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EVALUATION OF STORABLE PROPELLANT REFORMING FOR USE IN EMERGENCY LIFE SUPPORT SYSTEM DESIGN

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16. Abstract

The storable propellants Aerozine-50 and nitrogen tetroxide (N_2O_4) are evaluated as sources of hydrogen, oxygen, potable water, and heat for use in an emergency life support system. This study was based upon research work performed by Monsanto Research Corporation under NASA contract. Results of these laboratory studies indicate the feasibility of steam-reforming Aerozine-50 to obtain hydrogen-rich gas. This gas was then processed through a palladium-silver diffusion cell to yield 99.99-percent pure hydrogen. Oxygen was obtained through reforming N_2O_4 to yield an oxygen-rich gas containing nitrogen and residual N_2O_4. The N_2O_4 was removed by molecular sieves to yield a 67-percent-oxygen - 33-percent-nitrogen gas product. The data for these processes were used to estimate the volume and weight of several conceptual emergency life support systems. Comparisons were then made with life support system concepts which involved other hydrogen and oxygen sources. These sources were hydrogen peroxide and cryogenic oxygen for the oxygen supply; hydrazine reforming and cryogenic hydrogen were considered for the hydrogen supply.

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SUMMARY

During the period January 1965 to July 1969 Monsanto Research Corporation, under NASA contract, investigated the use of the storable propellants Aerozine-50 and nitrogen tetroxide (N_2O_4) as fuel-cell reactants.

Direct use of the propellants as fuel-cell reactants was not promising; therefore, NASA shifted emphasis on this work to storable propellant reforming. Hydrogen- and oxygen-rich gases were produced by catalytically reforming Aerozine-50 and N_2O_4, respectively. By feeding the hydrogen-rich gas to palladium-silver diffusion cells, 99.99-percent-pure hydrogen was recovered. A 67-percent-oxygen – 33-percent-nitrogen fuel-cell oxidant gas was obtained by processing the N_2O_4 reforming product gas through 13X molecular sieves to remove residual N_2O_4.

A comparison is made of Aerozine-50 reforming processes which use (1) single-reactor reforming, (2) dual-reactor reforming, and (3) triple-reactor reforming.

Process equipment weights and volumes, propellant consumption, heat, and material balances were estimated for each process combination considered.

Reported weight includes only the additional process equipment required above that normally carried aboard an Apollo Lunar Module. Fuel consumption is reported for a 1000-hour period.

Alternate sources of hydrogen and oxygen are considered. Oxygen sources include hydrogen peroxide reforming and cryogenic oxygen. Hydrogen sources include N_2H_4 reforming and cryogenic hydrogen. Disadvantages of these hydrogen and oxygen sources include additional transportation and handling of the materials.

INTRODUCTION

Beginning in 1965 the Lewis Research Center funded a contract, NAS 3-6476, with Monsanto Research Corporation (MRC) for studying the use of storable propellants for fuel-cell power production.

Previous contracts had verified the feasibility of pursuing such an investigation. Storable propellants investigated under contract NAS 3-6476 included Aerozine-50 (A-50), a 1:1 weight blend of unsymmetrical dimethyl hydrazine and hydrazine, hydrazine, and nitrogen tetroxide (N_2O_4).

MRC attempted direct use of these storable propellants as fuel-cell reactants; however, results were not satisfactory. Their major effort was then directed to propellant reforming. Reforming-type processes were investigated for production of hydrogen-rich gases from Aerozine-50 and hydrazine, while oxygen-rich gases were obtained by catalytic decomposition of nitrogen tetroxide.

Direct use of the reformer gases was unsuitable for fuel-cell operation. Consequently, these gases were treated to remove harmful impurities. By feeding the hydrogen-rich reformer gas to palladium-silver diffusion cells, 99.99-percent-pure hydrogen was recovered. Oxygen-rich gas, containing only nitrogen as an impurity, was obtained after removal of residual N_2O_4 by sorption on molecular sieves (Linde Corp., 13X sieves). Substantial process data were generated by MRC (refs. 1 to 5).

The reforming of Aerozine-50 and nitrogen tetroxide appears to be applicable to the extra-terrestrial emergency life support area. These reforming processes appear to be capable of supplying potable water, metabolic oxygen, and heat in addition to reactants for fuel-cell power production. An added attraction of these processes is that, with few exceptions, standard commercial production techniques are employed. Well-tested catalysts are used for reforming, while purification of reactants utilizes commercially available molecular sieve and diffusion membrane materials.

Presented herein is an engineering feasibility study of a life support system based on the use of storable propellants. Design considerations were based upon survival of two men for an arbitrary time period of 1000 hours. A 2-kilowatt power level was considered necessary (ref. 6). Heat and material balances allowed weights and volumes to be estimated for the various system configurations. In general, maximum values were obtained, since process optimization was not attempted.

Reactor sizing was accomplished by direct scaleup from MRC data and includes factors of safety.

Alternate sources of hydrogen and oxygen are discussed and compared with the reforming of Aerozine-50 and N_2O_4.

REQUIREMENTS AND APPLICATIONS OF AN EMERGENCY

LIFE SUPPORT SYSTEM

With increased manned space missions in and beyond near Earth orbit, the possibility for aborted missions becomes more probable with consequent hazards to the mission crew. Metabolic oxygen, heat, potable water, and electric power are necessarily limited on these missions. Therefore, it seemed that an emergency life support system which utilized the storable Apollo propellants Aerozine-50 and nitrogen tetroxide would be practical. The requirements of such a system were considered to be that necessary for sustaining two men for a period of 1000 hours.

Minimum values of life-sustaining necessities assume a maximum electric power demand of 2 kilowatts. Metabolic oxygen requirements are assumed to be 1.70 kilograms per day (3.74 lb/day), while potable water demand is about 7.03 kilograms per day (15.5 lb/day).

Utilization of such a system would take advantage of previously accumulated residual Apollo storable propellants in addition to supplies accompanying the stranded personnel. These reactants would be consumed by the emergency life support system, which would have been previously placed in proximity of the landing site or orbit plane.

Design of the emergency life support system should be simple as possible with easy startup capabilities and man-rated operation reliability over the 1000-hour period. For this reason a pressure cascading process was considered for this system.

PROCESS DESCRIPTIONS AND DATA ANALYSIS

Data which resulted from MRC storable propellant studies were examined for completeness in regard to their use for engineering design of emergency life support systems. These data were then used to estimate the size of systems capable of supplying sufficient hydrogen, oxygen, water, and heat to sustain two men for a period of 1000 hours.

Process descriptions with heat and material balances are given in this section. Material balances are within 2 percent, which is satisfactory for engineering calculations.

