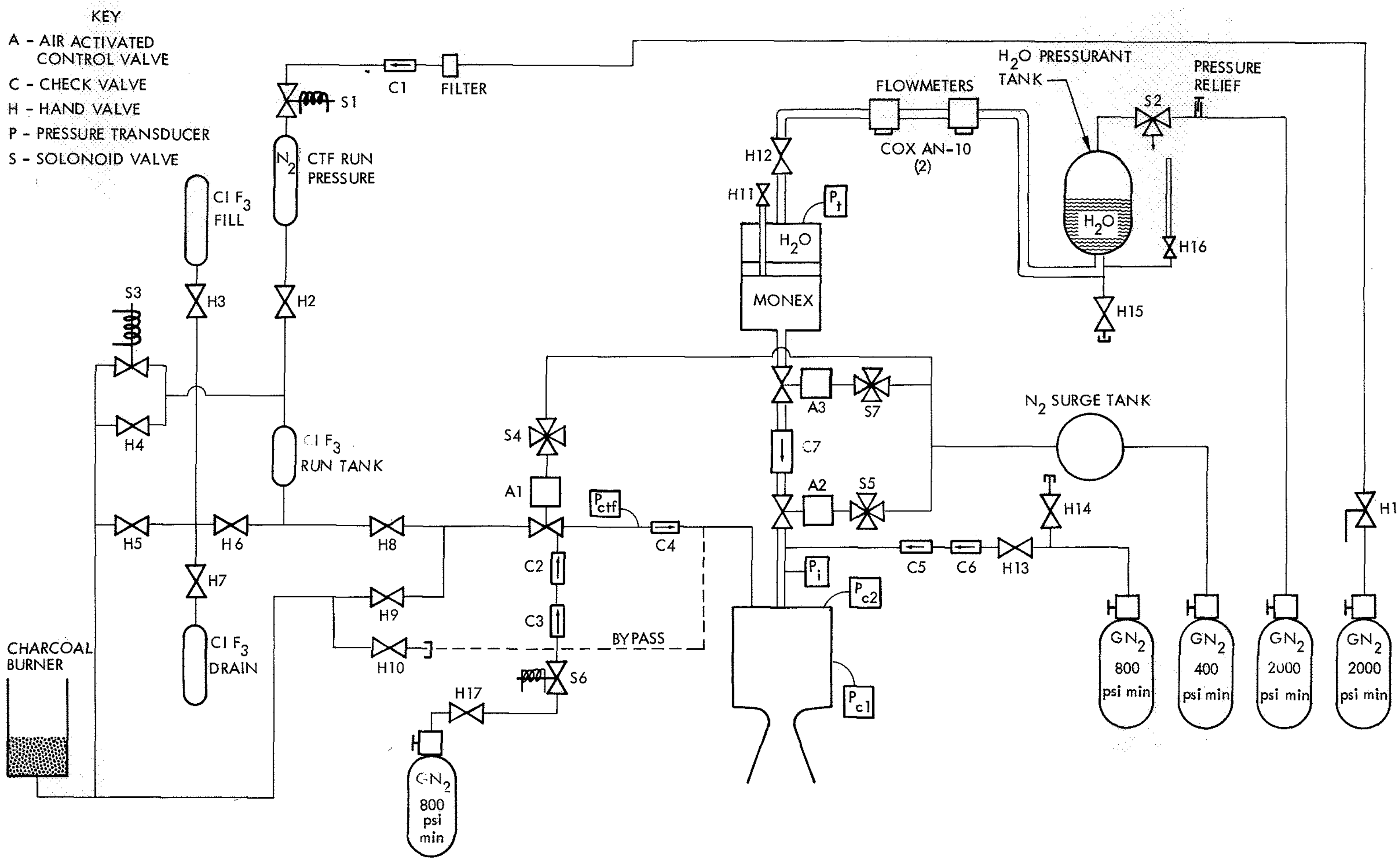

FIGURE 30. - MONEX W TEST INSTALLATION SCHEMATIC DIAGRAM

b. After samples were obtained for chemical analysis, the propellant was put into the expulsion tank. The piston was installed and the pressurization system was filled with water. Propellant was bled through the lead lines to the engine connection fitting.

c. Valve timing and leak checks were made. An Agastat timing mechanism was used to close automatically the ClF_3 valve after ignition and close the MONEX valve at the completion of the run. The ClF_3 valve actuation signal was set to precede the MONEX valve by 45 ± 5 msec. The ClF_3 valve closed at 45 ± 5 msec and the MONEX valve closed at 1.8 ± 0.2 sec. Run duration was limited to 2 sec to prevent excessive erosion to the engine throat insert and allow its subsequent use. An abort system was also set by placing a microswitch on the ClF_3 valve, which, if not actuated by full opening of the ClF_3 valve, prevents MONEX injection. The timing of the two cycles, run and abort, was checked by actuation of the fire switch and recording the function of the valves on a recorder. The ClF_3 valve was leak checked by pressurizing the upstream side and observing any pressure rise in a closed downstream loop.

d. The engine was mounted to the thrust stand and the transducers installed. Pressure transducers were installed midway in the engine chamber and in the injector plate. A pressure transducer, modified for compatibility with ClF_3, was installed downstream of the ClF_3 valve. To record injection characteristics, pressure transducers were installed in the expulsion tank and downstream of the MONEX valve. A thermocouple was attached to the MONEX feed line just upstream of the injector. All transducers were calibrated and channeled to a Honeywell 1612 Visicorder. For back-up, each parameter was also recorded on a Moseley strip chart.

e. The thrust load cell was dead weight calibrated to 350 lbs. Thrust transducer output was recorded on the Visicorder and the strip chart.

f. The small ClF_3 run tank was filled from a supply bottle. After filling, the supply bottle was isolated from the system.

g. The MONEX and ClF_3 nitrogen purges were activated.

h. The MONEX system was pressurized to 1,700 psi. If no abnormalities or leaks were observed, the ClF_3 system was pressurized to 1,300 psi.

i. The engine was fired.

j. Post-fire inspection consisted of engine disassembly, throat measurement (before and after cleaning) and photographing residue.

5.4.2 Data Reduction

a. Measured engine performance parameters were:

Propellant Density	ρ	Chamber Pressure	P_c
Mass Flow	$\dot{W}$	Nozzle Throat Area	A_t
Thrust	F	Expansion Ratio	ε

b. Actual performance calculations:

$$I_{sp} = F/\dot{W}$$

$$c^* = \frac{A_t P_c g}{\dot{W}}$$

$$C_f = F/A_t P_c$$

c. Theoretical values for various chemical compositions were obtained through the use of a Service Bureau Corporation computer program. Theoretical I_{sp}, c^*, C_f and γ were provided. These theoretical values were corrected for motor conditions as follows:

d. C_f correction for nonoptimum nozzle expansion

$$C_{f \text{ expected actual}} = C_{f \text{ opt theo}} + \varepsilon(P_e/P_c - P_a/P_c)$$

e. Theoretical C_f correction to motor chamber pressure conditions

$$C_f = C_f \text{ (1000 to 14.7)} \sqrt{\frac{1-\left(\frac{P_a}{P_c}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\frac{14.7}{1000}\right)^{\frac{\gamma-1}{\gamma}}}}$$

f. I_{sp} correction for 15^0 half angle nozzle

$$I_{sp} = (I_{sp \text{ optimum}})\ (0.983)$$

g. c* theoretical

$$c^*_{theo} = \frac{I_{sp} \text{ (corrected theoretical) } g}{C_f \text{ (corrected theoretical)}}$$

h. Efficiencies

$$\eta_{I_{sp}} = \frac{I_{sp} \text{ (delivered by motor)}}{I_{sp} \text{ (corrected theoretical)}}$$

$$\eta_{c^*} = \frac{c^* \text{ (delivered by motor)}}{c^* \text{ (corrected theoretical)}}$$

5.5 DESCRIPTION OF TESTS

A data summary of the 22 tests conducted is shown in Table 42. Figure 31 shows typical (MW-9) waste management propellant thrust and pressure vs. time performance curves. A brief description of each firing is presented in the following paragraphs.

5.5.1 MW-1

The first waste management propellant (W-20) to be fired in an engine contained 30% feces and 9.3% carbon (simulating residue from a Bosch type reactor) as waste materials. The remaining components were aluminum (22%) and ammonium nitrate, (35.2%). Propellant density was 1.375 grams/cc. The propellant was injected through a single, 0.109 inch diameter nozzle mounted in the center of a dished forward closure. ClF_3 was injected through an off-center nozzle. Injection pressures were 1,700 psi and 1,300 psi, respectively. The ClF_3 preceded the MONEX by 0.025 sec and was maintained for 0.4 sec. Ignition was instantaneous, and a pressure of 810 psi was achieved during the bipropellant mode. After ClF_3 shutoff, the chamber pressure varied from 145 to 635 psia. Although the monopropellant combustion did not stabilize, ignition method, injection pressure, and valve timing were adjudged satisfactory. A thin grey residue was deposited on all internal surfaces of the engine. No slag type material was present. All components were reusable.

5.5.2 MW-2

For the second firing the propellant formulation and test setup were unchanged; propellant density, however, was 1.407 grams/cc. Four 0.067 inch diameter injectors in a flat head were used to evaluate the effect on combustion stability. The ClF_3 injector was located in the center of the head with the four MONEX injectors equally spaced around it. ClF_3 entered the engine approximately 0.10 sec ahead of the MONEX. Ignition was within 0.025 sec and excellent bipropellant operation was achieved. At ClF_3 cutoff, however, combustion ceased. After the MONEX injection was terminated, the residual propellant in the chamber reignited and burned for 20 to 30 seconds. Post-fire inspection revealed a light deposit on all internal surfaces but no slag. Injectors and nozzle insert were reusable.

5.5.3 MW-3

In order to determine if the test setup was contributing to the combustion instability problems, a propellant of known characteristics, MONEX A was fired. Test conditions and hardware were maintained as similar as possible to setup MW-2. Ignition, bipropellant and monopropellant modes were satisfactory.

5.5.4 MW-4

After a series of injection spray tests, a single but larger 0.156 inch diameter) MONEX injector, mounted in a dished head, was selected. The same

TABLE 42

PRELIMINARY DATA SUMMARY
MONEX W TEST SERIES

Test No.	Injector	L* (in)	Data Time (sec)	P_c (psia)	ΔP_{inj} (psi)	$\dot{w}$ lbs/sec	Post Fire A_t (in^2)	c* (ft/sec)	c* (% theo)	F (lbs)	I_{sp} lbf-sec/ lbm	Theo I_{sp} lbf-sec/ lbm	I_{sp} (% theo)	A_e/A_t	ΔP_c (± % P_c)	Duration (sec)	Formulation					Lab Ident.
																	Al	AN	Feces	Ml	C	
1	1-.109D	525	1.05	145/635	-	Varies	.1207	-	-	30/145	Severe Pressure Fluctuations						22.00	35.2	30.0	3.5	9.3	W-20
2	4-.067-F	520	-	215	-	-	-	Burning Not Sustained After ClF_3 Shutoff									22.00	35.2	30.0	3.5	9.3	W-20
3	4-.067-F	398	.90	1225	335	1.385	.1562	4445	93.2	275	198.5	249.9	79.6	12.31	2.0	1.343	35.9	31.9	26.9[(a)]	5.0	.3[(b)]	A
4	1-.156-D	450	.90	643	405	2.145	.1392	1474	-	145	74.3	-	-	18.63	14.6	1.350	22.00	35.2	30.0	3.5	9.3	W-20
5	1-.109-D	415	1.60	870	546	1.096	.1534	3918	86.8	206	188	225.0	83.5	15.68	1.0	1.825	32.10	28.53	34.37	5.0	0	W-42
6	1-.109-D	498	1.50	955	452	1.022	.1288	3872	85.8	189	185	229.1	82.1	18.67	2.0	1.625	32.10	28.53	34.37	5.0	0	W-42
7	1-.109-D	490	1.65	965	494	1.106	.1385	3889	85.5	210	190	228.8	83.0	17.36	5.0	1.800	33.79	30.03	36.18	0	0	W-43
8	1-.109-D	432	1.50	913	503	1.084	.1459	3954	86.9	212	195.5	225.8	86.6	16.30	3.0	1.847	38.0	28.5	28.5	5.0	0	W-54
9	1-.109-D	396	1.65	955	464	1.075	.1514	4327	94.1	213.5	198.5	230.5	86.1	15.71	6.0	1.893	28.5	38.0	28.5	5.0	0	W-55
10	1-.109-D	467	-	-	-	-	.1314	-	Burning Not Sustained After ClF_3 Shutoff								28.5	19.0	47.5	5.0	0	W-56
11	1-.109-D	479	-	-	-	-	-	-	Burning Not Sustained After ClF_3 Shutoff								38.0	9.5	47.5	5.0	0	W-57
12	1-.109-D	481	MONEX Flow Ceased Due to Mechanical Difficulty														38.0	19.0	38.0	5.0	0	W-61
13	1-.109-D	481	1.67	992	450	1.343	.1320	3138	72.7	193	143.9	216.3	66.5	16.3	4.1	1.92	38.0	19.0	38.0	5.0	0	W-61
14	1-.109-D							Excessive Ignition Spike - Transducers Erratic									38.5	33.5	23.0	5.0	0	W-65
15	1-.104-D	486	1.35	675	664	1.265	.1225	2130	43.5	121	96	215.0	44.6	17.6	29.4	1.5	37.0	15.0	43.0	5.0	0	W-66
16	1-.109-D	600	1.75			1.093	.1000	Excessive Ignition Spike - Transducers Erratic									32.1	28.5	27.3	5.0	4.7[(c)]	W-67N
17	1-.110-D	533	1.90	1085	400	1.062	.1115	3660	74.7	165	155	233.9	66.3	20.0	.5	2.18	32.1	28.5	27.3	5.0	4.7[(c)]	W-67N
18	1-.109-D	635	1.90	1245	300	1.080	.0935	3470	70.7	168	156	236.6	65.9	23.2	.6	2.18	32.1	28.5	27.3	5.0	4.7[(c)]	W-67S
19	1-.109-D	475					.1250	Burning Not Sustained After ClF_3 Shut Off									45.0	12.0	38.0	5.0	0	W-68
20	1-.109-D	150					.1930	Burning Not Sustained After ClF_3 Shut Off									32.1	28.5	34.4	5.0	0	W-42
21	1-.109-D	502					.1185	Burning Not Sustained After ClF_3 Shut Off									32.1	28.5	34.4	5.0	0	W-42D
22	1-.109-D	473	1.90	1035	420	1.190	.1060	2970	65.8	164	138	215.2	64.1	21.1	8.9	2.18	45.0	19.0	31.0	5.0	0	W-69