Aerozine-50 Reforming

Aerozine-50, a 1:1 weight blend of unsymmetrical dimethyl hydrazine ($(CH_3)_2N_2H_2$ or UDMH) and hydrazine (N_2H_4), was reformed to a gas rich in hydrogen (H_2), and containing carbon dioxide (CO_2) and nitrogen (N_2), in accordance with the following stoichiometric equation, based upon 45.5 kilograms (100 lb) of A-50 and 52.6 kilograms (116 lb) of water (H_2O):

$$0.833 \ (CH_3)_2N_2H_2 + 1.56 \ N_2H_4 + 6.45 \ H_2O \rightarrow 9.77 \ H_2 + 1.66 \ CO_2 + 2.39 \ N_2 + 3.12 \ H_2O$$
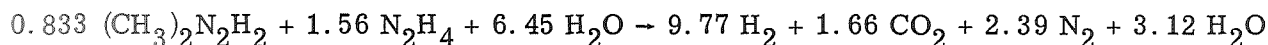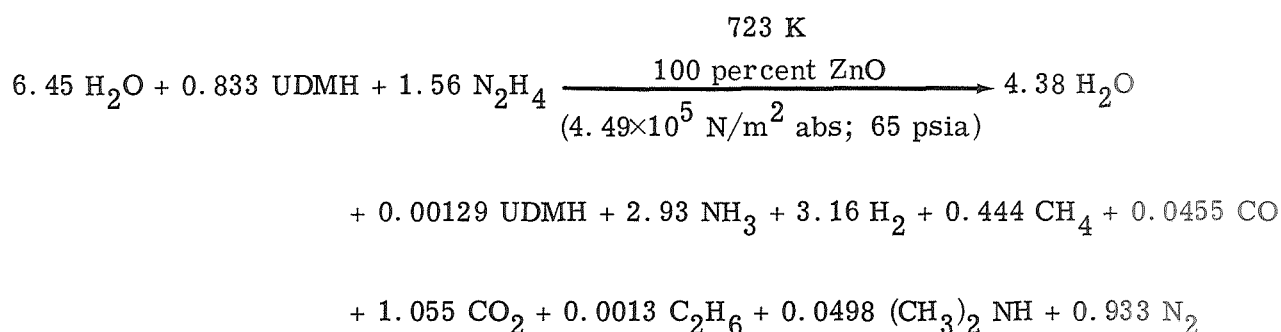
One-hundred percent hydrogen conversion should yield 4.43 kilograms (9.77 lb moles) of hydrogen gas per 45.4 kilograms (100 lb) of Aerozine-50 and 52.6 kilograms (116 lb) of H_2O at 100-percent hydrogen recovery efficiency. This gas was then processed through palladium-silver (Pd-Ag) membrane diffusion cells to yield 99.99-percent-pure hydrogen.

MRC investigated A-50 reforming by using combinations of reforming reactors in series. Each reactor will be discussed in detail as a unit.

Low-temperature steam reforming. - Aerozine-50 was decomposed at a relatively low temperature (723 K) using 100 percent zinc oxide (ZnO) catalyst at a catalyst weight to feed ratio W/F of 3.1. MRC obtained a hydrogen conversion of 27 to 31 percent using an A-50:H_2O weight ratio of 0.85 at 1.38×10^5 newtons per square meter absolute (20 psia) (ref. 5, table XI). When used in the two- and three-unit configurations, this reactor prevented excessive carbon deposition on the high-temperature reformer catalyst.

MRC asserted that over a long period of time the efficiency of this reactor dropped to around 11 percent, which suggests that the removal of this reactor from the two- and three-unit decomposition process train might be desirable (ref. 5).

Figure 1 shows hydrogen conversion efficiency based upon total available hydrogen as a function of reaction temperature at 4.49×10^5 newtons per square meter absolute (65 psia). This reactor was operated as the lead reactor in a three-reactor reforming chain selected for a 1000-hour process performance test. A 1000-hour low-temperature reforming process performance test resulted in the following reaction based on daily feed rates of 45.4 kilograms (100 lb) of Aerozine-50 and 52.6 kilograms (116 lb) of H_2O:

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$$6.45\ H_2O + 0.833\ \text{UDMH} + 1.56\ N_2H_4 \xrightarrow[\ (4.49\times10^5\ \text{N/m}^2\ \text{abs;}\ 65\ \text{psia})\ ]{\begin{array}{c}723\ \text{K}\\ 100\ \text{percent ZnO}\end{array}} 4.38\ H_2O$$

$$+\ 0.00129\ \text{UDMH} + 2.93\ NH_3 + 3.16\ H_2 + 0.444\ CH_4 + 0.0455\ CO$$

$$+\ 1.055\ CO_2 + 0.0013\ C_2H_6 + 0.0498\ (CH_3)_2\ NH + 0.933\ N_2$$

where NH_3, CH_4, CO, C_2H_6, and $(CH_3)_2\ NH$ (or DMA) are ammonia, methane, carbon monoxide, ethane, and dimethylamine, respectively.

Thermodynamic calculations for the stoichiometric reaction indicated an endothermic heat of reaction (298.2 K) of about 63.2×10^6 joules per 45.4 kilograms (60 000 Btu/100 lb) of A-50. This is insufficient heat to vaporize the excess water carried in the feed stream and to provide for heat losses. A total heat addition of about 10.54×10^7 joules per 45.4 kilograms (100 000 Btu/100 lb) of A-50 will be necessary to sustain this reaction. This heat should come from the high-temperature reformer product stream by way of the high-temperature reformer feed recuperator as shown by figure 2. (The heat addition equation just given includes heats of vaporization for 45.4 kg, 100 lb, of Aerozine-50 and 52.6 kg, 116 lb, of H_2O, plus heatup.)

High-temperature steam reforming. - Equilibrium calculations based upon free energies of formation of the individual reactions involved indicated conversion yields exceeding 90 percent could be obtained by steam reforming Aerozine-50 at 1073 K, using 100 to 200 percent excess water at reaction pressures between 3.45×10^5 and 10.35×10^5 newtons per square meter absolute (50 and 150 psia) (ref. 3). Carbon deposition was indicated to be minimal under these conditions.

Experimental testing of a single high-temperature steam reformer by MRC indicated a hydrogen conversion efficiency of 55 percent at 1073 K and 3.45×10^5 newtons per square meter absolute (50 psia) using a nickel-based catalyst with catalyst W/F = 4.6. Hydrogen efficiencies as a function of temperature are shown in figure 3. Long-term testing (1000 hr) of the high-temperature reformer as part of a three-reactor chain indicated a consistent hydrogen conversion efficiency of 52 percent. These conversion data are thought to be conservative since the reactors were acting as preheaters in the MRC tests.

Carbon monoxide shift reactor. - As shown by table I, substantial amounts of CO are generated by the high-temperature reformer. Therefore, the CO shift reaction was used by MRC to oxidize CO to CO_2 by the reaction

$$CO + H_2O \xrightarrow[\substack{Fe_2O_3 \text{ catalyst} \\ (Zn-Cu \text{ promoted})}]{523 \text{ K}} CO_2 + H_2$$
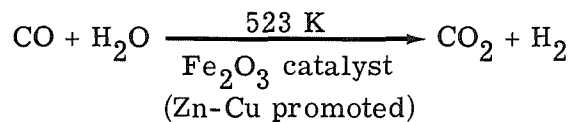
where Fe_2O_3, Zn, and Cu are iron oxide, zinc, and copper.

Tests were conducted which indicated that this reactor, coupled with the high-temperature reformer, could be used to achieve above 90 percent hydrogen conversion from Aerozine-50 (table II). A catalyst W/F of 6.6 was used for the CO shift reactor (ref. 2). Figure 4 shows the process flow schematic.

Palladium-silver diffuser. - As stated in the previous discussion, MRC investigated the recovery of 99.99 percent hydrogen from Aerozine-50 reformer product gases by Pd-Ag alloy membranes. These membranes selectively transport hydrogen, presumably in atomic form, by using the hydrogen partial pressure gradient as the driving force.

A Pd-Ag alloy tube 0.305 meter (1 ft) long by 0.154 centimeter (0.063 in.) in diameter with a 0.0076-centimeter (0.003-in.) wall thickness was tested by MRC. Results between observed hydrogen recovery efficiencies and calculated values are shown in figure 5.

This plot was computed by use of the manufacturer's diffusion rate equation given as

$$\text{rate } (m^3/hr) = 2.30 \times 10^{-6} \, \Delta P_{H_2}^{0.782} \, (kg/m^2 \text{ abs})$$

or

$$\text{rate (standard. } ft^3/hr) = 0.01 \, \Delta P_{H_2}^{0.85} \, (psia)$$

The hydrogen-rich gas feed contained about 67 percent hydrogen at 6.90×10^5 newtons per square meter absolute (100 psia). Hydrogen gas takeoff pressure was 1.015×10^5 newtons per square meter absolute (14.7 psia); ΔP represents differential pressure $(N/m^2$ abs; psia) between the partial pressure $(N/m^2$ abs; psia) of hydrogen in the gas feed stream and the hydrogen partial pressure in the product stream. An empirical constant C_0 with a value of about 2.30×10^{-6} (0.01) was determined.

Tail gases can be burned to provide process heat in case of need.

Aerozine-50 reforming by three-stage reactor chain. - In order to evaluate the overall A-50 reforming process, a three-stage reactor chain was assembled and tested by MRC. The reactor chain consisted of the low-temperature reactor, the high-temperature reactor, and the CO shift reactor previously described. These reactors were connected in series, with W/F ratios as discussed in previous sections. This reactor assembly was tested for 1000 hours of continuous operation (fig. 2).

6

Test results indicate the following overall reaction, based upon an average analysis of the product stream of 45.4 kilograms (100 lb) of Aerozine-50 and 52.6 kilograms (116 lb) of H_2O:
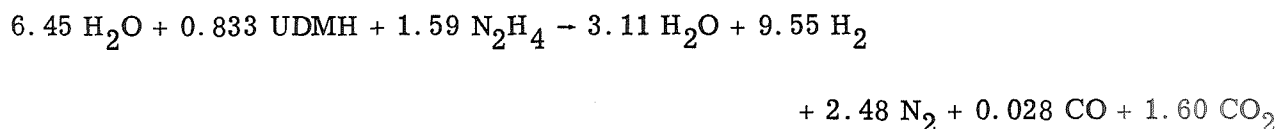
$$6.45\ H_2O + 0.833\ UDMH + 1.59\ N_2H_4 \rightarrow 3.11\ H_2O + 9.55\ H_2$$

$$+ 2.48\ N_2 + 0.028\ CO + 1.60\ CO_2$$

Table III shows this reaction to be endothermic, having an overall heat of reaction of 1.52×10^8 joules per 45.4 kilograms (144 200 Btu/100 lb) of A-50. As previously stated, reactors were used as preheaters for the laboratory testing, and consequently should perform better when separate, more efficient feed preheaters are utilized.
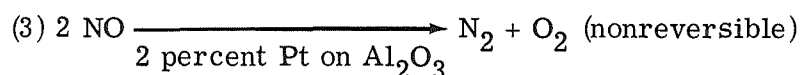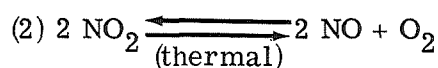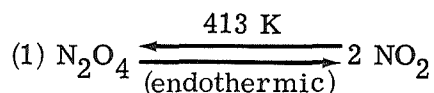
The lead reactor acted to prevent carbon deposition in the second reactor (high-temperature steam-reforming reactor). The third reactor (CO shift converter) was used for reaction cleanup for an additional hydrogen conversion of 15 percent. Table I shows reactor products as well as hydrogen conversion for the three-stage reactor system.

Monsanto's 1000-hour test of this process demonstrated the feasibility of reforming Aerozine-50 with a triple-reactor chain. An overall hydrogen conversion of >95 percent was attained throughout the test duration.

The product gas contained an average concentration of 56.9 percent hydrogen. Hydrogen concentration may be increased by condensing excess water prior to feeding the product gas to the palladium-silver diffusion cells.

Since direct use of N_2O_4 in a fuel cell presented several difficult problems, contract NAS 3-6476 required MRC to investigate reforming this material into an oxygen-rich gas mixture. Six catalysts were screened by MRC for this process, and a 2-percent-platinum-on-alumina catalyst proved superior to other catalysts tested.

Subsequent work indicated a reaction temperature of about 1073 K was necessary to decompose N_2O_4 at reasonable reactor catalyst W/F. Decomposition reactions were thought to proceed as follows:

$$(1)\ N_2O_4 \underset{\text{(endothermic)}}{\overset{413\ K}{\rightleftharpoons}} 2\ NO_2$$

$$(2)\ 2\ NO_2 \underset{\text{(thermal)}}{\rightleftharpoons} 2\ NO + O_2$$

$$(3)\ 2\ NO \xrightarrow[\text{2 percent Pt on }Al_2O_3]{} N_2 + O_2 \text{ (nonreversible)}$$

where NO_2, NO, Pt, and Al_2O_3 are nitrogen dioxide, nitric oxide, platinum, and aluminum oxide, respectively.

These reactions proceed with a net exothermic heat of reaction in the gaseous state; however, the overall reaction is slightly endothermic when reactant heat of vaporization and heat losses are considered (see table IV).

Products of N_2O_4 decomposition contain varying amounts of NO, NO_2, and unreacted N_2O_4 at lower temperatures. Before using this gas in an alkaline electrolyte fuel cell, essentially all oxides of nitrogen must be removed. Maximum allowable levels of NO and NO_2 in metabolic oxygen must not exceed 5 and 10 ppm, respectively.

MRC's investigation of nitrogen oxide removal indicated that the 13X molecular sieves appeared superior to other materials tested. The molecular sieves should be followed by a chemical scrubber, such as a lithium oxide (Li_2O) bed, since the exit gas is assumed to contain about 100 ppm N_2O_4.

A small converter similar to that shown in figure 6, with the exception of the Li_2O scrubber equipment, was tested for 1000 hours with encouraging results. An NO oxidizing converter was utilized whose design was based upon the work of Treacy and Daniels (ref. 7). Nitrogen tetroxide decomposition to $N_2 + 2\,O_2$ exceeded 95 percent completion at 1073 K at 1.015×10^5 newtons per square meter absolute (14.7 psia) for the first 80 hours of testing. Thereafter, oxygen conversion dropped to about 80 percent and remained at that level for the duration of the 1000-hour test. This conversion value (80 percent) was therefore utilized in sizing the process equipment discussed in later sections.

Short-term reactor optimization studies indicated a minimum W/F of 8 could be used in this converter (fig. 7). However, these optimization studies were not followed by long-term process evaluation at this W/F.

Removal of oxides of nitrogen involved oxidation of residual NO to N_2O_4 in the N_2O_4 decomposition reactor product stream, followed by sorption on sodium alumino silicate (Linde 13X) molecular sieves. Sorption proceeded under low temperature (323 to 348 K) and high pressure (1.035×10^5 to 4.14×10^5 N/m^2 abs; 15 to 60 psia), while desorption took place at high temperature (423 to 473 K) and low pressure (0 N/m^2 abs; 0 psia).