(a) H_2O

(b) Gellant

(c) Plus 2.4% Polyethylene

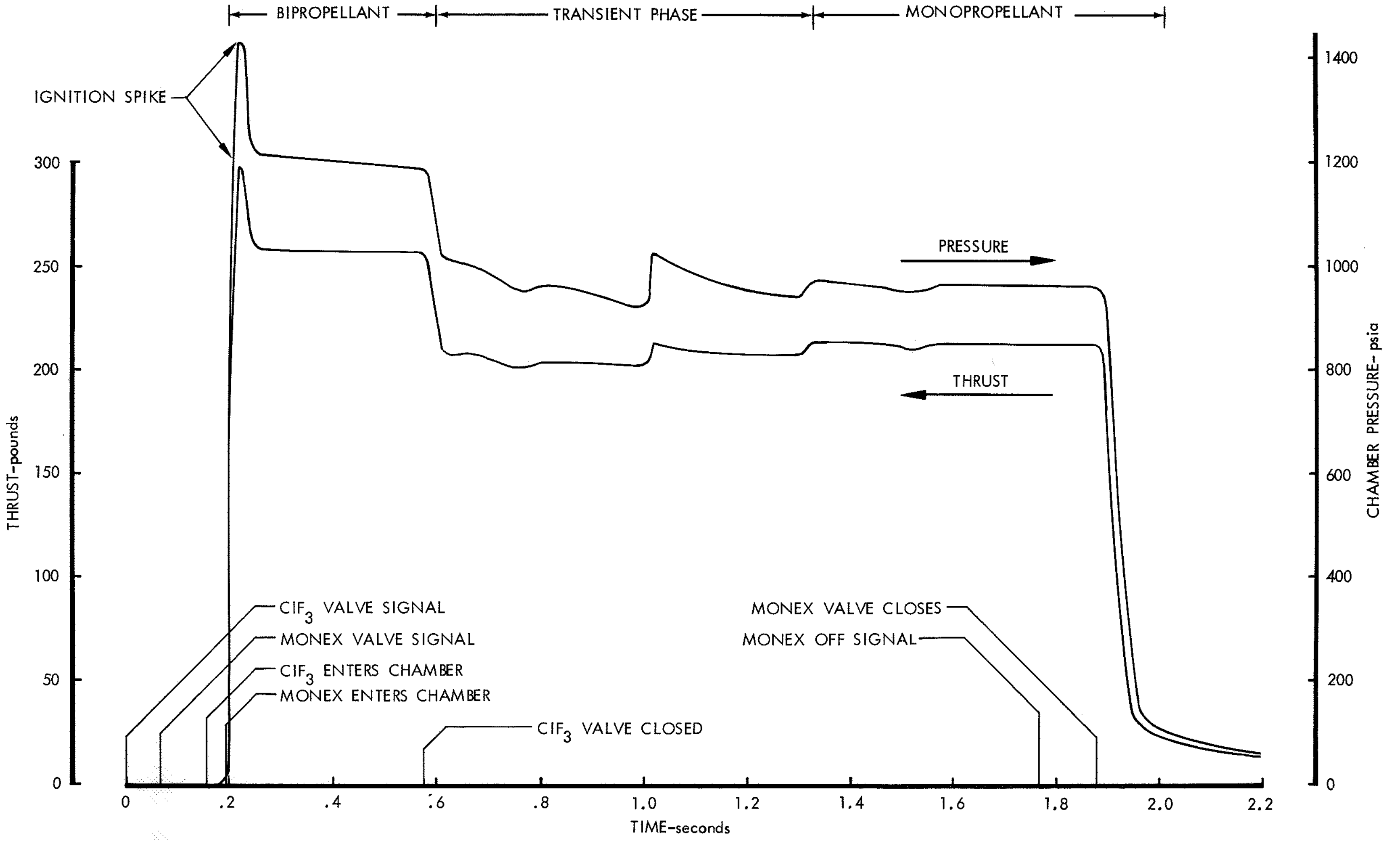

FIGURE 31. - TYPICAL WASTE MANAGEMENT ENGINE PERFORMANCE

propellant composition as in tests MW-1 and MW-2 was used. Density was 1.485 gms/cc. Combustion was improved in the monopropellant mode, but the characteristic large pressure drop after ClF_3 shutoff was still present. A full duration run was achieved but at a very low level of performance. A similar residue appearance was observed on the engine internal surfaces.

5.5.5 MW-5

This firing utilized a second formulation (W-42) which, based on MONEX A experience, was expected to be of superior performance. The carbon was eliminated from the formulation and aluminum content was increased. Density of the propellant was 1.510 gms/cc. Using a single 0.109 inch diameter injector nozzle, smooth ignition and transition to monopropellant burning were achieved. Chamber pressure was 870 psi and the I_{sp} efficiency was 83.5%. Run duration was 1.825 seconds, of which 1.4 seconds was stable monopropellant combustion. Residue was generally of lighter color than that deposited from the first formulation, and a light layer (0.1 inch) was deposited on the injector end.

5.5.6 MW-6

This firing was a repeat of MW-5. A chamber pressure of 955 psia and an I_{sp} efficiency of 82.1% were attained. Reproducibility was excellent. Residue was light except for minor slag deposits in the nozzle entrance.

5.5.7 MW-7

The effect of the M-1 burning rate additive was investigated by firing the same formulation used in MW-5 and MW-6 with no additive. Density was 1.488 gms/cc. Performance was satisfactory but roughness (pressure fluctuations) increased to ±5% as opposed to ±1% and ±2% for the preceding two runs. However, no firm conclusions were reached on the evidence of this single test.

5.5.8 MW-8

Firing MW-8 was the first of a test series to determine the approximate composition limits for satisfactory performance in a liquid injection engine. This formulation (W-54), 38% Al, 28.5% AN, 28.5% feces, and 5% M1 (density 1.552 gms/cc), burned smoothly. A chamber pressure of 913 psia and an I_{sp} efficiency of 86.6% were attained. Ignition was instantaneous and transition to the monopropellant mode was smooth. A light residue of powder with little slag was observed.

5.5.9 MW-9

This propellant formulation (W-55) 28.5% Al, 38% AN, 28.5% feces and 5% M1 (density 1.460 gms/cc) also burned well. A chamber pressure of 955 psia and an I_{sp} efficiency of 86.1% were attained. Engine roughness increased to ±6%. Ignition was instantaneous and transition to the monopropellant mode was smooth. Residue was extremely light.

5.5.10 MW-10

This engine test attempted to burn a propellant of high feces content (W-56). The MW-9 test formulation was modified by increasing feces content to 47.5% and decreasing AN content to 19%. Ignition and bipropellant modes were satisfactory but combustion ceased after ClF_3 shutoff. Unburned propellant was ejected. A small amount of aluminum oxide was observed in the nozzle.

5.5.11 MW-11

This firing also used a 47.5% feces formulation (Al-38%, AN-9.5%, M1-5%) and, as in test MW-10, did not burn after ClF_3 shutoff. Ignition and bipropellant modes were satisfactory.

5.5.12 MW-12

The propellant formulation W-61 (38% Al, 19% AN, 38% feces and 5% M1) (density 1.478 gms/cc) was selected to determine the propellant with maximum feces content which could be fired successfully. Ignition was normal, but MONEX flow did not stabilize in either the bipropellant or monopropellant modes. Large pressure fluctuations occurred and flow ceased completely at 1.50 sec. Since this anomaly was attributed to sticking of the expulsion piston, corrections were made, and the test was repeated (MW-13).

5.5.13 MW-13

This test was a repeat of MW-12. Propellant formulation was identical although the bulk density was 1.446 gms/cc. The transition from bipropellant to monopropellant burning was smooth and pressure variations during monopropellant firing were only ±4.1%. Chamber and nozzle were relatively clean following the firing. Only a light gray powder-like residue remained.

5.5.14 MW-14

The test was to demonstrate a high specific impulse formulation (W-65) with relatively low feces content (23%). Overpressurization occurred during the ignition phase of the firing, resulting in gas leakage through the flange connecting the nozzle to the body of the engine. The cause of overpressurization was due to excessive ClF_3 buildup in the reaction chamber because the opening of the MONEX W propellant valve was delayed. Upon contact with a large quantity of ClF_3, the fuel reacted so rapidly that overpressurization occurred, damaging the test engine.

5.5.15 MW-15

The propellant (W-66) utilized for this firing contained 43% feces, providing a data point between firings No. 10 and No. 11 (47.5% feces) which did not burn and firing No. 13 (38% feces) which had excellent monopropellant characteristics. The firing was successful although pressure fluctuations during monopropellant burning were severe (±29%) and I_{sp} efficiency was only 44.6%.

This represents the lowest efficiency obtained in an engine firing where monopropellant burning was sustained. Engine deposits were normal except for a moderately heavy slag coating on the injector face.

5.5.16 MW-16

This firing was of formulation W-67N (32.1% Al, 28.5% AN, 27.3% feces plus polyethylene, carbon, and M1) and was designed to provide a control firing for MONEX W-38 which had been subjected to long term aging. The data acquisition system was lost during the firing because of a severe ignition spike (about 7,000 psi). The spike appeared to be caused by the MONEX being injected prior to the oxidizer.

5.5.17 MW-17

This test was a repeat of test MW-16 and was also to provide a control firing for the stored W-38 propellant. Both bipropellant and monopropellant burning were exceptionally smooth. An I_{sp} efficiency of 66.3% was attained. Heavy slag deposits were observed during post-fire disassembly.

5.5.18 MW-18

This test utilized the long-term aged propellant W-38 which was modified and redesignated W-67. The original W-38 formula 24% Al, 30% AN, 35% feces plus carbon polyethylene and M1 was expected to be unsatisfactory because its theoretical flame temperature would be below the melting point of Al_2O_3. Additional aluminum and ammonium nitrate were, therefore, added to bring the resultant formulation into a region of known monopropellant stability. There appeared to be no significant difference in performance between this propellant and the unstored propellant (test MW-17). An I_{sp} efficiency of 65.9% was attained.

5.5.19 MW-19

This test utilized a formulation with high aluminum content (W-68) 45% Al, 12% AN, 38% feces and 5% M1 in order to explore monopropellant combustion with a fuel-rich composition (above the OMOX line - see Fig. 10). This formulation burned during the ignition phase but not as a monopropellant.

5.5.20 MW-20

This test utilized a known satisfactory monopropellant formulation (W-42) in an attempt to determine the feasibility of reducing the size of the combustion chamber. An L* of 150 inches was used in place of the nominal 450 inch L*. Propellant burning was not sustained after the bipropellant (ignition) phase.

5.5.21 MW-21

Feces obtained from the 60-day, four-man space cabin simulation tests conducted by McDonnell Douglas Corporation were blended into the W-42 formulation.

This propellant was notably more viscous than propellant blended from "normal diet" feces. The engine ignited and operated at 1,000 psia during the bipropellant phase but pressure dropped rapidly to zero after the monopropellant phase began. It is possible that the normal injection pressures were not sufficient to maintain full flow of the viscous propellant. This propellant is discussed further in Par. 4.2.5 and Par. 4.3.3.

5.5.22 MW-22

This firing was conducted with a high aluminum content propellant to further describe the area of satisfactory monopropellant performance. The formulation (W-69) consisted of 45% Al, 19% AN, 31% feces and 5% M1 with a density of 1.607 gm/cc. This represents formulation of highest-density prepared during the program. Bipropellant, transition, and monopropellant burning modes were smooth. An I_{sp} efficiency of 64.1% was attained. Slag deposits were unusually light. Of particular interest was the slag free injector face, probably the result of the high (2,800°K) theoretical flame temperatures.

5.6 DISCUSSION OF RESULTS

Figure 32 is a photograph of the waste management monopropellant being burned in a small rocket engine. The principal conclusion drawn from the engine test program is that the use of waste management propellant is a practical means of disposing and sterilizing of astronaut waste, and that engine operation is satisfactory over a large range of propellant compositions.

Ten propellant formulations which varied only ingredient proportions are superimposed on the ternary composition diagrams in Figs. 33 and 34. These propellants were fired in identical engine hardware and in the narrowest range of combustion conditions possible. Results are directly comparable.

5.6.1 Waste Disposal

The waste management propellant provides a means of storing, sterilizing and disposing of astronaut wastes. Mixing the feces with ammonium nitrate retards bacteriological growth and permits long term storage of the feces containing propellant. The high flame temperature of propellant combustion destroys viable materials during the rocket firing. Propellant containing about 43% feces appears satisfactory for maximum efficiency of waste disposal.

5.6.2 Propulsion Results

As a rocket propellant, the waste management fuel performed extremely well. A measured I_{sp} of 198.5 lbf-sec/lbm was attained in the small and relatively inefficient engine design used throughout this program. This was attained using a formulation containing 28.5% feces which has potential I_{sp} of about 230 (1,000 - 14.7). With larger engine sizes and by optimizing engine configuration and injector design, efficiencies greater than 90-percent would be expected.

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FIGURE 32. MONEX W TEST FIRING

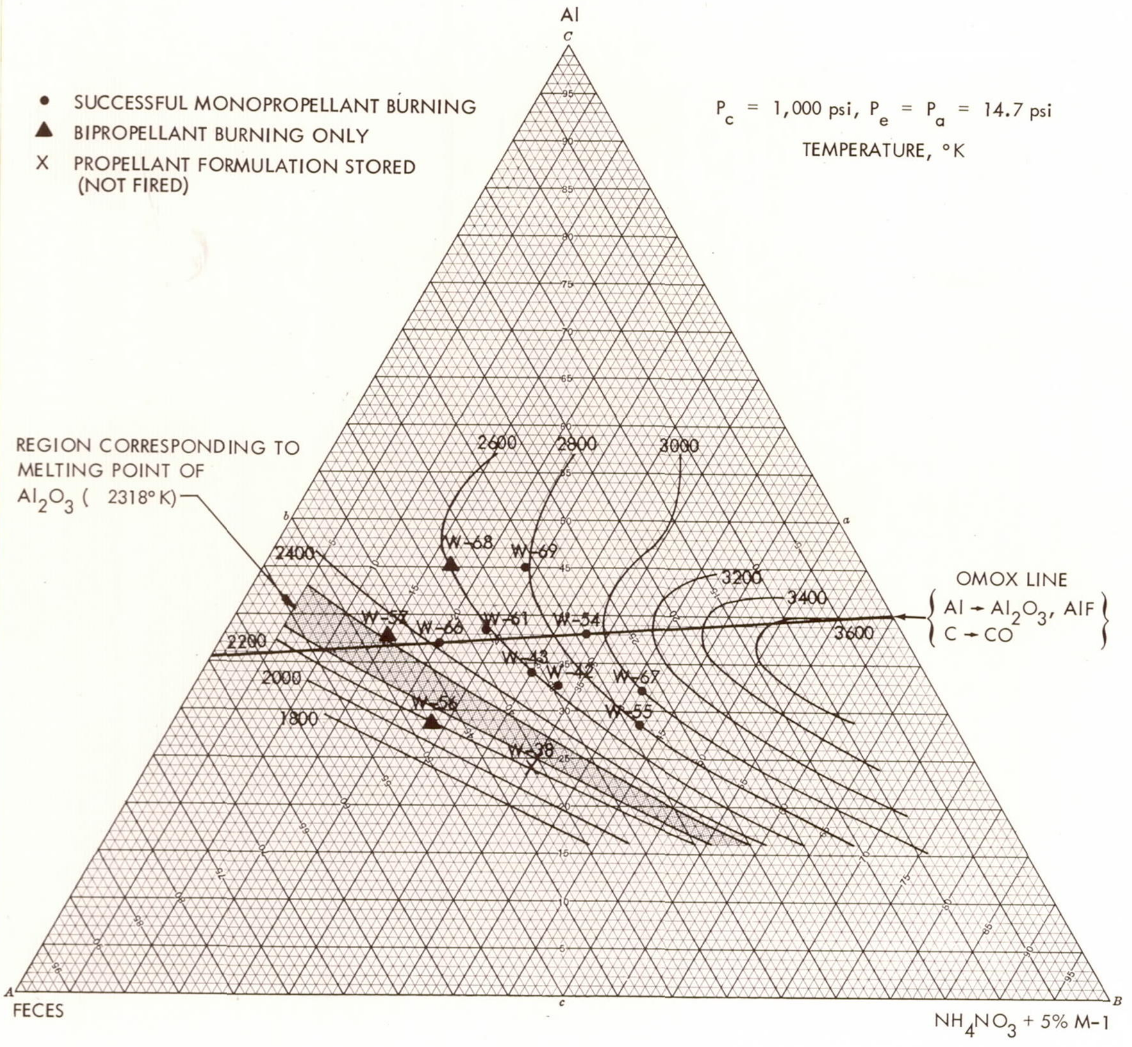

FIGURE 33. - THEORETICAL CHAMBER TEMPERATURE AS A FUNCTION OF COMPOSITION

MONEX W (DRY)