A schematic of a proposed N_2O_4 sorption process is shown in figure 8.

Alternate Sources for Hydrogen and Oxygen Supply

In order to evaluate properly hydrogen and oxygen production processes from Aerozine-50 and nitrogen tetroxide, it was necessary to compare them with alternate sources. Although it is not likely that alternate propellants will be available, hydrogen peroxide and cryogenic oxygen appear to be good sources of oxygen, while hydrazine

reforming and cryogenic hydrogen are possible sources for hydrogen gas. These are discussed in this section.

Alternate sources of oxygen. - Hydrogen peroxide (H_2O_2) decomposes exothermically in the presence of a silver screen catalyst according to the following reaction:

$$H_2O_2 \xrightarrow{Ag} H_2O + \frac{1}{2}O_2$$
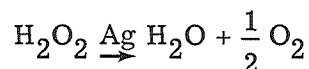
Approximately 6.17×10^7 joules (58 500 Btu) are evolved per kilogram (lb mole) of reactant.

The United States Air Force has had a small H_2O_2 reforming unit designed and built which has an oxygen production capacity of about 2.18 kilograms per day (4.8 lb/day) (ref. 8). Figure 9 shows a simplified flow schematic for this process. The oxygen gas and condensed water are separated by a nongravitational phase separator.

Cryogenic oxygen appears to be the best source of fuel-cell oxygen for an emergency life support system. Low boiloff losses (≤ 0.05 percent/day), coupled with high density (~ 1120 kg/m^3; ~ 70 lb/ft^3), assure an oxygen supply of minimum volume and weight. Low-pressure oxygen gas would be provided by solar heating of the oxygen liquid during the lunar day, while vaporization during the lunar night would be provided by a gas generator burning oxygen and the bleed gas from the hydrogen palladium-silver diffuser unit, or other available fuels.

Alternate sources of hydrogen. - Alternate methods of producing pure hydrogen gas include catalytic decomposition of N_2H_4 or vaporization of cryogenic hydrogen. Hydrazine may be catalytically decomposed to yield a hydrogen-rich gas using a system similar to A-50 reforming. Hydrogen (99.99 percent purity) is then separated by palladium-silver diffusion cells. Residual diffusion cell tail gases may be burned for heat management. Total weight of such a hydrogen production subsystem should not exceed 45.4 kilograms (100 lb) for a production rate of 2.14 kilograms (2.34 lb moles) of H_2 gas per day.

Cryogenic hydrogen also appears to be a good source of hydrogen for fuel cells. Advanced insulation and storage technology have made cryogenic hydrogen attractive except for volumetric considerations. About 0.0283 cubic meter (1 ft^3) of liquid hydrogen would be required per day at 2-kilowatt fuel-cell power output. Total volume of liquid hydrogen for 1000-hour operation will exceed 14.15 cubic meters (50 ft^3), including losses.

APPLICATION TO DESIGN OF EMERGENCY LIFE SUPPORT SYSTEMS

Data from MRC studies on reforming the storable propellants Aerozine-50 and nitrogen tetroxide were evaluated in regard to their utilization in design of emergency life support systems.

Process equipment weights and volumes were estimated for emergency life support systems capable of sustaining two men over an arbitrary time period of 1000 hours and providing 2 kilowatts of power. The power source was considered to be a hydrogen-oxygen fuel-cell stack operating at 60-percent efficiency. The requirements for the system are shown in table V.

Several criteria were considered essential for emergency life support systems. These were (1) reliability; (2) simplicity in regard to hardware, instrumentation, and controls; (3) efficiency; (4) light weight with minimum volume; and (5) proper capacity to meet the required needs.

A limited propellant supply was assumed, based upon available residual propellants on board the descent and ascent stages of the Apollo lunar module after a lunar landing. These propellants should total about 2680 kilograms (5900 lb) of Aerozine-50 and nitrogen tetroxide, including reaction control propellants.

Aerozine-50 reforming processes using one, two, and three reactors were considered for hydrogen production, while N_2O_4 reforming provided the oxygen requirement. These processes have been discussed in the section PROCESS DESCRIPTION AND DATA ANALYSIS.

Three-stage-reactor Aerozine-50 reforming was coupled with N_2O_4 reforming for emergency life support systems, as shown in figure 10. This system was studied in regard to weight and size and is discussed in the next section. The single reactor and dual reactor Aerozine-50 processes are also discussed in regard to their use in emergency life support systems.

Three-Stage Reactor Aerozine-50 Reforming System

Coupled With Nitrogen Tetroxide Reforming

Figure 10 presents the flow schematic for an emergency life support system using Aerozine-50 reforming for hydrogen production and N_2O_4 reforming for the oxygen source. As described in previous sections, a hydrogen-rich gas is produced by reforming Aerozine-50 in the presence of excess water. This gas is then fed to a palladium-silver diffuser, where the tail gas is exhausted to a gas generator, and the 99.99-percent-pure hydrogen stream is sent to a fuel cell. The products from each reactor are listed in table I.

Oxygen-rich gas is generated by catalytically decomposing N_2O_4. This gas is then treated to remove residual N_2O_4 on 13X molecular sieves. The resultant gas is then scrubbed by Li_2O to yield a gas suitable for fuel-cell oxidant or metabolic usage.

Startup of the system requires that each reactor of the system be heated to reaction temperature prior to the start of propellant feed. This is accomplished by a gas generator using Aerozine-50 and N_2O_4. After the system is heated, the gas generator switches to palladium-silver diffuser tail gas for fuel and continues to use N_2O_4 as oxidant to supply heat to the system.

Sizing Process Reactors

In order to provide the required supply of hydrogen gas (2.13 kg/day; 4.68 lb/day), about 17.0 kilograms per day (37.5 lb/day) of Aerozine-50 and 19.5 kilograms per day (43 lb/day) of water must be fed to the three-stage reactor A-50 reforming plant. This assumes an overall hydrogen yield of 70 percent.

A catalyst W/F of 3.1 was used for the low-temperature reformer, 4.6 for the high-temperature reformer, and 6.6 for the CO shift reactor; catalyst weights were determined at the Aerozine-50 feed rate of 0.708 kilogram per hour (1.56 lb/hr). From this, the catalyst volumes for each reactor were determined. Catalyst densities were obtained by measuring vendors' samples.

Reactor	Catalyst volume		Catalyst
	m^3	$in.^3$	
Low-temperature reformer	2.11×10^{-3}	129	ZnO (100 percent)
High-temperature reformer	4.07×10^{-3}	248	Ni
CO shift reactor	3.16×10^{-3}	193	Fe_2O_3 (Zn-Cu promoted)

Similarly, the N_2O_4 reformer catalyst volume was determined to be 1.09×10^{-2} cubic meter (665 $in.^3$) at a feed rate of 40.3 kilograms per day (89 lb/day) of N_2O_4 and at a catalyst W/F of 16. For a W/F of 8, as shown by figure 7, the catalyst volume would be 5.46×10^{-3} cubic meter (333 $in.^3$). Molecular sieve sorbers were of the same total volume, 1.09×10^{-2} cubic meter (666 $in.^3$).

Reactor design was based upon direct scale up, using 2.54-centimeter- (1-in.-) outside-diameter tubing. Catalyst volumes were used to determine the amount of tubing necessary for containment. The tubing was packed into the reactor in a triangular array with 3.17-centimeter-(1.25-in.-)diameter tube center to tube center spacing, and the shell

size was determined by the size of the resultant array. Material of construction was assumed to be 310 stainless steel.

Reactor shell and tubing thickness were estimated by the equation

$$t = \frac{PR}{2S}$$

where

t   metal thickness, cm; in.

P   reaction pressure (1.035×10^6 N/m^2 abs; 150 psia)

R   tube radius, cm; in.

S   maximum allowable tensile strength at temperature of operation, N/m^2; psi

Reactor weights were computed, and other process equipment weights and volumes were estimated. The weights are listed in table VI. Reactors and other equipment were scaled according to process efficiency and heat balance.

Heat recuperator weight and volume were estimated by determining an average overall heat-transfer coefficient for each fluid and computing the heat-transfer area by the equation

$$q = UA(\Delta T_{LM})$$

where

q   heat transferred from hotter to colder fluid

U   overall heat-transfer coefficient

A   area over which heat is transferred

ΔT_{LM} log mean temperature difference between heat-exchange fluids

Fluid properties were averaged for the log mean temperature; then an estimated U was calculated from the Nusselt correlation for determining the forced-convective heat-transfer coefficient. This assumed negligible heat transfer by radiation. The amount of heat to be transferred was determined by heat and material balances.

The total weight of volume for each emergency life support concept is shown by figures 2, 4, 6, 11, and 12. Table VI lists the estimated maximum weight of each component.

The total weights of such a system should not exceed 152 kilograms (335 lb) nor be larger than 0.244 cubic meter (8.6 ft^3). All reactors are envisioned as operating vertically. Insulation and shadow shields may surround the package to conserve heat within

the high-temperature reactors. About 1.15×10^8 joules per day (109 000 Btu/day) of heat would be necessary to sustain the reaction. This heat should be supplied by the gas generator, which burns tail gases from the palladium-silver diffuser. Total reactant consumption should not exceed 69.9 kilograms per day (154 lb/day) of N_2O_4 and Aerozine-50. Figure 13 shows total reactant consumption as compared with alternate systems.

Single-Reactor Aerozine-50 Reforming Coupled

With Nitrogen Tetroxide Reforming

An emergency life support system may also be considered utilizing the single-reactor Aerozine-50 reforming concept as shown in figure 12 and the N_2O_4 reformer process as shown in figure 6. The component weights are listed in table VI.

Total weight and volume (maximum) may be as low as 142 kilograms (313 lb) and 0.212 cubic meter (7.5 ft^3) if a minimum W/F of 8 is used for the N_2O_4 reformer (fig. 7). Reactant consumption should not exceed 82.5 kilograms per day (182 lb/day) of A-50 and N_2O_4.

Dual Reactor Aerozine-50 Reforming Coupled

With Nitrogen Tetroxide Reforming

Two dual-reactor Aerozine-50 reforming concepts are available which can be used with the N_2O_4 reforming to provide processes suitable for emergency life support systems.

Coupling the dual reactor A-50 reforming scheme (fig. 11) with N_2O_4 reforming (fig. 6) results in a system which should weigh less than 142 kilograms (312 lb). Total volume of the equipment should be less than 0.224 cubic meter (7.9 ft^3). Propellant consumption should be less than 72.0 kilograms per day (159 lb/day), while heat additions of about 1.41×10^8 joules per day (134 000 Btu/day) will be necessary to sustain the reaction. Approximately the same fuel consumption and volume may be expected for a system using a dual high-temperature Aerozine-50 reformer - CO shifter process and the N_2O_4 reformer (fig. 4). Overall weight for this system should not exceed 148 kilograms (326 lb) or 0.229 cubic meter (8.1 ft^3).

Alternate Systems

Hydrogen peroxide and Aerozine-50 reforming processes were coupled (figs. 2 and 9) into a system for supplying the hydrogen and oxygen requirement of table V. Propellant consumption was calculated to be less than 57.1 kilograms per day (126 lb/day) for this system. However, H_2O_2 must be transported with the emergency life support system for lunar use. Total equipment weight of such a system should not exceed 138 kilograms (305 lb). Hydrogen peroxide decomposition is sufficiently exothermic so that no additional external heat is necessary for Aerozine-50 reforming process heat.

An emergency life support system, comprising cryogenic hydrogen and oxygen supplies, appears to be satisfactory except for the large volumes. A gas generator would be necessary to vaporize the cryogenic liquid during the lunar night. This system should consume about 19.1 kilograms per day (42 lb/day) of reactants. The gas generator should consume about 36.2 kilograms (80 lb) of oxygen and 4.54 kilograms (10 lb) of hydrogen during a 1000-hour stay to provide heat for vaporization of reactants.

Table VII shows comparative fuel consumption and system weights for all systems discussed. The cryogenic tankage weights are included.

PROBLEM AREAS

A substantial amount of process information exists which is suitable for use in engineering design of hydrogen and oxygen generators using storable propellants. However, this information is not considered sufficient for development of optimum flight weight equipment for extra-terrestrial use. Several of the more important problems are discussed in this section.

Nitrogen Tetroxide Reforming and Purification

Process equipment weights, as calculated in this report, are based upon a W/F of 8 for the N_2O_4 conversion process at 80 percent efficiency. Evidence indicates a higher conversion is possible. This should reduce the weight and volume of this process equipment and reduce reactant consumption proportionately. Further testing should be completed to assure maximum N_2O_4 conversion efficiency.

Heat management is a problem which must be resolved. Although only a small amount of heat is required for steady-state operation, heat must be conserved to minimize propellant consumption. Proper temperature control must be maintained for the molecular sieves as well.

Process control is considered a major problem. One possible solution which should be considered involves the use of process vent gases to drive fluidic controls. As many as 1600 fluidic logic elements may be driven by the process vent gases from a 2-kilowatt two-man emergency life support system.

Aerozine-50 Reforming and Purification

The Aerozine-50 reactors must be optimized with respect to catalyst weight to feed ratio at higher pressures (8.28×10^5 N/m^2 abs, 120 psia, for example) and hydrogen conversion efficiencies.

High pressures will afford easily controlled pressure cascading and maximum hydrogen recovery from the palladium-silver diffuser. The W/F should be optimized for all reactors considered essential for this reforming process. A test reforming chain should then be assembled and actual Aerozine-50 reforming tests should be made over a test period of at least 1000 hours at pressures of 8.28×10^5 newtons per square meter absolute (120 psia). Preheaters should be utilized for heating reactants rather than the reactor catalyst bed itself.

Heat management is more complicated in the Aerozine-50 reforming and purification processes. Heat must be conserved while temperatures must be controlled at a minimum of four levels for a three-stage reactor system.

Overall process control remains a major problem. Fluidic type controls may be a solution; however, substantial engineering and test work will be necessary in this area.

CONCLUSIONS

Data from Monsanto Research Corporation (MRC) studies on reforming of the storable propellants Aerozine-50 and nitrogen tetroxide (N_2O_4) were evaluated with regard to their utilization for the design of extra-terrestrial emergency life support systems. The basic emergency life support system design concepts evolved from MRC's work.

MRC data were used to determine the feasibility of building an emergency life support system capable of sustaining two men over an arbitrary time period of 1000 hours with a 2-kilowatt power source. This power source was considered to be a hydrogen-oxygen fuel cell operating at 60 percent efficiency.