55142A

FIG 38

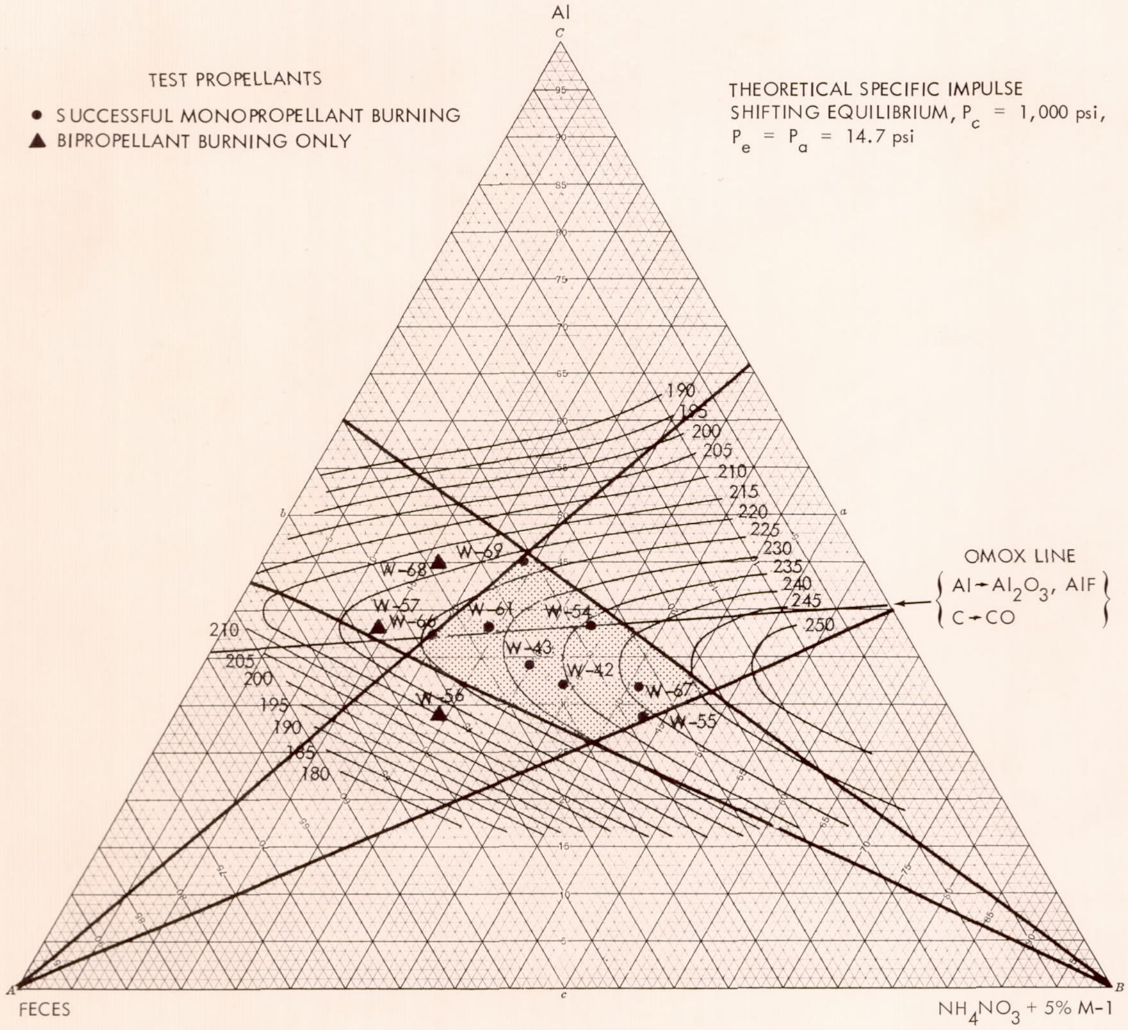

FIGURE 34. - WASTE PROPELLANT COMPOSITIONS EMPLOYED IN TEST FIRINGS

The results of this engine test program, therefore, clearly indicate that on extended space missions a prime propulsion role should be sought for the waste management propellant.

5.6.3 Propellant Formulation

In the ternary diagram (Fig. 34) the area of successfully test fired compositions is limited by lines corresponding to an aluminum : ammonium nitrate + M-1 weight ratio from 0.66 to 1.94 and an aluminum : feces weight ratio from 0.75 to 1.5 respectively. This corresponds to aluminum : ammonium nitrate molar ratios of 2.14 to 6.75. The molar ratio of aluminum : water depends on the water content of feces. With an assumed water content of 68%, the molar ratio of aluminum to water in the successfully tested compositions ranges from 0.74 to 1.48.

As combustion efficiency is probably determined by the combustion temperature as well as the degree of atomization, it is not uniformly distributed over the area of successfully test fired compositions. The area of usable formulations may possibly be wider than that shown in Fig. 34 (in particular in direction of lower aluminum content), depending on the type of engine utilized and the degree of atomization achieved. It is very difficult to discern between the effects of low flame temperature or high viscosity on narrowing the range of successful operation in a liquid injection rocket engine.

5.6.4 Storage Stability

The firings of two identical propellants (tests MW-17 and MW-18) one of which was stored for 9-1/2 months at 75 ±5^{o}F, demonstrate that the propellant may be mixed, accumulated, and stored for long periods of time. Measured performance parameters of the stored and freshly prepared propellants varied by less than 1% for I_{sp} efficiency and less than 5% for c* efficiency. The indication is that the propellant could be prepared and stored in a common storage container as it is accumulated, and then fired without a final batch blending operation on the entire mass.

5.6.5 Hardware Reusability

Deposits formed in the higher flame temperature formulations were consistently lighter than those in which the flame temperature approached the melting point of Al_2O_3 (See Fig. 33). These engines were readily reusable; in field use only the rocket nozzle would have required replacement perhaps every fifth firing. During the program, heavy deposits were removed, injector elements examined, and nozzle diameter examined. To maintain consistent results, injector elements and nozzle inserts were replaced at the first measurable sign of erosion. MONEX injectors were replaced every third to fifth firing and engine nozzles every second or third firing.

5.6.6 Safety

The propellant proved to be extremely easy and safe to handle during the engine firing program. No mishaps, accidents or personnel injuries occurred during the program. The propellant is not highly flammable in air. Raw propellant, spewed out of the engine on tests which failed to burn as a monopropellant, was easily disposed of by flushing with water. In one instance the MONEX shutoff valve failed to close and the expulsion piston bottomed. No combustion occurred due to this event. Further, the propellant did not burn back up the injector line further than two inches. Utilizing an injector line smaller than the critical diameter would prevent combustion propagation and is expected to be a simple and effective backup safety shutoff.

The autodecomposition temperature of the propellant is very high (486°F). The propellant was found to be nondetonable when tested with zero attenuation in the JANAF card gap test. MONEX W compositions were not shock-sensitive when tested in an Olin drop weight tester at 120 kg-cm.

6.0 SUMMARY AND CONCLUSIONS

The concept of the Integrated Waste Management/Rocket Propulsion System has been investigated from the standpoint of mission application, thermodynamic properties, physical and chemical properties of the propellant, and ballistic performance of the propellant on small test engines. These preliminary studies have demonstrated that many potential future applications for the system exist and that the excellent properties of the waste management propellant and its combustion behavior in simple monopropellant engines make the concept appear highly feasible.

A mission survey, including visits to selected aerospace firms and government agencies was performed to obtain information necessary to assure possible application of an Integrated Waste Management/Rocket Propulsion System to projected future manned space missions. Comparisons have been made of the potential total impulse available from an Integrated Waste Management/Rocket Propulsion System with the propulsion requirements of these proposed missions. Potential areas of application for such a system have been defined and are summarized in Par. 2.3. Maximum benefit from a waste management propulsion system, however, will be achieved with missions initially designed to accommodate the system. In none of the proposed missions or life support systems surveyed, however, is a truly efficient disposal and sterilization method outlined for feces and miscellaneous solid wastes. The Integrated Waste Management/Rocket Propulsion System concept provides an effective means of eliminating and sterilizing these and other wastes and, at the same time, providing propulsion.

Thermodynamic calculations were performed over a wide range of compositions for waste management propellant compositions containing feces and feces-urine mixtures as the waste component. This theoretical performance data supported mission application and propellant formulation efforts as well as provided a basis for determining performance efficiency of the propellant in engine test firings.

Laboratory testing of waste management propellant included determinations of the following: freezing point, density as a function of temperature, vapor pressure as a function of temperature, rheological properties, thermal stability, card gap tests (detonability), handling characteristics, autodecomposition temperature, biological activity (both propellant and engine exhaust), compatibility tests, and impact sensitivity. The results of these tests have shown that MONEX W propellant possesses excellent physiochemical, safety, and handling properties. Although the propellants formulated to date have not proven to be sterile, bacterial growth in the propellants is definitely inhibited. Long-term storage tests have demonstrated the propellant to be completely stable for a period of greater than 18 months at ambient conditions. Furthermore, ballistic performance has been shown to be unchanged for propellant stored for as long as 9.5 months at ambient temperatures.

In a series of 22 test firings, MONEX W propellants have been demonstrated to be easily ignited and to burn with good efficiency in a nominal 200 lb thrust liquid injection engine.

A survey was conducted with propellant formulations containing only feces as the waste component to determine the effect of composition variation on combustion behavior and test engine performance. A range of propellant compositions containing from 27 to 43 percent feces was shown to sustain monopropellant combustion. Engine tests were also conducted of propellants containing carbon and polyethylene powder (to simulate other expected spacecraft wastes) in addition to feces.

In conjunction with the above studies, feces samples were obtained for evaluation from a 60-day manned spacecraft simulation experiment conducted at McDonnell-Douglas. Both the feces and the propellant prepared from the feces were of considerably higher viscosity than feces produced under normal diet and environment although the overall composition of the feces was essentially the same. Although the propellant was shown to sustain combustion, the high viscosity of the propellant prevented good injector atomization in a single test, and a successful engine firing was not obtained. The limited supply of waste prevented further engine testing with improved injection techniques.

6.1 RECOMMENDATIONS

The Integrated Waste Management/Rocket Propulsion System offers unique advantages for future manned space missions. Not only does it provide a more sanitary spacecraft environment, since waste will not have to be stored on board the spacecraft for extended periods of time, but it also presents additional performance capability. Now that an initial feasibility study has been conducted, the next step should be to perform a system study. A system study will provide weight, volume and power requirement data for integration and optimization of the system. A breadboard system should be set up to study the basic operations of waste transport, grinding, blending, screening and metering in a continuous process. Future missions designed to make optimum use of the Integrated Waste Management/Rocket Propulsion System would have to incorporate this system in a very early stage of design. The Waste Management/Rocket Propulsion System may also be considered an emergency Propulsion System as a back-up to a conventional propulsion system. The redundancy and increase in probability of mission success would have to be evaluated.

The range of usable propellant compositions should be further investigated, especially in regions of high waste content, in order to obtain maximum effective specific impulse. Many expected spacecraft wastes other than human excrement should also be evaluated as propellant ingredients.

Another aspect which deserves further study is the concept of expendable spacecraft hardware made from aluminum powder and included in the propellant mixture during latter stages of the mission. The type of water soluble binder, mechanical properties and possible locations for application in spacecraft would require investigation.

Some potential applications of the Integrated Waste Management/Rocket Propulsion System will require multiple starts. The multiple start capability has not yet been demonstrated and will require further development of the ignition system.

The performance of MONEX W might be further increased by employing high-energy metals such as beryllium and/or oxidizers with higher oxygen content (e.g. $LiNO_3$, $NH_3OH\ NO_3$, $LiClO_4$).

APPENDIX A

CALCULATION OF AN APPROXIMATE VALUE FOR THE HEAT OF FORMATION OF FECES AND URINE

Composition and Heat of Formation of Feces:

The average composition of dried feces was determined as follows:

Composition	Weight %
Carbon	48.97
Hydrogen	6.42
Nitrogen	5.81
Oxygen (organic)	24.60
Inert (other)	14.20

The portion of dried feces described as inert refers to all other elements present in the feces and includes oxygen present in other than organic compounds. Because it would be pointless to include the numerous trace elements and compounds present in the thermodynamic calculations, the inert materials have been assumed to be approximated by calcium phosphate, $Ca_3(PO4)_2$, both from the standpoint of composition and heat of formation.

The heat of combustion of dry feces has been reported as approximately 4.26 kcal/gm (Ref. 80). The following reaction may be assumed for the combustion of feces:

$$\text{Feces} + O_2 \rightarrow CO_2,\ H_2O,\ N_2,\ Ca_3(PO_4)_2$$

Since the heats of formation of the products are known, the heat of formation of dried feces may be calculated in the usual manner from the equation

$$\Delta H_{f(\text{Dry Feces})} = \Sigma\Delta H_{f(\text{Products})} - \Delta H_{(\text{Combustion})}$$

The heats of formation used for the products are as follows:

Product	Heat of Formation (kcal/100 gm)
CO_2	- 41.5
H_2O	-379.2
$CA_3(PO_4)_2$	-317.9
N_2	0

Using these values, the heat of formation of dry feces was found to be -220 kcal/100 gm.

The water content of random feces samples appears to vary between approximately 60 and 75 percent by weight depending on the nutritional intake and metabolism of the individual. The average value as determined in these laboratories is approximately 68%. If raw feces is simply assumed to be dried feces plus 68% water, the heat of formation of raw feces is then calculated to be approximately - 328 kcal/100 gm.

The overall composition of raw feces as derived for use in theoretical performance calculations is as follows:

Composition	Weight %	gm atm/100 gm
C	15.7	1.3071
H	9.7	9.6233
N	1.9	0.1356
O	70.1	4.3814
Ca	1.7	0.0424
P	0.9	0.0291

Calculation of an Approximate Value for the Heat of Formation of Urine and of Wet Waste

Calcium phosphate was assumed to provide a good approximation for the minor components of urine, both from the standpoint of composition and heat of formation. The following overall composition for urine was assumed (Ref. 80).