Aerozine-50 reforming studies involved four process concepts: (A) single high-temperature (1073 K) reforming; (B) low-temperature reforming (723 K) followed by high-temperature reforming; (C) high-temperature reforming followed by a carbon

monoxide shift reaction; and (D) a three-stage reactor process consisting of low-temperature reforming, high-temperature reforming, and a CO shift reaction.

Results of this study indicated Aerozine-50 reforming to be an efficient source for fuel-cell hydrogen. The dual-reactor processes appeared to weigh less than the three-reactor concept; however, reactor consumption was less for the latter. Each process is summarized in the following table with regard to weight, volume, reactant consumption, and reactor conditions:

	Concept			
	A	B	C	D
Total weight, kg (lb)	61.2 (134)	67.1 (148)	67.1 (148)	66.1 (146)
Total volume, m^3 (ft^3)	0.079 (2.8)	0.091 (3.2)	0.096 (3.4)	0.110 (3.9)
Reactant consumption, kg/day (lb/day)	29.8 (65.7)	19.4 (42.8)	18.8 (41.5)	17.0 (37.4)
Reactant temperature, K	1073	723	1073	723
		1073	523	1073
				523
Catalyst	Nickel base	Zinc oxide (100 percent), nickel base	Nickel base, iron oxide (zinc-copper)	Zinc oxide (100 percent), nickel base, iron oxide (zinc-copper)
Catalyst weight to reactant feed ratio, W/F	4.96	3.1	4.96	3.1
		4.96	6.6	4.96
				6.6
Hydrogen yield, percent	~40	~61	~63	~70+

Nitrogen tetroxide reforming was investigated by MRC as a source of oxygen. A 67-percent-oxygen - 33-percent-nitrogen gas was produced after removal of residual N_2O_4 by adsorption on molecular sieves. Process equipment for producing the required oxygen had a weight of 80.7 kilograms (178 lb) and a volume of 0.133 cubic meter (4.7 ft^3). Reaction conditions were as follows: temperature, 1073 K; catalyst, 2 percent platinum on alumina; reactor catalyst weight to reactant feed ratio, 8; N_2O_4 conversion, >80 percent.

From the evaluation it appears that the best overall system in regard to equipment weight and volume would be the Aerozine-50 reforming process B coupled with N_2O_4 reforming. Total system weight should not exceed 142 kilograms (312 lb) with a maximum volume of 0.224 cubic meter (7.9 ft^3). Aerozine-50 processes C and D would be more attractive if reactant supply were the limiting criterion.

Alternate sources of hydrogen indicate hydrazine reforming and cryogenic hydrogen to have weight and volume disadvantages. This is due to the fact that reactants would

have to be carried in addition to process equipment. Cryogenic hydrogen would be superior because of simplicity of process equipment yet its low bulk density makes this reactant unattractive volumewise (14.1 m^3, 50 ft^3, for reactant volume alone).

Similar conclusions can be made concerning cryogenic oxygen and hydrogen peroxide for an oxygen supply. Each reactant provides oxygen, however, with minimum process complexity. This is most important when considering the difficulty of extraterrestrial human mobility.

In conclusion, it appears that suitable supplies of hydrogen and oxygen may be obtained by Aerozine-50 and nitrogen tetroxide reforming. However, process equipment is rather complex, and outside of use as an emergency measure more suitable sources are recommended. These alternate sources include cryogenic hydrogen and oxygen, with hydrogen peroxide as a secondary oxygen source.

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Component	Feed to low-temperature reformer			Feed to high-temperature reformer			Feed to CO shift reactor		
	kg moles/day	lb moles/day	Mole percent	kg moles/day	lb moles/day	Mole percent	kg moles/day	lb moles/day	Mole percent
UDMH	0.378	0.833	9.43	------	------	-------	-----	------	------
N_2H_4	.707	1.56	17.66	------	------	-------	-----	------	------
H_2O	2.93	6.45	73.0	2.20	4.40	33.7	1.80	3.97	23.8
H_2	-----	-----	------	1.43	3.16	24.2	3.90	8.60	51.5
N_2	-----	-----	------	.423	.933	7.16	1.075	2.37	14.2
NH_3	-----	-----	------	1.33	2.94	22.5	.023	.05	.33
CH_4	-----	-----	------	.22	.44	3.4	-----	0	0
CO	-----	-----	------	.0204	.045	.35	.45	.992	5.95
CO_2	-----	-----	------	.480	1.06	8.10	.328	.723	4.33
C_2H_6	-----	-----	------	------	------	<.1	-----	------	------
DMA	-----	-----	------	------	------	<.1	-----	------	------
Total	-----	8.84	100	5.89	13.0	100	4.42	16.7	100
Total H_2 conversion, percent	-----	-----	32.0	------	------	55.1	-----	------	10.6

[a]Efficiency.

PURIFICATION PRODUCT DISTRIBUTION

A-50 and 52.6 kg (116 lb) of H_2O.]

Feed to Pd-Ag diffusion cells			Gas from Pd-Ag·diffusion cells			
kg moles/day	lb moles/day	Mole percent	Product kg moles/day	Product lb moles/day	Tail gas kg moles/day	Tail gas lb moles/day
-----	------	-----	----	----	-----	------
-----	------	-----	----	----	-----	------
1.41	3.11	18.6	----	----	1.41	3.11
4.32	9.55	56.9	2.95	6.50	1.38	3.05
1.12	2.48	14.8	----	----	1.12	2.48
-----	------	-----	----	----	-----	------
-----	------	-----	----	----	-----	------
.013	.028	.2	----	----	.013	.028
.725	1.60	9.5	----	----	.725	1.60
-----	------	-----	----	----	-----	------
-----	------	-----	----	----	-----	------
7.62	16.8	100	2.95	6.50	4.53	10.27
-----	------	[a]68	----	----	-----	32

TABLE II. - PRODUCT ANALYSES FOR DUAL-

REACTOR REFORMING CHAIN USING

HIGH-TEMPERATURE REFORMER

AND CARBON MONOXIDE

SHIFT REACTOR

[Reaction temperature, 1023 K for high-
temperature reformer (W/F = 9.3) and
423 to 473 for CO shift reactor (W/F =
6.6); reaction pressure, 1.38×10^5
N/m^2 abs (20 psia); feed composition,
14.7 percent UDMH, 14.7 percent
N$_2$H$_4$, 70.3 percent H$_2$O.]

Component	Mole percent
UDMH	0
H$_2$O	43.0
N$_2$H$_4$	0
NH$_3$	.2
DMA	0
H$_2$	39.8
N$_2$	9.9
CH$_4$	0
CO	.5
CO$_2$	6.5
C$_2$H$_6$	0
Other	0

TABLE III. - THERMODYNAMIC BALANCE FOR

Feed composition, 45.4 kg (100 lb) of A-50 and 52.6 kg (116 lb)

Component	Feed to low-temperature reformer (723 K)				Products of low-temperature reformer (723 K)			
	kg moles/day	lb moles/day	Total enthalpy		kg moles/day	lb moles/day	Total enthalpy	
			J	Btu			J	Btu
UDMH	0.378	0.833	2.10×10^{7}	19 100	-----	------	---------	-------
N_2H_4	-----	1.56	3.58×10^{7}	34 000	-----	------	---------	-------
H_2O	-----	6.45	-8.35×10^{8}	-793 000	2.00	4.40	-4.80×10^{8}	-456 000
H_2	-----	-----	---------	--------	1.43	3.16	0	0
N_2	-----	-----	---------	--------	.423	.933	0	0
NH_3	-----	-----	---------	--------	1.33	2.94	-6.1×10^{7}	-57 900
CH_4	-----	-----	---------	--------	.20	.44	1.517×10^{7}	14 300
CO	-----	-----	---------	--------	.021	.045	-2.50×10^{6}	-2 370
CO_2	-----	-----	---------	--------	-----	1.06	-1.89×10^{8}	-178 500
Total	-----	-----	---------	--------	5.90	13.0	-7.16×10^{8}	-679 300
Net heat of reaction[a]	-----	-----	---------	--------	-----	------	6.39×10^{7}	60 600

[a]Including heat of vaporization of reactants.