Composition	Weight (%)	kcal/100g
Water	96.0	-379.2
Urea	2.3	-132.5
Sodium chloride	1.1	-168.2
Other (calcium phosphate)	0.6	-317.9
Urine		-370.8

Wet waste is composed of urine and feces. A ratio of 1,200 grams of urine to 150 grams of feces per day (the ratio of excretion products for a normal adult) was used in the calculations.

Component	Weight (%)	kcal/100g
Urine	88.89	-370.8
Feces	11.11	-328.0
"Wet" waste		-366.0

APPENDIX B

THEORETICAL PERFORMANCE CALCULATIONS

Theoretical performance calculations were obtained for a total of 26 MONEX W compositions containing only feces as waste. In a number of cases data were also obtained at various chamber and exhaust pressures. A summary of this data appears in Table 43. The formulations designated by a "W" number represent propellants that were prepared and fired in a liquid injection engine. These computations are the basis of the ternary diagrams presented in Figs. 9 and 10 of the text. Because of the large volume of calculations obtained, detailed printouts of only four selected cases (1, 2, 5, and 6) are presented here.

A summary of performance calculations obtained for 15 "wet" MONEX W compositions are tabulated in Table 44. These data were used to prepare the ternary diagrams appearing in Figs. 11 and 12 of the text. Detailed calculations for two selected compositions (cases 9 and 11) are also presented in Appendix B.

TABLE 43

WASTE MANAGEMENT PROPELLANT (DRY)
THEORETICAL PERFORMANCE COMPUTATIONS

Composition Weight % Al/AN/Feces/M-1	P_c (psia)	P_e (psia)	Specific Impulse (shifting-sec)	T_c °K	T_e °K	Frozen Gamma (chamber)	c* Throat (ft/sec)	A_e/A_t	C_f	Exhaust Velocity (ft/sec)
32.10/28.53/	500	14.7	219.4	2,698	1,941	1.151	4,510.5	6.32	1.564	
34.37/5.0	750	14.7	229.4	2,704	1,837	1.151	4,513.3	8.57	1.633	
(W-42)	1,000	20.0	229.0	2,708	1,843	1.151	4,515.4	8.43	1.630	
	1,000	14.7	236.0	2,708	1,767	1.151	4,515.4	10.67	1.680	
	1,000	10.0	244.1	2,708	1,676	1.151	4,516.9	14.37	1.738	
	1,000	5.0	257.1	2,708	1,519	1.151	4,518.8	24.73	1.831	
	1,000	2.0	271.6	2,708	1,330	1.151	4,515.3	51.25	1.934	
	1,000	1.0	280.9	2,708	1,200	1.151	4,515.7	89.45	1.997	
	1,000	0.1	304.4	2,708	851	1.151	4,516.9	585.61	2.167	
	1,250	14.7	240.8	2,711	1,714	1.151	4,517.2	12.67	1.714	
	1,500	14.7	244.6	2,713	1,672	1.151	4,518.8	14.60	1.742	
33.79/30.03/	500	14.7	220.8	2,759	2,023	1.145	4,546.2	6.43	1.561	
36.18/0	750	14.7	231.2	2,765	1,920	1.145	4,549.1	8.74	1.635	
(W-43)	1,000	20.0	230.7	2,769	1,926	1.144	4,551.4	8.60	1.629	
	1,000	14.7	237.9	2,769	1,850	1.144	4,551.7	10.90	1.680	
	1,000	10.0	246.3	2,769	1,759	1.144	4,552.7	14.70	1.739	
	1,000	5.0	259.7	2,769	1,601	1.144	4,554.5	25.37	1.833	
	1,000	2.0	274.7	2,769	1,410	1.144	4,551.4	52.79	1.939	
	1,000	1.0		2,769	1,281	1.144	4,551.7	93.38		
	1,000	0.1		2,769	646	1.144	4,552.7	491.70		
	1,250	14.7	242.9	2,772	1,798	1.144	4,553.4	12.95	1.715	
	1,500	14.7	246.7	2,774	1,755	1.144	4,555.2	14.93	1.742	

TABLE 43 (Cont'd)

WASTE MANAGEMENT PROPELLANT (DRY)
THEORETICAL PERFORMANCE COMPUTATIONS

Composition Weight % Al/AN/Feces/M-1	P_c (psia)	P_e (psia)	Specific Impulse (shifting-sec)	T_c °K	T_e °K	Frozen Gamma (chamber)	c* Throat (ft/sec)	A_e/A_t	C_f	Exhaust Velocity (ft/sec)
38.0/28.5/28.5/5.0	1,000	20.0	228.8	2,945	2,110	1.146	4,548.8	8.83	1.618	
(W-54)		14.7	236.2	2,945	2,033	1.146	4,548.8	11.17	1.671	
		5.0	258.8	2,945	1.843	1.146	4,549.6	26.76	1.830	
28.5/38.0/28.5/5.0		20.0	231.5	2,813	1,889	1.153	4,599.6	8.37	1.619	
(W-55)		14.7	238.6	2,813	1,810	1.153	4,596.0	10.59	1.670	
		5.0	259.8	2,813	1,551	1.153	4,596.1	24.49	1.819	
28.5/19.0/47.5/5.0		20.0	207.2	2,172	1,200	1.175	4,267.3	7.27	1.561	
(W-56)		14.7	212.9	2,172	1,144	1.175	4,269.7	9.17	1.605	
		5.0	230.0	2,172	977	1.175	4,264.4	21.22	1.735	
19.0/28.5/47.5/5.0		20.0	184.9	1,618	917	1.200	3,813.0	7.35	1.560	
		14.7	190.1	1.618	888	1.200	3,813.0	9.36	1.603	
		5.0	205.9	1,618	801	1.200	3,813.0	22.30	1.737	
38.0/9.5/47.5/5.0		20.0	216.0	2,318	1,804	1.250	4,345.3	8.51	1.600	
(W-57)		14.7	222.9	2,318	1,761	1,250	4,345.8	10.90	1,650	
		5.0	244.0	2,318	1,587	1.250	4,346.2	26.12	1.807	
38.0/19.0/38.0/5.0		14.7	228.2	2,529	1,842	1.149	4,314.1	11.27	1.702	
(W-61		20.0	221.7	2,529	1,876	1.149	4,313.4	8.7	1.651	
		5.0	250.1	2,529	1,732	1.149	4,315.5	27.69	1.865	
28.5/28.5/38.0/5.0		20.0	221.6	2,366	1,518	1.161	4,507.2	7.65	1.582	
		14.7	228.0	2,366	1,449	1.161	4,507.2	9.66	1.626	
		5.0	247.0	2,366	1,229	1.161	4,507.2	22.24	1.763	

TABLE 43 (Cont'd)

WASTE MANAGEMENT PROPELLANT (DRY)
THEORETICAL PERFORMANCE COMPUTATIONS

Composition Weight % Al/AN/Feces/M-1	P_c (psia)	P_e (psia)	Specific Impulse (shifting-sec)	T_c oK	T_e oK	Frozen Gamma (chamber)	c* Throat (ft/sec)	A_e/A_t	C_f	Exhaust Velocity (ft/sec)
47.5/0/47.5/5.0	1,000	20.0	200.0	2,445	1,990	1.115	3,848.8	9.34	1.672	
		14.7	206.7	2,445	1.953	1.115	3,849.2	12.01	1.728	
		5.0	227.5	2,445	1,825	1.115	3,850.2	29.47	1.901	
47.5/9.5/38.5/5.0		20.0	204.9	2,583	2,094	1.126	4,001.5	9.31	1.648	
		14.7	211.8	2,583	2,061	1.126	3,998.4	11.99	1.704	
		5.0	233.5	2,583	1,954	1.126	3,998.7	29.59	1.879	
47.5/19.0/28.5/5.0		20.0	211.1	2,820	2,237	1.134	4,177.3	9.25	1.616	
		14.7	218.2	2,820	2,187	1.134	4,175.2	11.84	1.681	
		5.0	240.3	2,820	2,010	1.134	4,175.8	28.64	1.851	
47.5/28.5/19.0/5.0		20.0	214.9	2,977	2,365	1.140	4,273.3	8.80	1.618	
		14.7	221.9	2,977	2,325	1.140	4,271.5	11.33	1.671	
		5.0	244.9	2,977	2,239	1.140	4,272.0	29.57	1.844	
38.0/38.0/19.0/5.0		20.0	235.7	3,374	2,318	1.140	4,744.2	8.31	1.598	
		14.7	243.3	3,374	2,318	1.140	4,744.5	10.97	1.649	
		5.0	267.6	3,374	2,226	1.140	4,745.7	28.16	1.814	
28.5/47.5/19.0/5.0		20.0	238.6	3,211	2,285	1.147	4,792.5	8.81	1.602	
		14.7	246.4	3,211	2,198	1.147	4,792.5	11.16	1.654	
		5.0	269.8	3,211	1,911	1.147	4,793.4	25.98	1.811	
57.0/0/38.0/5.0		14.7	186.4	2,447	1,987	1.101	3,570.0		1.670	5,996.0

TABLE 43 (Concluded)

WASTE MANAGEMENT PROPELLANT (DRY)
THEORETICAL PERFORMANCE COMPUTATIONS

Composition Weight % Al/AN/Feces/M-1	P_c (psia)	P_e (psia)	Specific Impulse (shifting-sec)	T_c °K	T_e °K	Frozen Gamma (chamber)	c* Throat (ft/sec)	A_e/A_t	C_f	Exhaust Velocity (ft/sec)
57.0/9.5/28.5/5.0	1,000	14.7	190.2	2,589	2,145	1.207	3,680		1.66	6,118.3
57.0/19.0/19.0/5.0	↕	↕	195.1	2,843	2,202	1.116	3,800		1.65	6,275.7
57.0/28.5/9.5/5.0			203.5	3,037	2,390	1.126	3,999		1.64	6,547.4
47.5/38.0/9.5/5.0			225.2	3,067	2,417	1.150	4,440		1.63	7,245.0
38.0/47.5/9.5/5.0			250.5	3,727	2,604	1.137	4,930		1.635	8,060.6
28.5/57.0/9.5/5.0			252.6	3,569	2,332	1.144	4,960		2.633	8,127.3
19.0/57.0/19.0/5.0			239.0	2,803	1,678	1.162	4,740		1.623	7,690.8
19.0/47.5/28.5/5.0			226.3	2,351	1,338	1.172	4,480		1.62	7,281.2
19.0/38.0/38.0/5.0			209.4	2,071	1,054	1.185	4,180		1.61	6,737.4
19.0/19.0/57.0/5.0			173.8	1,271	821	1.206	3,510		1.59	5,592.8
28.5/9.5/57.0/5.0			195.0	1,736	980	1.187	3,900		1.61	6,274.9
38.0/0/57.0/5.0			215.1	2,285	1,507	1.149	4,245		1.63	6,920.6

TABLE 44

WASTE MANAGEMENT PROPELLANT (WET)
THEORETICAL PERFORMANCE CALCULATIONS

(P_c = 1,000 psi P_e = 14.7 psi)

Case	Formulation*			Specific Impulse		T_c	T_e	Gamma (Chamber)
	Al	AN	Waste	Shifting	Frozen	°K	°K	
1	50	25	20	223.5	219.6	2,999	2,378	1.139
2	50	17.5	27.5	223.5	220.0	2,900	2,318	1.135
3	50	10	35	223.8	221.8	2,884	2,301	1.129
4	43	32	20	243.2	224.1	3,567	2,485	1.129
5	44	23.5	27.5	239.3	234.8	3,396	2,318	1.127
6	45	15	35	235.6	235.2	3,216	2,318	1.125
7	46	6.5	42.5	233.0	232.3	3,025	2,284	1.125
8	35	40	20	248.2	229.6	3,533	2,371	1.132
9	35	32.5	27.5	243.7	242.5	3,813	2,318	1.132
10	35	25	35	240.3	239.6	3,070	2,191	1.132
11	35	17.5	42.5	236.1	235.6	2,808	1.945	1.135
12	35	10	50	230.9	230.7	2,535	1,709	1.138
13	25	42.5	27.5	240.1	239.2	2,904	1,880	1.146
14	25	35	35	233.6	233.1	2,626	1,649	1.149
15	25	27.5	42.5	226.1	225.9	2,343	1,433	1.153

* Each composition contains 5 weight percent M-1 additive.