AEROZINE-50 REFORMING

of H_2O; see process schematic in fig. 2.]

Products of high-temperature reformer (1073 K)				Products of CO shift reactor (523 K)			
kg moles/day	lb moles/day	Total enthalpy		kg moles/day	lb moles/day	Total enthalpy	
		J	Btu			J	Btu
-----	------	---------	--------	-----	------	---------	--------
-----	------	---------	--------	-----	------	---------	--------
1.80	3.97	4.36×10^8	-413 000	1.41	3.11	-3.42×10^8	-324 000
3.89	8.60	0	0	4.32	9.55	0	0
1.08	2.37	0	0	1.095	2.42	0	0
.023	.05	-1.08×10^6	-1 020	-----	------	---------	--------
0	0	---------	--------	-----	------	-------	--------
.445	.992	-5.45×10^7	-51 700	.018	.028	-1.54×10^6	-1 460
.327	.723	-1.285×10^8	-122 000	.723	1.60	-2.85×10^8	-270 000
7.58	16.7	-6.20×10^8	-587 700	7.61	16.8	-6.28×10^8	-595 460
-----	------	9.66×10^7	91 600	-----	------	-8.43×10^6	-8 000

TABLE IV. - ENTHALPY BALANCE FOR NITROGEN TETROXIDE REFORMING

[Data from refs. 9 and 10; catalyst, 2 percent Pt on Al_2O_3; temperature, 1073 K; pressure, $1.035×10^5$ N/m^2 abs (15 psia).]

(a) Reactant

Reactant	Reactant feed		Heat of vaporization per mole		Heat of vaporization per day	
	kg moles/day	lb moles/day	J/kg mole	Btu/lb mole	J/day	Btu/day
N_2O_4 (liquid)	0.398	0.967	$2.85×10^7$	12 240	$1.25×10^7$	11 830

(b) Products

Product	Product flow		Heat of formation		(Mole fraction) × (Heat of formation)		Increase in enthalpy		(Mole fraction) × (Increase in enthalpy)	
	kg moles/day	lb moles/day	J/kg mole	Btu/lb mole	J	Btu	J	Btu	J	Btu
N_2O_4 (gas)	0.068	0.194	$1.78×10^7$	7640	$1.54×10^6$	1460	$3.71×10^7$	35 200	$7.19×10^6$	6 820
N_2 (gas)	.351	.774	--------	----	--------	----	$1.08×10^7$	10 250	$8.35×10^6$	7 920
O_2 (gas)	.702	1.548	--------	----	--------	----	$1.14×10^7$	10 850	$1.77×10^7$	16 800
Total	-----	-----	--------	----	--------	----	--------	------	$3.32×10^7$	31 550

TABLE V. - EMERGENCY LIFE SUPPORT SYSTEM REQUIREMENTS[a]

[Based on survival of two men for 1000 hr at 2 kW power.]

```
Metabolic oxygen, kg/day (lb/day) . . . . . . . . . . . . . . . . . . . . . 1.70 (3.74)
Fuel-cell oxygen (at 66 percent efficiency), kg/day (lb/day) . . . . . . . . 17.4 (38.4)
   Total oxygen, kg/day (lb/day) . . . . . . . . . . . . . . . . . . . . . . 19.1 (42.1)
   Total oxygen losses, kg/day (lb/day) . . . . . . . . . . . . . . . . . . 3.04 (6.70)
Fuel-cell hydrogen, kg/day (lb/day) . . . . . . . . . . . . . . . . . . . . 2.12 (4.68)
Water for men, kg/day (lb/day) . . . . . . . . . . . . . . . . . . . . . . 7.03 (15.5)
Power, kW/man
   Closed-loop control  . . . . . . . . . . . . . . . . . . . . . . . . . . . 1.0
   Open-loop control  . . . . . . . . . . . . . . . . . . . . . . . . . . . . 0.6
```

[a]All calculations given in this report are based upon the requirements listed in this
table; process requirements in the form of heat or water are not listed since they
depend upon process type and efficiency.

TABLE VI. – ESTIMATED MAXIMUM WEIGHTS AND VOLUMES FOR AEROZINE-50

AND NITROGEN TETROXIDE REFORMING PROCESS EQUIPMENT

(a) Aerozine-50 reforming process

Equipment	Single reactor (fig. 1)		Dual reactor (fig. 4)		Dual reactor (fig. 11)		Triple reactor (fig. 2)	
	Weight							
	kg	lb	kg	lb	kg	lb	kg	lb
H_2O and A-50 feed pumps	4.5	10	4.5	10	4.5	10	4.5	10
Feed valving	.68	1.5	.68	1.5	.68	1.5	.68	1.5
A-50 evaporator and preheater	6.8	15	5.5	12	5.5	12	4.5	0
Low-temperature reactor	-----	-----	9.5	21	-----	-----	8.2	18
High-temperature reactor preheater	4.1	9	2.7	6	2.3	5	2.3	5
High-temperature reactor	25.8	57	16.8	37	16.4	36	14.5	32
CO shift reactor preheater	-----	-----	-----	-----	2.3	5	2.3	5
CO shift reactor	-----	-----	-----	-----	14.5	32	13.2	25
Pd-Ag diffusion preheater	4.1	9	2.7	6	2.7	6	2.3	5
Gas generator	1.4	3	1.4	3	1.4	3	1.4	3
Radiator	9.1	20	9.1	20	9.1	20	9.1	20
Zero-gravity H_2O separator	2.3	5	2.3	5	2.3	5	2.3	5
H_2O pumps and return sump	4.5	10	4.5	10	4.5	10	4.5	10
Total	63.3	142.5	59.7	131.5	66.2	145.5	59.8	151.5
	Volume							
	m^3	ft^3	m^3	ft^3	m^3	ft^3	m^3	ft^3
Total	0.079	2.8	0.091	3.2	0.096	3.4	0.111	3.9

(b) Nitrogen tetroxide reforming process

Equipment	Weight	
	kg	lb
N_2O_4 feed pump	4.5	10
N_2O_4 control valve (three)	2.3	5
N_2O_4 evaporator and preheater	4.5	10
N_2O_4 reactor	26.7	55
NO time delay chamber	2.3	5
Molecular sieves	26.7	59
Remotely operated valving	2.3	5
Li_2O scrubber	2.3	5
Radiator	9.1	20
Total	80.7	178
	Volume	
	m^3	ft^3
Total	0.134	4.74

TABLE VII. - MAXIMUM EMERGENCY LIFE SUPPORT SYSTEM WEIGHTS AND

PROPELLANT CONSUMPTION FOR VARIOUS CONCEPTS

[Two men at 2-kW power level.]