Composition: 38.0 Al/28.5 NH_4NO_3/
28.5 Feces/5 M-1

```
ROCKET RESEARCH CO

52C S. PORTLAND STREET

SEATTLE, WASHINGTON 98108

ATT. DAVID GOOD

  CASE 1     EXIT PRESSURE = 14.7 PSI

ELEMENTS IN REACTANTS, ATOMS                     FUEL  OXIDIZER   BINDERS
H                                     4.1667    0.        4.00      9.62
C                                     0.4725    0.        0.        3.31
O                                     2.3168    0.        3.00      4.38
N                                     0.7507    0.        2.00      0.14
F                                     0.2000    0.        0.        4.00
AL                                    1.4085    1.00      0.        0.
P                                     0.0083    0.        0.        0.03
CA                                    0.0121    0.        0.        0.04
ENTHALPY OF REACTANTS, KCAL        -134.2218

SHIFTING IMPULSE, SEC                   236.2198

                               CHAMBER          THROAT          EXHAUST
PRESSURE, ATM                  68.0457          39.5429          1.0000
TEMPERATURE, DEG K           2944.7959        2775.5126        2032.7043
HEAT CAPACITY, CAL /DEG K      49.2871          49.0934          45.6335
ENTHALPY, KCAL               -134.2218        -143.9516        -198.3504
ENTROPY, CAL / DEG K          205.7303         205.7399         205.7312
FROZEN GAMMA                    1.1458           1.1460           1.1575
MOLS OF GAS                     3.1565           3.1467           3.1239
VELOCITY, FT / SEC                            2960.3924        7600.1460
MOLECULAR WEIGHT               26.5345          26.5766          26.6851
DENSITY, GM / CC           0.008904532      0.005511113      0.000191905
C *, FT/SEC                                   4548.8030
AREA RATIO                                                        11.1861

PRODUCTS OF COMBUSTION, MOLS
H                         4.0635602E-02   3.0140948E-02   5.1303724E-03
C                         2.6980720E-08   1.0902718E-08   3.8662029E-11
O                         8.4410223E-07   2.3516859E-07   8.1782579E-11
N                         1.2618451E-06   4.9725681E-07   1.5343436E-09
F                         2.9641615E-06   1.3791101E-06   1.5698984E-08

AL                        6.8517426E-03   4.8161931E-03   4.1343275E-04
P                         1.1376827E-04   8.5291194E-05   1.3807994E-05
CA                        8.3537549E-03   6.5971802E-03   1.7462349E-03
CAO                       4.0779420E-04   1.8902793E-04   1.5149967E-06
ALC                       1.7008986E-08   6.9605160E-09   1.6506735E-11

ALF                       1.6585255E-01   1.6958328E-01   1.7817629E-01
ALOF                      1.9301412E-03   1.3423094E-03   1.1486027E-04
ALF2                      2.9582693E-03   2.7413873E-03   1.7719423E-03
ALF3                      5.2883331E-04   6.1443333E-04   1.9998376E-03
ALH                       2.7336673E-03   1.7505727E-03   7.2634201E-05

HALO                      6.3220676E-07   2.1524925E-07   1.5079531E-10
ALOH                      3.6026454E-05   1.5097687E-05   3.7819391E-08
ALO2H                     1.0847284E-08   2.3916686E-09   9.6349038E-14
ALN                       5.0604384E-07   2.0842170E-07   5.2669829E-10
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ALO                     3.9536229E-05    1.5636360E-05    3.1144144E-08

AL2                     4.5897935E-06    2.2877852E-06    1.3576365E-08
AL2O                    4.8722456E-03    3.1280500E-03    8.5337704E-05
(ALO)2                  1.7902401E-06    6.7010477E-07    5.6269152E-10
CF                      5.6175442E-10    2.1274019E-10    5.6070678E-13
FCN                     5.7363225E-08    3.6273139E-08    2.2883215E-09

CF2                     6.4236724E-12    2.4373285E-12    7.4600447E-15
COF2                    2.6592475E-11    1.0877533E-11    5.0888208E-14
CF3                     4.3332567E-16    1.3221708E-16    1.2097522E-19
CF4                     1.6665582E-19    4.9952310E-20    4.8755359E-23
CH                      8.7763283E-08    3.7445216E-08    1.6172553E-10

CHFO                    4.1817837E-08    2.0635836E-08    2.4219238E-10
CHF3                    1.7144209E-15    6.6141681E-16    2.4392299E-18
HCN                     3.8646128E-03    3.9061320E-03    3.7800033E-03
HNCO                    4.4205562E-06    2.5730574E-06    6.7001209E-08
CHO                     2.9466759E-04    1.7781233E-04    6.2979653E-06

CH2                     2.7657755E-07    1.4724643E-07    2.3271237E-09
CH2F2                   4.4501641E-12    2.1810213E-12    2.7992836E-14
CH2O                    1.1608271E-05    6.8985395E-06    2.0180260E-07
CH3                     7.4098595E-05    5.8425276E-05    9.9455237E-06
CH3F                    1.3238666E-08    8.7950134E-09    5.9397350E-10

CH4                     1.0872851E-04    1.1156964E-04    9.1393805E-05
CN                      2.9965480E-06    1.7887175E-06    6.7422509E-08
CO                      4.6771429E-01    4.6796123E-01    4.6847684E-01
CO2                     3.4437649E-04    2.0952325E-04    8.4513772E-06
CP                      1.2310684E-06    9.6181823E-07    1.7115229E-07

C2                      2.5481965E-10    1.1002593E-10    5.1704496E-13
C2F2                    1.2495616E-11    7.9467686E-12    6.0811739E-13
C2F4                    1.6937446E-24    3.3720024E-25    2.2140867E-29
C2H2                    3.4862517E-05    3.8668659E-05    6.0228991E-05
C2H4                    3.7358193E-07    3.8663278E-07    3.0346489E-07

C2H4O                   3.1479410E-13    1.2730984E-13    2.4114169E-16
C2N2                    7.9626238E-08    7.0836581E-08    2.7626998E-08
C3                      2.3100693E-11    1.5629037E-11    1.1245571E-12
C3O2                    3.8998474E-12    1.8699095E-12    1.3552487E-14
C4N2                    4.7061857E-13    4.5969903E-13    2.6710273E-13

HF                      2.4663200E-02    2.1710141E-02    1.2134415E-02
HOF                     1.0879671E-11    1.9709839E-12    4.3641868E-17
NF                      1.4474734E-11    3.4427553E-12    4.8058254E-16
NOF                     6.1323494E-13    9.7302483E-14    9.5156472E-19
FO                      8.6589251E-14    1.0975409E-14    2.8623557E-20

PF                      4.0156468E-06    2.7371195E-06    2.6996672E-07
F2                      3.2902295E-14    6.3381647E-15    3.0251812E-19
F2O                     1.7849990E-21    9.7672957E-23    1.4151308E-30
PF2                     7.3491607E-09    4.3223299E-09    1.9203724E-10
NF3                     1.0017497E-24    6.5263292E-26    3.3528579E-33

PF3                     2.0127114E-11    1.1759099E-11    5.9070896E-13
PF5                     2.5390804E-20    8.8333880E-21    2.3803049E-23
NH                      1.2785743E-05    5.6127562E-06    2.9650736E-08
OH                      7.0449725E-05    2.6073233E-05    4.7248741E-08
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PH                      2.5805221E-04   1.8715635E-04   2.0997310E-05

H2                      2.0352917E 00   2.0474130E 00   2.0723048E 00
NH2                     2.1621748E-05   1.1146835E-05   1.4191726E-07
H2O                     1.0648686E-02   6.1911020E-03   1.7369171E-04
H2C2                    3.6339849E-11   4.8114073E-12   1.1434480E-17
PH2                     3.7937400E-04   2.8671051E-04   3.6741033E-05

NH3                     2.1305544E-04   1.4412719E-04   9.2924887E-06
PH3                     2.2994209E-05   1.6771555E-05   1.5686404E-06
N2H4                    2.2334341E-11   5.6410078E-12   7.3373374E-16
NF2                     5.6993163E-17   7.6163785E-18   3.1505570E-23
NO                      2.9358815E-06   9.4563667E-07   7.2173804E-10

NO2                     6.8245705E-13   7.7794285E-14   7.3840277E-20
NO2F                    5.1663787E-21   2.5487741E-22   1.4083412E-30
PN                      7.2207848E-03   7.4291974E-03   7.7861124E-03
N2                      3.6968632E-01   3.6962617E-01   3.6922608E-01
N2O                     4.8396433E-10   1.1838119E-10   1.4530783E-14

N2O3                    2.4544017E-23   5.5548045E-25   1.5522874E-35
N2O4                    4.7280669E-31   3.7684477E-33   0.
N2O5                    2.2922226E-39   0.              0.
PO                      8.4739684E-05   4.6455826E-05   9.0993016E-07
O2                      1.7882632E-09   2.9050523E-10   2.9612195E-15

PO2                     4.5202628E-07   1.5648926E-07   1.5134739E-10
O3                      3.0463707E-19   1.0577799E-20   5.4325836E-30
P4O6                    6.5703438E-20   1.7122492E-20   1.1895663E-24
P4O10                   0.              0.              0.
P2                      1.0393678E-04   1.1913598E-04   2.1635727E-04

P4                      5.7200629E-11   7.3849915E-11   1.8139868E-10
FNO3                    1.2781292E-29   1.4966738E-31   0.
HNO                     8.9797616E-09   2.1769694E-09   2.4025695E-13
HNO2-CIS                4.6563368E-13   5.2639011E-14   4.3007177E-20
HNO2-TRA                5.2143910E-13   5.9251075E-14   4.9970145E-20

HNO3                    3.7883220E-20   1.4872668E-21   1.3851522E-30
POF3                    1.6833511E-14   6.1231386E-15   1.4548808E-17
AL2O3      S            0.              0.              6.1252139E-01
AL2O3      L            6.0888084E-01   6.1068960E-01   0.
CAO        S            3.3221486E-03   5.2981803E-03   1.0336131E-02

ALN        S            0.              0.              6.9200630E-04




SBC COMPUTING SCIENCES DIVISION, PALO ALTO, CALIF.     MAY 9,67    002
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                    THROAT CALCULATIONS                               MARG.

PRESSURE, ATM                                39.1514
DENSITY, GM/CC                             0.0054631
VELCCITY, CM/SEC                             90989.4
DV,  GM/(CM CM SEC)                         497.0853

PRESSURE, ATM                                39.5430
DENSITY, GM/CC                             0.0055111
VELCCITY, CM/SEC                             90232.8
DV,  GM/(CM CM SEC)                         497.2834

PRESSURE, ATM                                39.9384
DENSITY, GM/CC                             0.0055597
VELOCITY, CM/SEC                             89428.5
DV,  GM/(CM CM SEC)                         497.2008

PRESSURE, ATM                                39.5429
DENSITY, GM/CC                             0.0055111
VELOCITY, CM/SEC                             90232.8
DV,  GM/(CM CM SEC)                         497.2832
C*, FT/SEC                                 4548.8030
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ROCKET RESEARCH CO

520 S. PORTLAND STREET

SEATTLE, WASHINGTON 98108

ATT.  DAVID GOOD
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Composition: 28.5 Al/38.0 NH_4NO_3/
28.5 Feces/5 M-1

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  CASE 2     EXIT PRESSURE = 14.7 PSI

ELEMENTS IN REACTANTS, ATOMS                     FUEL  OXIDIZER   BINDERS
H                                     4.6414     0.          4.00      9.62
C                                     0.4725     0.          0.        3.31
O                                     2.6728     0.          3.00      4.38
N                                     0.9881     0.          2.00      0.14
F                                     0.2000     0.          0.        4.00
AL                                    1.0563     1.00        0.        0.
P                                     0.0083     0.          0.        0.03
CA                                    0.0121     0.          0.        0.04
ENTHALPY OF REACTANTS, KCAL        -144.5789

SHIFTING IMPULSE, SEC                         238.5928

                                CHAMBER          THROAT          EXHAUST
PRESSURE, ATM                   68.0457         39.1514           1.0000
TEMPERATURE, DEG K            2813.0536       2627.3476        1810.2097
HEAT CAPACITY, CAL /DEG K       51.1752         50.8393          46.8082
ENTHALPY, KCAL                -144.5789       -154.7586        -210.0024
ENTROPY, CAL / DEG K           220.1837        220.1940         220.1933
FROZEN GAMMA                     1.1525          1.1534           1.1681
MOLS OF GAS                      3.4074          3.4021           3.3903
VELOCITY, FT / SEC                            3028.0527        7676.4951
MOLECULAR WEIGHT                25.3440         25.3718          25.4419
DENSITY, GM / CC            0.008637726     0.005332611      0.000198558
C *, FT/SEC                                   4596.0237
AREA RATIO                                                       10.5937

PRODUCTS OF COMBUSTION, MOLS
H                        2.4370825E-02   1.6093038E-02   9.2207854E-04
C                        1.2527609E-10   2.1556257E-11   1.3089570E-16
O                        2.3252331E-05   8.6025252E-06   8.8640971E-09
N                        6.0112054E-07   1.8463412E-07   5.6429571E-11
F                        1.3578931E-05   6.0312683E-06   2.1971174E-08

AL                       3.5671638E-06   7.7280999E-07   6.8942136E-12
P                        4.0751138E-05   2.8071023E-05   3.4450278E-07
CA                       4.8274953E-05   1.6760299E-05   8.6343586E-09
CAO                      1.6131334E-04   5.6655527E-05   3.0972290E-08
ALC                      7.6313133E-14   4.9058123E-15   1.1753846E-23

ALF                      1.3309273E-03   5.6544372E-04   5.0401523E-07
ALOF                     1.1869779E-03   6.1170853E-04   2.1655482E-06
ALF2                     2.5442775E-04   1.1950234E-04   2.1709095E-07
ALF3                     6.2529824E-04   4.8240726E-04   2.8312715E-05
ALH                      1.4014868E-06   2.8501599E-07   1.7278282E-12

HALO                     2.0559602E-08   3.7602769E-09   1.1567463E-14
ALOH                     1.3744648E-06   3.2264473E-07   5.1005192E-12
ALO2H                    2.6038003E-08   5.4328988E-09   4.1275811E-14
ALN                      2.3865018E-10   2.8458331E-11   4.4717145E-18
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ALO	1.3639366E-06	2.8401192E-07	1.9027411E-12
AL2	1.7562813E-12	9.2238648E-14	1.6758256E-23
AL2O	2.3331580E-07	3.2208511E-08	4.4241914E-15
(ALO)2	5.8364638E-09	8.1103165E-10	1.2460655E-16
CF	2.8686382E-11	5.6761278E-12	8.8763280E-17
FCN	5.9284822E-09	2.3055910E-09	4.0765024E-12
CF2	3.7971283E-12	9.3801006E-13	6.8387160E-17
COF2	1.7156966E-09	8.9921663E-10	1.1960580E-11
CF3	2.5039382E-15	5.9276654E-16	3.5013986E-20
CF4	1.0977668E-17	3.1748421E-18	7.9902218E-22
CH	4.4944424E-10	8.6758333E-11	1.1869075E-15
CHFO	2.8517098E-07	1.5835090E-07	3.1969713E-09
CHF3	1.2545134E-14	4.1578088E-15	2.7062300E-18
HCN	5.2391548E-05	3.0409107E-05	8.7517961E-07
HNCO	4.0426287E-06	2.3196215E-06	6.0907338E-08
CHO	2.0292488E-04	1.1523515E-04	2.5152618E-06
CH2	1.7756105E-09	4.7187607E-10	6.2354066E-14
CH2F2	3.5811790E-12	1.3387734E-12	2.0257752E-15
CH2O	8.3557082E-06	4.9065877E-06	1.4937733E-07
CH3	6.8025914E-07	3.0622453E-07	1.5914199E-09
CH3F	1.2314746E-09	5.6182954E-10	3.3918840E-12
CH4	1.2923661E-06	8.4329759E-07	6.0501774E-08
CN	2.5633784E-08	7.4607227E-09	1.7385969E-12
CO	4.4897691E-01	4.4779783E-01	4.3459395E-01
CO2	2.3245243E-02	2.4563707E-02	3.7894540E-02
CP	5.9431246E-09	2.4588831E-09	9.8505737E-13
C2	1.6252471E-14	1.7346589E-15	4.4331379E-22
C2F2	1.4331216E-13	3.8067308E-14	5.6234699E-18
C2F4	1.0636180E-24	1.0740693E-25	2.3828597E-32
C2H2	5.1321476E-09	1.9086216E-09	3.0333571E-12
C2H4	5.8340369E-11	2.2064313E-11	4.4708980E-14
C2H4O	2.4615651E-15	5.7669104E-16	4.7071602E-20
C2N2	1.6491724E-11	4.7081991E-12	1.2322492E-15
C3	2.7154176E-17	2.8616571E-18	7.5824359E-25
C3O2	3.7353439E-14	9.7244016E-15	1.4176426E-18
C4N2	1.7841876E-20	1.8772081E-21	7.3597704E-28
HF	1.9502342E-01	1.9708430E-01	1.9986764E-01
HOF	2.6333251E-09	7.5585829E-10	1.4235804E-13
NF	5.4093700E-11	1.1201943E-11	2.2831118E-16
NOF	1.7305638E-10	4.2402040E-11	2.7762995E-15
FO	1.5061331E-11	2.6662287E-12	1.7553672E-17
PF	1.5456197E-05	1.1795009E-05	2.8719321E-07
F2	8.8521093E-13	1.6798471E-13	1.8453293E-18
F2O	1.8827560E-18	1.4991708E-19	4.3380099E-27
PF2	2.9194301E-07	2.3206323E-07	7.6717654E-09
NF3	1.8500026E-22	1.2387807E-23	1.2580036E-31
PF3	9.1927489E-09	9.0489892E-09	1.4002916E-09
PF5	1.0401724E-15	8.5079255E-16	4.3643279E-17
NH	6.9999896E-06	2.5741755E-06	2.7610855E-09
OH	2.5532019E-03	1.3997497E-03	2.1562399E-05

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PH                           9.5330387E-05   6.6208700E-05   8.7601320E-07

H2                           1.6316544E 00   1.6374176E 00   1.6650807E 00
NH2                          1.4166972E-05   6.6522592E-06   3.9264511E-08
H2O                          5.7743934E-01   5.7568747E-01   5.5520751E-01
H2O2                         6.5121880E-08   2.1071864E-08   1.0441371E-11
PH2                          1.5300481E-04   1.1744117E-04   3.2554082E-06

NH3                          1.8189014E-04   1.2503185E-04   1.0897901E-05
PH3                          9.5437082E-06   7.3932214E-06   2.4391268E-07
N2H4                         1.2894578E-11   3.0422852E-12   2.7296608E-16
NF2                          1.5812448E-15   2.0276375E-16   1.6130827E-22
NO                           1.2345597E-04   5.7309392E-05   2.8737485E-07

NO2                          1.3319114E-09   3.3899327E-10   2.8357129E-14
NO2F                         6.1251703E-17   7.0455391E-18   2.7973958E-24
PN                           4.5042182E-03   4.7899954E-03   1.1720458E-03
N2                           4.9159363E-01   4.9155504E-01   4.9344651E-01
N2O                          2.2491704E-08   7.8928757E-09   6.5576211E-12

N2O3                         1.9471561E-18   1.4232671E-19   2.7136115E-27
N2O4                         1.7337639E-24   6.9325106E-26   2.3906042E-35
N2O5                         3.4107407E-31   6.0606894E-33   0.
PO                           2.4599871E-03   2.2360730E-03   1.7694167E-04
O2                           3.3547598E-06   1.2463420E-06   1.3104263E-09

PO2                          9.5002921E-04   9.5583298E-04   1.5400184E-04
O3                           1.8008942E-14   1.9894369E-15   5.3246228E-22
P4O6                         3.0759198E-09   3.9377891E-08   1.7466565E-03
P4O10                        4.7685512E-24   1.9785392E-23   5.1103534E-22
P2                           3.2326157E-05   4.0253282E-05   4.6091861E-06

P4                           7.6520837E-12   1.2921992E-11   3.6610316E-13
FNO3                         5.1742712E-24   2.0140893E-25   5.1963983E-35
HNO                          3.2111967E-07   1.1103662E-07   7.8633634E-11
HNO2-CIS                     9.5496835E-10   2.5342969E-10   3.1167107E-14
HNO2-TRA                     1.0736476E-09   2.8669200E-10   3.6728695E-14

HNO3                         3.5534105E-15   5.0624366E-16   9.4251895E-22
POF3                         5.5050808E-10   5.9068061E-10   1.7583464E-10
AL2O3        S               0.              0.              5.2815344E-01
AL2O3        L               5.2646613E-01   5.2730504E-01   0.
CAO          S               1.1874109E-02   1.2010898E-02   1.2083657E-02
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                           THROAT CALCULATIONS                                  MARG.

PRESSURE, ATM                               40.3378
DENSITY, GM/CC                            0.0054734
VELOCITY, CM/SEC                            89810.5
DV,  GM/(CM CM SEC)                        491.5681

PRESSURE, ATM                               40.7411
DENSITY, GM/CC                            0.0055209
VELOCITY, CM/SEC                            89023.4
DV,  GM/(CM CM SEC)                        491.4865

PRESSURE, ATM                               39.9384
DENSITY, GM/CC                            0.0054261
VELOCITY, CM/SEC                            90632.8
DV,  GM/(CM CM SEC)                        491.7845

PRESSURE, ATM                               39.5429
DENSITY, GM/CC                            0.0053791
VELOCITY, CM/SEC                            91489.7
DV,  GM/(CM CM SEC)                        492.1288

PRESSURE, ATM                               39.1514
DENSITY, GM/CC                            0.0053326
VELOCITY, CM/SEC                            92294.5
DV,  GM/(CM CM SEC)                        492.1710

PRESSURE, ATM                               38.7638
DENSITY, GM/CC                            0.0052866
VELOCITY, CM/SEC                            93091.8
DV,  GM/(CM CM SEC)                        492.1363

PRESSURE, ATM                               39.1514
DENSITY, GM/CC                            0.0053326
VELOCITY, CM/SEC                            92295.0
DV,  GM/(CM CM SEC)                        492.1740
C*, FT/SEC                                4596.0237
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ROCKET RESEARCH CO                                                    MARG.

52C S. PORTLAND STREET

SEATTLE, WASHINGTON 98108

ATT.  DAVID GOOD
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Composition: 38.0 Al/9.5 NH_4NO_3/
47.5 Feces/5 M-1

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  CASE 5      EXIT PRESSURE = 14.7 PSI

ELEMENTS IN REACTANTS, ATOMS                        FUEL   OXIDIZER    BINDERS
H                                        5.0457     0.         4.00       9.62
C                                        0.7208     0.         0.         3.31
O                                        2.4371     0.         3.00       4.38
N                                        0.3018     0.         2.00       0.14
F                                        0.2000     0.         0.         4.00
AL                                       1.4085     1.00       0.         0.
P                                        0.0138     0.         0.         0.03
CA                                       0.0201     0.         0.         0.04
ENTHALPY OF REACTANTS, KCAL           -175.8260

SHIFTING IMPULSE, SEC                       222.9221

                                  CHAMBER            THROAT            EXHAUST
PRESSURE, ATM                     68.0457           39.9384             1.0000
TEMPERATURE, DEG K              2318.0000         2288.6240          1760.6303
HEAT CAPACITY, CAL /DEG K         51.9888           49.8651            49.2661
ENTHALPY, KCAL                  -175.8260         -184.2423          -232.9378
ENTROPY, CAL / DEG K             201.0837          201.0931           201.0838
FROZEN GAMMA                       1.2496            1.1581             1.1467
MOLS OF GAS                        3.3220            3.4254             3.1713
VELOCITY, FT / SEC                                2753.3164          7172.3074
MOLECULAR WEIGHT                  28.1173           24.1703            23.9839
DENSITY, GM / CC              0.010765381       0.006202310        0.000218242
C *, FT/SEC                                       4345.8621
AREA RATIO                                                             10.9095

PRODUCTS OF COMBUSTION, MOLS
H                          3.6404208E-03   4.1670991E-03   7.1570510E-04
C                          5.9196103E-10   6.4643762E-10   3.0498390E-13
O                          2.6783624E-10   2.4640388E-10   4.3468348E-13
N                          3.5529630E-09   3.1161421E-09   1.1995614E-11
F                          5.5806223E-08   4.7588918E-08   1.5524597E-09

AL                         1.3747426E-04   2.3176821E-04   9.7755706E-07
P                          2.2772066E-05   2.7926470E-05   3.6986008E-06
CA                         2.8052000E-04   4.6718844E-04   2.1193560E-05
CAO                        1.2161240E-06   1.4931406E-06   1.0375436E-08
ALC                        3.8889879E-10   5.1836265E-10   8.1310915E-15

ALF                        1.0107542E-01   1.2943061E-01   1.8924501E-02
ALOF                       2.0453553E-04   2.0134735E-04   1.2570677E-05
ALF2                       6.7612124E-03   5.7995177E-03   1.5202084E-03
ALF3                       1.9381964E-02   1.2168355E-02   4.7651384E-02
ALH                        1.2607907E-04   1.6883846E-04   3.5342532E-07

HALO                       1.6966512E-09   1.6347414E-09   3.0339403E-13
ALCH                       2.3892884E-07   2.4282543E-07   1.5441318E-10
ALO2H                      4.0218282E-12   2.9351485E-12   1.5969582E-16
ALN                        1.7093468E-09   1.8455630E-09   2.8906298E-13
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ALC                       5.8458080E-08     7.1848050E-08     3.5698576E-11

AL2                       1.9741824E-08     3.6925259E-08     5.3921491E-13
AL2O                      6.1253296E-05     1.0434252E-04     3.5305634E-08
(ALO)2                    1.9813467E-09     2.4907036E-09     1.3711713E-13
CF                        5.3171586E-11     3.9200243E-11     3.9306981E-14
FCN                       9.6404842E-08     6.0348342E-08     1.8274973E-09

CF2                       3.5545327E-12     1.8028861E-12     6.0852936E-15
COF2                      1.9752264E-11     8.7127579E-12     2.3269088E-13
CF3                       5.3661912E-16     1.7690405E-16     5.3627850E-19
CF4                       1.1216675E-18     2.5354522E-19     2.4479741E-21
CH                        8.4717864E-09     7.6393175E-09     4.4405367E-12

CHFO                      4.2764006E-08     2.3487975E-08     5.5188627E-10
CHF3                      2.1155747E-14     6.0579048E-15     7.7181920E-17
HCN                       3.1387986E-02     2.6404833E-02     4.3220547E-03
HNCO                      2.9327071E-06     1.8098097E-06     4.0520266E-08
CHO                       1.2515614E-04     1.0530814E-04     2.4933681E-06

CH2                       2.4971870E-07     1.9478582E-07     4.2887580E-10
CH2F2                     9.5032220E-11     3.4353428E-11     5.3274179E-13
CH2O                      1.6244740E-05     1.1107122E-05     2.2873863E-07
CH3                       1.3329488E-03     9.4111561E-04     2.2833242E-05
CH3F                      6.5251491E-07     3.0300317E-07     8.6385561E-09

CH4                       2.2109965E-02     1.3660664E-02     1.6474577E-03
CN                        6.7079806E-07     6.0101739E-07     3.7033973E-09
CO                        5.3658773E-01     6.3444011E-01     4.0638000E-01
CO2                       4.1950003E-05     3.7019980E-05     5.0436721E-06
CP                        3.6849700E-06     4.1710656E-06     7.9610766E-08

C2                        9.4447043E-11     9.5964408E-11     7.9669922E-15
C2F2                      8.8276494E-10     4.7156425E-10     5.5220106E-12
C2F4                      2.3740569E-23     4.4057972E-24     3.9852262E-28
C2H2                      1.0506524E-02     9.1434401E-03     2.7000595E-04
C2H4                      1.0083773E-03     5.7195884E-04     9.0979931E-06

C2H4O                     1.2681921E-11     4.7692657E-12     9.7724375E-16
C2N2                      2.4249397E-06     1.6376657E-06     1.8051216E-08
C3                        7.9271291E-10     8.3070059E-10     1.4080767E-13
C3O2                      2.6912707E-11     1.8688285E-11     8.6792952E-15
C4N2                      3.5417677E-09     2.0573301E-09     6.3722168E-13

HF                        2.7022908E-02     2.2227832E-02     3.5025043E-02
HOF                       1.0241706E-14     4.6981241E-15     1.5592967E-18
NF                        2.4978791E-14     1.3147571E-14     6.6246824E-18
NOF                       1.6727069E-16     6.7246262E-17     1.2181959E-20
FO                        4.8088279E-18     2.4617208E-18     9.5015931E-23

PF                        3.0234399E-06     2.4822337E-06     5.7225920E-07
F2                        7.1864980E-17     3.3280203E-17     1.3462876E-20
F2O                       1.3915100E-26     3.9147626E-27     2.5131303E-33
PF2                       1.6693644E-08     9.0610151E-09     2.7484290E-09
NF3                       1.8989852E-28     3.3510165E-29     5.6273060E-35

PF3                       2.6114086E-10     9.7483368E-11     1.0121906E-10
PF5                       1.1447835E-18     1.7659591E-19     8.7864612E-20
NH                        2.0090444E-07     1.4759907E-07     9.8074522E-10
OH                        2.7169149E-07     2.1940025E-07     2.0134153E-09
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PH                        1.5366864E-04   1.5195765E-04   1.4127674E-05

H2                        2.4301647E 00   2.4553588E 00   2.4989462E 00
NH2                       2.4013329E-06   1.4992459E-06   2.4288846E-08
H20                       1.0585319E-03   7.8558086E-04   1.1259573E-04
H202                      5.1208249E-15   2.1895561E-15   1.4552995E-19
PH2                       9.4397091E-04   7.6879879E-04   8.3921310E-05

NH3                       2.7724201E-04   1.5179526E-04   1.2876915E-05
PH3                       1.7264169E-04   1.1366632E-04   9.5790782E-06
N2H4                      2.6335773E-12   6.7685773E-13   1.7195078E-16
NF2                       4.4391946E-20   1.3777569E-20   6.1039083E-25
NO                        3.1815412E-09   2.2470398E-09   1.0678474E-11

NO2                       7.0293546E-18   3.2005731E-18   9.8976680E-23
NO2F                      7.6371008E-27   1.9150780E-27   1.0552251E-33
PN                        1.0518411E-02   1.0363151E-02   1.0833937E-02
N2                        1.1584310E-01   9.6227698E-02   1.4329850E-01
N20                       2.8374773E-13   1.3787971E-13   1.3669118E-16

N203                      3.4063368E-31   6.3468742E-32   0.
N204                      0.              0.              0.
N205                      0.              0.              0.
PO                        3.9716987E-06   3.8058598E-06   3.0518435E-07
02                        4.9124454E-14   3.3273745E-14   8.7427379E-18

PO2                       2.6241296E-09   1.8925266E-09   3.8550703E-11
03                        8.5002992E-27   3.2435029E-27   2.2857436E-34
P406                      3.9484445E-20   9.2356528E-21   6.4292501E-21
P4010                     0.              0.              0.
P2                        9.9989250E-04   1.1933454E-03   1.4378511E-03

P4                        5.1956176E-08   4.8563735E-08   5.7207499E-08
FNO3                      3.0970338E-38   4.5074558E-39   0.
HNO                       9.6174389E-12   5.1286712E-12   3.6584782E-15
HNO2-CIS                  1.6280619E-17   6.0340527E-18   1.6881567E-22
HNO2-TRA                  1.8645806E-17   6.9198537E-18   1.9965724E-22

HNO3                      1.1716890E-26   2.7898175E-27   4.7667800E-34
POF3                      2.5714703E-14   7.2088447E-15   1.8404793E-15
AL203       S             8.0619054E-02   5.9395602E-01   6.7017081E-01
AL203       L             5.4576276E-01   0.              0.
CAO         S             1.9857758E-02   1.9671810E-02   2.0118291E-02

C           S             1.0619007E-01   2.5830439E-02   3.0789644E-01
ALN         S             2.7885485E-02   7.2399002E-02   0.
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                         THROAT CALCULATIONS                                  MARG.

PRESSURE, ATM                           39.5429
DENSITY, GM/CC                        0.0061470
VELOCITY, CM/SEC                        84637.7
DV,  GM/(CM CM SEC)                    520.2704

PRESSURE, ATM                           39.9384
DENSITY, GM/CC                        0.0062023
VELOCITY, CM/SEC                        83921.3
DV,  GM/(CM CM SEC)                    520.5062

PRESSURE, ATM                           40.3377
DENSITY, GM/CC                        0.0062584
VELOCITY, CM/SEC                        83145.1
DV,  GM/(CM CM SEC)                    520.3517

PRESSURE, ATM                           39.9384
DENSITY, GM/CC                        0.0062023
VELOCITY, CM/SEC                        83921.1
DV,  GM/(CM CM SEC)                    520.5050
C*, FT/SEC                            4345.8621
```

MARG.

Composition: 38.0 Al/19.0 NH_4NO_3/
38.0 Feces/5M-1

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ROCKET RESEARCH CO

520 S. PORTLAND STREET

SEATTLE, WASHINGTON 98108

ATT.  DAVID GOOD

  CASE 6     EXIT PRESSURE = 14.7 PSI

ELEMENTS IN REACTANTS, ATOMS                         FUEL  OXIDIZER   BINDERS
H                                        4.6062     0.        4.00      9.62
C                                        0.5967     0.        0.        3.31
O                                        2.3770     0.        3.00      4.38
N                                        0.5262     0.        2.00      0.14
F                                        0.2000     0.        0.        4.00
AL                                       1.4085     1.00      0.        0.
P                                        0.0111     0.        0.        0.03
CA                                       0.0161     0.        0.        0.04
ENTHALPY OF REACTANTS, KCAL           -155.0239

SHIFTING IMPULSE, SEC                        228.2489

                                 CHAMBER          THROAT            EXHAUST
PRESSURE, ATM                    68.0457          39.9384            1.0000
TEMPERATURE, DEG K             2529.3618        2391.0232         1841.8989
HEAT CAPACITY, CAL /DEG K        50.4943          50.1830           47.1618
ENTHALPY, KCAL                 -155.0239        -163.6120         -214.8977
ENTROPY, CAL / DEG K            204.1925         204.2020          204.2001
FROZEN GAMMA                      1.1493           1.1496            1.1550
MOLS OF GAS                       3.3011           3.2868            3.1846
VELOCITY, FT / SEC                              2781.2731         7343.6898
MOLECULAR WEIGHT                 25.3612          25.3417           25.3511
DENSITY, GM / CC             0.009911038      0.006185122       0.000207745
C *, FT/SEC                                     4314.1333
AREA RATIO                                                          11.2757

PRODUCTS OF COMBUSTION, MOLS
H                          9.4133893E-03   6.5485311E-03   1.3552656E-03
C                          4.8209966E-09   1.3607914E-09   2.6487404E-12
O                          3.8419212E-09   1.1618211E-09   1.7691826E-12
N                          4.0282921E-08   1.3753261E-08   6.1806836E-11
F                          1.6349590E-07   9.7922952E-08   3.5458013E-09

AL                         1.4353198E-03   5.8097802E-04   1.1957988E-05
P                          3.9816744E-05   2.8021539E-05   5.4505276E-06
CA                         1.8282003E-03   9.7137763E-04   1.2815810E-04
CAO                        1.2315510E-05   4.8003462E-06   5.4431418E-08
ALC                        6.9380276E-09   1.2641156E-09   2.9120644E-13

ALF                        1.6829940E-01   1.5315772E-01   6.9784204E-02
ALOF                       4.0430073E-04   3.1995461E-04   3.2908747E-05
ALF2                       4.0742921E-03   4.9549081E-03   2.9728003E-03
ALF3                       2.3796691E-03   5.5655858E-03   3.2848355E-02
ALH                        9.4143665E-04   3.5475119E-04   3.3442189E-06

HALO                       2.3133608E-08   5.7688993E-09   2.7546909E-12
ALOH                       2.2946888E-06   7.1519183E-07   1.1123533E-09
ALO2H                      7.1514911E-11   1.4618125E-11   1.1099216E-15
ALN                        4.0161630E-08   9.1680733E-09   5.9096415E-12
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ALO                      1.0201833E-06   2.8921509E-07   3.9823699E-10

AL2                      8.4036305E-07   1.4805045E-07   4.1939388E-11
AL2O                     1.0249898E-03   3.1674176E-04   9.1026616E-07
(ALO)2                   5.1381881E-08   1.1658347E-08   3.0175861E-12
CF                       1.4869610E-10   5.8009343E-11   1.7558148E-13
FCN                      9.6993670E-08   6.8258862E-08   3.7746559E-09

CF2                      3.0226966E-12   1.7599589E-12   1.2782907E-14
COF2                     8.9344227E-12   7.5286023E-12   1.9855363E-13
CF3                      2.0144883E-16   1.3810897E-16   6.7995892E-19
CF4                      1.3121200E-19   1.3211979E-19   1.4706657E-21
CH                       3.8296172E-08   1.1821176E-08   2.5100460E-11

CHFO                     2.7817792E-08   1.9977555E-08   5.5060810E-10
CHF3                     3.1811920E-15   2.9315545E-15   5.0184557E-17
HCN                      2.7676462E-02   2.2722476E-02   7.3672674E-03
HNCO                     4.1510625E-06   2.4488974E-06   6.1195282E-08
CHO                      1.8971681E-04   1.1364521E-04   4.1995825E-06

CH2                      4.6414981E-07   1.8944117E-07   1.2690191E-09
CH2F2                    1.8787951E-11   1.5619958E-11   3.8069252E-13
CH2O                     1.5225603E-05   9.3071361E-06   2.6696851E-07
CH3                      7.5780873E-04   4.9347956E-04   2.8852445E-05
CH3F                     1.5146376E-07   1.2206019E-07   6.2689157E-09

CH4                      4.7945119E-03   4.3294694E-03   1.0352141E-03
CN                       2.4511511E-06   1.0854303E-06   1.7521931E-08
CO                       5.5574583E-01   5.6334712E-01   5.3868610E-01
CO2                      6.2545018E-05   4.8781351E-05   5.4223365E-06
CP                       4.0146013E-06   2.4126360E-06   1.7078812E-07

C2                       4.5551642E-10   1.1335744E-10   9.6859822E-14
C2F2                     1.9939353E-10   1.7006223E-10   9.1233709E-12
C2F4                     3.7250314E-24   1.9673054E-24   5.8508986E-28
C2H2                     3.5607321E-03   2.7032818E-03   4.8604702E-04
C2H4                     1.4173179E-04   1.0648887E-04   8.4235831E-06

C2H4O                    5.5459765E-12   1.9661262E-12   1.2548061E-15
C2N2                     2.5689503E-06   1.4874362E-06   6.7852282E-08
C3                       1.1595054E-09   3.8888346E-10   1.4963860E-12
C3O2                     2.6341170E-11   1.0716352E-11   2.7689185E-14
C4N2                     1.3804893E-09   6.0198156E-10   4.7463753E-12

HF                       1.5962380E-02   1.9881846E-02   2.5844038E-02
HOF                      5.7936299E-14   1.6691141E-14   3.5126635E-18
NF                       2.0926198E-13   6.0723312E-14   2.9923759E-17
NOF                      1.7319300E-15   4.2617711E-16   4.0472614E-20
FO                       8.3369793E-17   1.5681439E-17   4.7732641E-22

PF                       1.9168617E-06   1.8012575E-06   4.5066100E-07
F2                       2.9849921E-16   1.0046904E-16   4.2265615E-20
F2O                      3.1685541E-25   3.5149058E-26   1.6380077E-32
PF2                      4.1716478E-09   4.9623892E-09   1.2176107E-09
NF3                      1.3935044E-27   2.1612802E-28   2.6521341E-34

PF3                      1.9940650E-11   3.5273603E-11   2.0953546E-11
PF5                      1.9663536E-20   4.4028654E-20   7.3202054E-21
NH                       1.1516411E-06   4.5622684E-07   3.0844782E-09
OH                       1.4524785E-06   6.1851920E-07   4.0525324E-09
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PH                         1.7404609E-04   1.2145276E-04   1.5087104E-05

H2                         2.2586313E 00   2.2640568E 00   2.2830136E 00
NH2                        6.3388745E-06   3.0914019E-06   4.3622828E-08
H2O                        1.5663214E-03   1.1340509E-03   9.0681847E-05
H2O2                       5.8917805E-14   1.1252020E-14   3.0713516E-19
PH2                        6.0436701E-04   4.5577173E-04   5.8764114E-05

NH3                        2.7529207E-04   1.8782401E-04   1.1382271E-05
PH3                        7.0708114E-05   5.3248413E-05   4.7532340E-06
N2H4                       7.2004563E-12   1.8290413E-12   2.7572607E-16
NF2                        3.0884148E-19   7.0698532E-20   2.6018806E-24
NO                         3.1532370E-08   1.1377392E-08   3.2037386E-11

NO2                        2.5966307E-16   3.9438420E-17   4.7036195E-22
NO2F                       3.6615680E-25   3.3032933E-26   6.4061734E-33
PN                         9.4504633E-03   9.5764242E-03   9.5802721E-03
N2                         2.3117673E-01   2.2427309E-01   2.1059056E-01
N2O                        3.9814709E-12   1.0864213E-12   4.9086475E-16

N2O3                       1.1222721E-28   3.8887565E-30   0.
N2O4                       7.6163151E-38   0.              0.
N2O5                       0.              0.              0.
PO                         7.3842698E-06   4.8503860E-06   3.0002983E-07
O2                         1.1048362E-12   2.4368082E-13   3.1027837E-17

PO2                        6.6364235E-09   3.4784603E-09   2.9783515E-11
O3                         1.7144191E-24   9.1182851E-26   2.3636883E-33
P4O6                       1.5721049E-21   2.1210236E-21   4.1476333E-23
P4O10                      0.              0.              0.
P2                         3.5249268E-04   4.0713742E-04   6.9622291E-04

P4                         2.5831638E-09   3.6447676E-09   6.9382035E-09
FNO3                       1.0991493E-35   2.6993416E-37   0.
HNO                        9.4884639E-11   2.5837255E-11   1.0666761E-14
HNO2-CIS                   3.6764014E-16   5.7396764E-17   5.5182214E-22
HNO2-TRA                   4.1739256E-16   6.5526724E-17   6.4885778E-22

HNO3                       1.0108872E-24   6.5368763E-26   2.4923775E-33
POF3                       2.7151225E-15   3.7911274E-15   3.0056697E-16
AL2O3        S             0.              0.              6.0738456E-01
AL2O3        L             6.0119724E-01   5.9886386E-01   0.
CAO          S             1.4271080E-02   1.5136280E-02   1.5983383E-02

ALN          S             2.6466799E-02   4.5224934E-02   8.8101572E-02
C            S             0.              0.              4.8547360E-02
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                         THROAT CALCULATICNS                              MARG.
PRESSURE, ATM                                39.5429
DENSITY, GM/CC                             0.0061311
VELOCITY, CM/SEC                             85488.9
DV,  GM/(CM CM SEC)                         524.1388

PRESSURE, ATM                                39.9384
DENSITY, GM/CC                             0.0061851
VELCCITY, CM/SEC                             84773.3
DV,  GM/(CM CM SEC)                         524.3339

PRESSURE, ATM                                40.3377
DENSITY, GM/CC                             0.0062399
VELOCITY, CM/SEC                             84003.0
DV,  GM/(CM CM SEC)                         524.1698

PRESSURE, ATM                                39.9384
DENSITY, GM/CC                             0.0061851
VELCCITY, CM/SEC                             84773.2
DV,  GM/(CM CM SEC)                         524.3332
C*, FT/SEC                                 4314.1333
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AGHAZ
ROCKET RESEARCH CO.                                                              MARG.

520 SOUTH PORTLAND STREET

SEATTLE, WASHINGTON   98108

ATT. DR. D. GOOD          PO 21186-112001          FEB 68
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Composition: 35Al/32.5 NH_4NO_3/
27.5 Waste/5 M-1
Waste - Urine: Feces Wt. Ratio of 8:1

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 CASE  9

ELEMENTS IN REACTANTS, ATOMS                        FUEL  OXIDIZER   BINDERS
H                                   4.5704         10.71     4.00        0.
C                                   0.1480          0.17     0.          2.00
O                                   2.6669          5.27     3.00        0.
N                                   0.8356          0.09     2.00        0.
CL                                  0.0062          0.02     0.          0.
AL                                  1.2973          0.       0.          1.00
NA                                  0.0096          0.03     0.          0.
F                                   0.2000          0.       0.          4.00
ENTHALPY OF REACTANTS, KCAL      -145.4759

SHIFTING IMPULSE, SEC                  243.7101

FROZEN IMPULSE, SEC                    242.5120

                                 CHAMBER           FROZEN             EXHAUST
PRESSURE, ATM                    68.0457           1.0000             1.0000
TEMPERATURE, DEG K             3313.5204        2317.0256          2318.0000
HEAT CAPACITY, CAL /DEG K        51.8142          48.0003            48.8478
ENTHALPY, KCAL                 -145.4759        -213.0673          -213.7359
ENTROPY, CAL / DEG K            214.7277         214.7277           214.7277
FROZEN GAMMA                      1.1315           1.1434             1.1738
MOLS OF GAS                       3.0297           3.0297             2.9740
VELOCITY, FT / SEC                              7802.6395          7841.1409
MOLECULAR WEIGHT                 27.2686          27.2686            29.7187
DENSITY, GM / CC             0.008245349      0.000173591        0.000176765

PRODUCTS OF COMBUSTION, MOLS
H                         9.9291507E-02     9.9291507E-02     2.3120391E-02
C                         1.6669440E-09     1.6669440E-09     1.9189438E-13
O                         5.7428603E-04     5.7428602E-04     1.3068839E-05
N                         1.1781946E-05     1.1781946E-05     5.2661927E-08
CL                        2.1784609E-04     2.1784609E-04     4.9477968E-05

AL                        2.5041474E-04     2.5041474E-04     3.6943503E-07
NA                        4.1550768E-03     4.1550768E-03     4.8481273E-03
F                         1.2319261E-04     1.2319261E-04     3.9215799E-06
ALC                       7.6430056E-12     7.6430056E-12     5.5609960E-18
ALCL                      1.2903895E-04     1.2903894E-04     1.7747260E-06

ALCLF                     3.0153219E-04     3.0153219E-04     1.0444448E-05
ALCLF2                    9.2812070E-06     9.2812068E-06     7.1363083E-07
ALOCL                     5.0113299E-07     5.0113299E-07     1.8048604E-09
ALCL2                     3.3679173E-06     3.3679173E-06     8.5705973E-08
ALFCL2                    6.1107615E-08     6.1107615E-08     2.0073324E-09

ALCL3                     5.6256773E-10     5.6256773E-10     1.6389178E-11
ALF                       1.2204469E-02     1.2204469E-02     3.1332391E-04
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ALOF                 7.4034250E-03   7.4034249E-03   5.0785172E-04
ALF2                 1.0415091E-03   1.0415091E-03   2.4177063E-05
ALF3                 4.9581076E-04   4.9581075E-04   7.9948070E-05

ALH                  6.5091773E-05   6.5091771E-05   3.5322870E-08
ALOH                 4.7597656E-05   4.7597656E-05   5.3616922E-08
ALN                  3.2460985E-08   3.2460984E-08   1.1176493E-12
ALO                  1.0568148E-04   1.0568147E-04   1.2587923E-07
(ALCL3)2             1.4808669E-21   1.4808669E-21   6.5266243E-26

AL2O                 4.0170125E-05   4.0170125E-05   5.8161526E-09
(ALO)2               1.0203723E-06   1.0203723E-06   1.5069099E-10
CCL                  4.7339866E-13   4.7339865E-13   1.9407997E-17
CLCN                 3.1384690E-10   3.1384690E-10   9.0836567E-13
CF                   1.5564518E-10   1.5564518E-10   1.9881875E-14

FCN                  4.1554682E-09   4.1554682E-09   8.7707237E-12
CF2                  7.0899742E-12   7.0899742E-12   1.5331746E-15
COF2                 6.6086965E-10   6.6086964E-10   6.8241109E-12
CF4                  4.5770591E-18   4.5770591E-18   6.4377710E-22
CHFO                 1.0145663E-07   1.0145663E-07   1.3352812E-09

CHF3                 4.0831975E-15   4.0831975E-15   1.0973987E-18
HCN                  1.6419872E-05   1.6419872E-05   2.5808635E-07
CHO                  1.2316486E-04   1.2316486E-04   3.3877817E-06
CH2F2                9.4151952E-13   9.4151953E-13   4.4557549E-16
CH2O                 2.7598068E-06   2.7598068E-06   4.5842934E-08

CH3F                 2.2104664E-10   2.2104664E-10   2.7647587E-13
CH4                  1.1298188E-07   1.1298188E-07   8.4668130E-10
CN                   6.0325539E-08   6.0325540E-08   5.2905055E-11
NACN                 7.1858271E-06   7.1858270E-06   1.0735871E-07
CO                   1.4123537E-01   1.4123537E-01   1.3931815E-01

CO2                  6.6608285E-03   6.6608284E-03   8.7249715E-03
C2F2                 2.4953256E-14   2.4953256E-14   2.0260651E-18
C2F4                 4.5325108E-25   4.5325108E-25   7.2504011E-32
C2H2                 4.7904065E-10   4.7904065E-10   1.9696890E-13
C2H4                 1.7653833E-12   1.7653833E-12   2.0547275E-16

C2N2                 2.3709832E-12   2.3709832E-12   2.4760801E-16
C4N2                 2.5206783E-22   2.5206783E-22   1.0239577E-29
CLF                  4.5442916E-09   4.5442916E-09   3.3396286E-11
HCL                  5.0247099E-03   5.0247099E-03   4.6453992E-03
HOCL                 1.9728312E-07   1.9728312E-07   3.5231277E-09

NACL                 5.2474750E-04   5.2474750E-04   1.5070872E-03
CLO                  7.6050678E-08   7.6050677E-08   4.8299369E-10
CL2                  4.3388305E-09   4.3388305E-09   1.8237663E-10
CL2O                 9.9711338E-15   9.9711338E-15   2.3489691E-18
HF                   1.7544443E-01   1.7544443E-01   1.9797336E-01

HOF                  3.5560749E-08   3.5560749E-08   6.0099015E-11
NF                   1.3523323E-09   1.3523323E-09   4.2707941E-13
NOF                  3.0815734E-09   3.0815734E-09   2.2907479E-12
NAF                  8.8999876E-04   8.8999876E-04   8.5753266E-04
FO                   9.8721683E-10   9.8721682E-10   2.7066874E-13

F2                   2.7304383E-11   2.7304383E-11   5.8254156E-15
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F20                     3.7727554E-16   3.7727554E-16   9.0347489E-22
NF3                     1.6006058E-20   1.6006058E-20   4.3203710E-27
NH                      5.3782198E-05   5.3782198E-05   3.1045014E-07
NAH                     2.8531826E-04   2.8531826E-04   3.1741391E-05

NAOH                    3.6799947E-03   3.6799947E-03   2.3240555E-03
OH                      1.5648404E-02   1.5648404E-02   1.3821017E-03
H2                      1.5643075E 00   1.5643075E 00   1.6090725E 00
NH2                     3.7242042E-05   3.7242042E-05   3.8685760E-07
H20                     5.7083477E-01   5.7083477E-01   5.6138924E-01

NH3                     1.2349078E-04   1.2349078E-04   4.6564407E-06
N2H4                    3.1632471E-11   3.1632471E-11   1.1220090E-15
NF2                     6.1023251E-14   6.1023250E-14   8.7553310E-19
NO                      1.0131999E-03   1.0131999E-03   3.7771467E-05
NO2                     4.0256420E-08   4.0256420E-08   6.6843967E-11

NO2F                    5.6507481E-15   5.6507481E-15   8.3773447E-20
N2                      4.1715642E-01   4.1715642E-01   4.1776789E-01
N20                     1.8400003E-07   1.8400003E-07   8.1962935E-10
N203                    4.7444723E-16   4.7444723E-16   6.3126783E-22
NAO                     2.7324491E-05   2.7324491E-05   1.4124473E-06

O2                      8.3522193E-05   8.3522193E-05   1.9199314E-06
FNO3                    4.9811147E-21   4.9811147E-21   2.7210979E-28
HNO                     2.8632757E-06   2.8632757E-06   1.1903704E-08
HNO2-CIS                1.5418950E-08   1.5418950E-08   1.6140378E-11
HNO2-TRA                1.7104014E-08   1.7104014E-08   1.8485196E-11

HNO3                    2.2312023E-13   2.2312023E-13   9.3041317E-18
CH2CL2                  3.0604796E-12   3.0604796E-12   2.4043157E-17
C2H5CL                  2.2940363E-12   2.2940363E-12   5.9247604E-21
C2H4CL2 11              1.5397204E-14   1.5397204E-14   1.6197979E-24
C2H4CL2 12              5.8896988E-17   5.8896988E-17   6.4092540E-26

C2H3CL                  3.4430745E-09   3.4430744E-09   1.1170806E-16
C2CL4                   1.0230184E-22   1.0230184E-22   3.2193594E-32
AL2O3        S          0.              6.3755862E-01   3.9087013E-01
AL2O3        L          6.3755862E-01   0.              2.5728900E-01
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Composition: 35Al/17.5 NH_4NO_3/
42.5 Waste/5 M-1
Waste - Urine: Feces Wt. Ratio of 8:1

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AGHAZ
ROCKET RESEARCH CO.                                                             MARG.

520 SOUTH PORTLAND STREET

SEATTLE, WASHINGTON  98108

ATT. DR. D. GOOD            PO 21186-112001          FEB 68

 CASE  11

ELEMENTS IN REACTANTS, ATOMS                        FUEL  OXIDIZER   BINDERS
H                                        5.4280    10.71     4.00      0.
C                                        0.1743     0.17     0.        2.00
O                                        2.8950     5.27     3.00      0.
N                                        0.4737     0.09     2.00      0.
CL                                       0.0096     0.02     0.        0.
AL                                       1.2973     0.       0.        1.00
NA                                       0.0148     0.03     0.        0.
F                                        0.2000     0.       0.        4.00
ENTHALPY OF REACTANTS, KCAL        -183.8703

SHIFTING IMPULSE, SEC                   236.0503

FROZEN IMPULSE, SEC                     235.6251

                                 CHAMBER           FROZEN            EXHAUST
PRESSURE, ATM                    68.0457           1.0000             1.0000
TEMPERATURE, DEG K             2807.5875        1913.8645          1944.5896
HEAT CAPACITY, CAL /DEG K        54.5459          49.9018            50.0126
ENTHALPY, KCAL                 -183.8703        -247.6773          -247.9070
ENTROPY, CAL / DEG K            217.0829         217.0829           217.0829
FROZEN GAMMA                      1.1345           1.1489             1.1478
MOLS OF GAS                       3.2536           3.2536             3.2402
VELOCITY, FT / SEC                              7581.0605          7594.6943
MOLECULAR WEIGHT                 25.6349          25.6349            25.7148
DENSITY, GM / CC             0.009059459      0.000195689        0.000193395

PRODUCTS OF COMBUSTION, MOLS
H                          2.4794075E-02   2.4794075E-02   2.6899964E-03
C                          3.7464573E-11   3.7464574E-11   5.6800014E-16
O                          2.4795401E-05   2.4795401E-05   1.0589916E-07
N                          3.9155236E-07   3.9155237E-07   3.4562421E-10
CL                         6.9434415E-05   6.9434415E-05   4.6541170E-06

AL                         2.5572788E-06   2.5572788E-06   1.6368587E-10
NA                         3.6041605E-03   3.6041605E-03   3.0926212E-03
F                          1.2109655E-05   1.2109655E-05   1.0524287E-07
ALC                        1.7659805E-14   1.7659805E-14   2.4304055E-22
ALCL                       1.0899746E-05   1.0899746E-05   1.0468910E-08

ALCLF                      8.5327674E-05   8.5327675E-05   3.6034498E-07
ALCLF2                     8.2570798E-06   8.2570798E-06   1.3730399E-07
ALOCL                      2.7525789E-08   2.7525789E-08   5.6248483E-12
ALCL2                      1.1908378E-06   1.1908378E-06   2.4198329E-09
ALFCL2                     5.4107840E-08   5.4107840E-08   2.2364529E-10

ALCL3                      6.7361884E-10   6.7361884E-10   1.6859320E-12
ALF                        9.4253904E-04   9.4253905E-04   2.7570448E-06
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ALCL                9.8477374E-04   9.8477374E-04   1.0434143E-05
ALF2                1.7520072E-04   1.7520072E-04   6.4747124E-07
ALF3                4.2325726E-04   4.2325726E-04   2.4755713E-05

ALH                 1.0974542E-06   1.0974542E-06   3.2178641E-11
ALOH                1.2592387E-06   1.2592387E-06   9.2806972E-11
ALN                 1.2041544E-10   1.2041544E-10   1.2306149E-16
ALO                 1.1382415E-06   1.1382415E-06   5.8133962E-11
(ALCL3)2            3.2281093E-21   3.2281094E-21   1.5601032E-27

AL2O                1.5306315E-07   1.5306315E-07   2.6686055E-13
(ALO)2              4.4626245E-09   4.4626245E-09   8.7665844E-15
CCL                 2.2441547E-14   2.2441547E-14   9.4027668E-20
CLCN                1.5419601E-10   1.5419601E-10   1.9081920E-13
CF                  8.3509564E-12   8.3509566E-12   2.0021911E-16

FCN                 1.2579904E-09   1.2579904E-09   1.5081124E-12
CF2                 1.0784431E-12   1.0784431E-12   7.0021961E-17
COF2                5.7971897E-10   5.7971897E-10   4.6080313E-12
CF4                 2.9441339E-18   2.9441339E-18   2.5027838E-22
CHFO                1.0890444E-07   1.0890444E-07   1.2651418E-09

CHF3                3.8108872E-15   3.8108872E-15   7.7390099E-19
HCN                 1.2683717E-05   1.2683717E-05   1.9573520E-07
CHO                 7.9970799E-05   7.9970800E-05   1.5403503E-06
CH2F2               1.2316571E-12   1.2316571E-12   5.4143105E-16
CH2O                3.6062845E-06   3.6062845E-06   6.0773475E-08

CH3F                4.8055566E-10   4.8055567E-10   7.5126899E-13
CH4                 5.7471498E-07   5.7471498E-07   8.7106819E-09
CN                  5.5648679E-09   5.5648679E-09   1.5849738E-12
NACN                9.7575409E-06   9.7575409E-06   1.4715438E-07
CO                  1.6423396E-01   1.6423396E-01   1.5927905E-01

CO2                 9.9242580E-03   9.9242580E-03   1.4983926E-02
C2F2                1.3612012E-14   1.3612012E-14   6.7967777E-19
C2F4                9.2488458E-26   9.2488459E-26   4.9474060E-33
C2H2                6.2646396E-10   6.2646396E-10   2.7390532E-13
C2H4                8.5300895E-12   8.5300895E-12   1.9743437E-15

C2N2                8.5451275E-13   8.5451276E-13   7.1397300E-17
C4N2                1.0019289E-22   1.0019289E-22   3.4898783E-30
CLF                 7.8290039E-10   7.8290039E-10   1.1209603E-12
HCL                 7.2764668E-03   7.2764669E-03   4.1184822E-03
HOCL                6.2764876E-08   6.2764876E-08   3.0252022E-10

NACL                2.1516357E-03   2.1516357E-03   5.4809529E-03
CLO                 6.2347530E-09   6.2347530E-09   5.5230351E-12
CL2                 2.2080898E-09   2.2080898E-09   1.8625185E-11
CL2O                6.6342635E-16   6.6342635E-16   1.0564689E-20
HF                  1.9466879E-01   1.9466879E-01   1.9831846E-01

HOF                 2.9587364E-09   2.9587365E-09   1.1463093E-12
NF                  3.3798369E-11   3.3798369E-11   1.6376214E-15
NOF                 1.2658966E-10   1.2658966E-10   1.8484953E-14
NAF                 1.6256391E-03   1.6256391E-03   1.5481690E-03
FO                  1.5261151E-11   1.5261151E-11   4.1357307E-16

F2                  7.4777092E-13   7.4777092E-13   2.0547416E-17
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F20                       1.8095987E-18   1.8095987E-18   2.1779669E-25
NF3                       1.0535317E-22   1.0535317E-22   1.9798082E-30
NH                        5.0139856E-06   5.0139856E-06   9.2386836E-09
NAH                       2.3155005E-04   2.3155005E-04   1.7664781E-05

NAOH                      7.1592683E-03   7.1592683E-03   4.6496870E-03
OH                        3.0116251E-03   3.0116251E-03   1.0209621E-04
H2                        1.8374638E 00   1.8374638E 00   1.8538293E 00
NH2                       1.1178601E-05   1.1178601E-05   6.4868528E-08
H20                       7.5765717E-01   7.5765718E-01   7.5520692E-01

NH3                       1.5869531E-04   1.5869531E-04   7.0976277E-06
N2H4                      8.5487123E-12   8.5487123E-12   2.7198147E-16
NF2                       9.4544762E-16   9.4544762E-16   1.5179768E-21
NO                        9.4785869E-05   9.4785870E-05   1.1430973E-06
NO2                       1.1721083E-09   1.1721084E-09   3.3691107E-13

NO2F                      5.1135064E-17   5.1135064E-17   6.9260771E-23
N2                        2.3668306E-01   2.3668306E-01   2.3682500E-01
N20                       1.2260079E-08   1.2260080E-08   1.8220859E-11
N203                      1.3803866E-18   1.3803866E-18   1.1697811E-25
NAO                       7.3915988E-06   7.3915988E-06   1.4740672E-07

O2                        4.1693822E-06   4.1693822E-06   1.8814880E-08
FNO3                      4.8856384E-24   4.8856385E-24   7.8533528E-33
HNO                       2.6759077E-07   2.6759078E-07   3.4742942E-10
HNO2-CIS                  9.2058423E-10   9.2058424E-10   2.4323653E-13
HNO2-TRA                  1.0351680E-09   1.0351680E-09   2.8410192E-13

HNO3                      3.9238752E-15   3.9238753E-15   2.2329855E-20
CH2CL2                    9.7069256E-13   9.7069256E-13   6.6973249E-18
C2H5CL                    4.4449821E-13   4.4449821E-13   7.8580515E-21
C2H4CL2 11                8.4095907E-16   8.4095908E-16   3.8951140E-25
C2H4CL2 12                1.0820808E-17   1.0820808E-17   3.4627311E-26

C2H3CL                    3.3390402E-10   3.3390402E-10   3.8650480E-17
C2CL4                     3.0605546E-24   3.0605546E-24   3.2490980E-34
AL203        S            0.              6.4730970E-01   6.4860907E-01
AL203        L            6.4730970E-01   0.              0.
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