Concept	Volume		Weight		Fuel consumption	
	m^3	ft^3	kg	lb	kg/day	lb/day
N_2O_4 plus A-50 reforming (figs. 2 and 5)	0.243	8.6	153	3.35	69.8	154
N_2O_4 plus A-50 reforming (figs. 4 and 5)	.229	8.1	148	3.26	76.6	169
N_2O_4 plus A-50 reforming (figs. 10 and 5)	.224	7.9	141	3.12	72.0	159
N_2O_4 plus A-50 reforming (figs. 11 and 5)	.212	7.5	142	3.13	82.4	182
H_2O_2[a] plus A-50 reforming (figs. 2 and 8)	-----	---	138	3.05	57.0	126
H_2O_2[a] plus N_2H_4 reforming	-----	---	113	2.50	64.8	143
Cryogenic oxygen[a] plus cryogenic hydrogen[a]	-----	---	68	1.50	19.0	42

[a]Total equipment and reactants must be carried in addition to normal load.
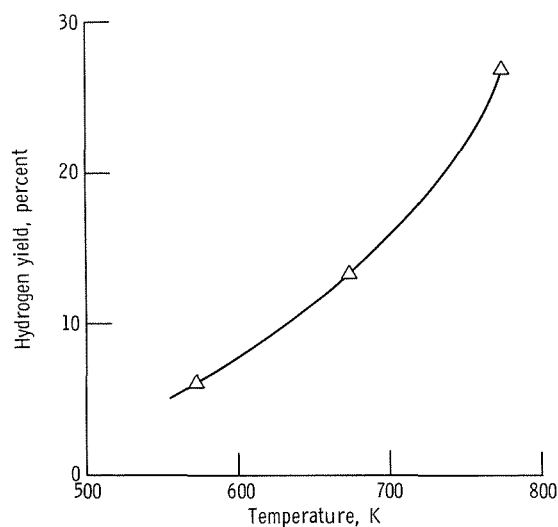
Figure 1. - Hydrogen yield from Aerozine-50 decomposition at 4.49×10^5 newtons per square meter (64.7 psia). Feed composition, 46.2 percent Aerozine-50 and 53.8 percent water; zinc oxide catalyst.
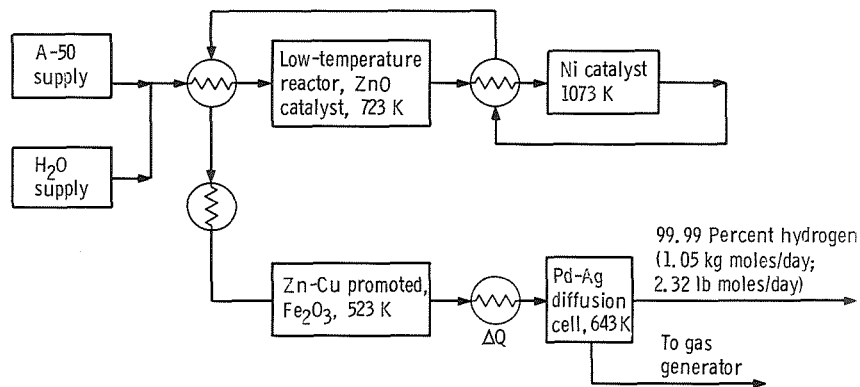
Figure 2. - Aerozine-50 reforming process with three-reactor chain. Reactor feed rate, 16.9 kilograms per day (37.4 lb/day) of Aerozine-50 and 19.5 kilograms per day (43 lb/day) of water; hydrogen conversion, 95 percent; hydrogen yield, 70 percent, 99.99 percent pure hydrogen; estimated weight of subsystem, 70.7 kilograms (156 lb), excluding supply tankage; overall heat of reaction, 5.99×10^7 joules per day (56 900 Btu/day); total process heat addition, 9.48×10^7 joules per day (90 000 Btu/day); volume, 0.11 cubic meter (3.9 ft) (max).
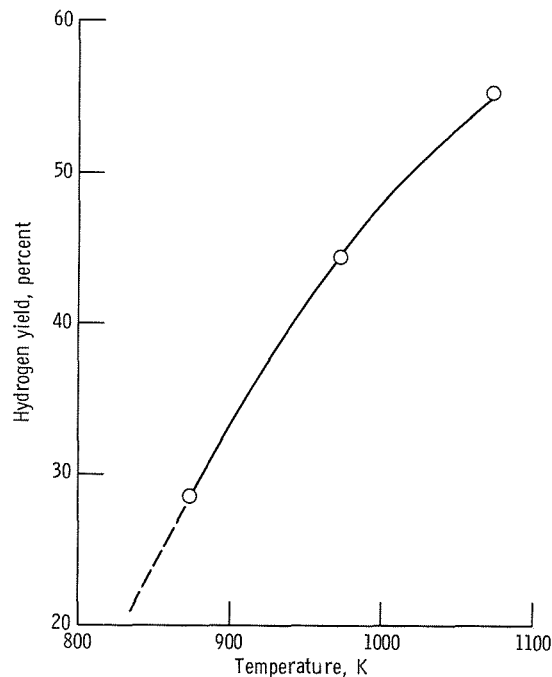
Figure 3. - Hydrogen yield from Aerozine-50 decomposition at 4.49×10^5 newtons per square meter (64.7 psia). Feed composition, 46.2 percent Aerozine-50 and 53.8 percent water; nickel based catalyst.
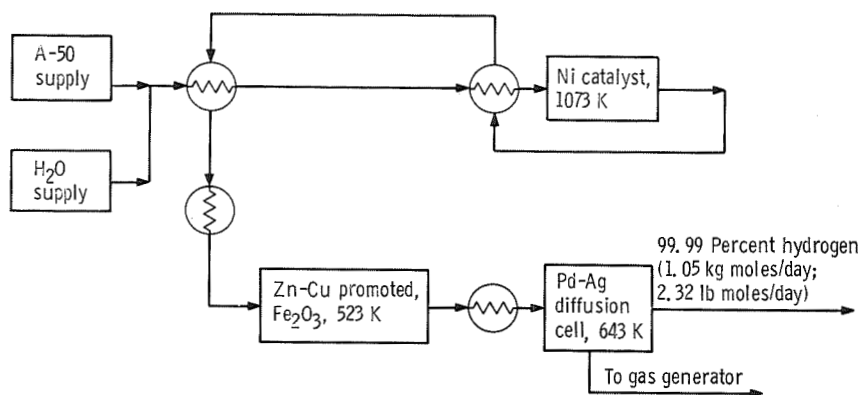
Figure 4. - Aerozine-50 reforming process with dual-reactor chain. High-temperature steam reformer plus carbon monoxide shift reactor; reactor feed rate, 19.0 kilograms per day (42 lb/day) of Aerozine-50 and 21.8 kilograms per day (48 lb/day) of water; hydrogen conversion, 90 to 98 percent; hydrogen yield, ~63 percent; estimated weight of subsystem (max), 60.8 kilograms (134 lb); net heat of reaction, 5.26×10^7 joules (50 000 Btu); net heat addition to sustain reaction, 1.29×10^8 joules per day (123 000 Btu/day); volume, 0.0765 cubic meter (2.8 ft^3).
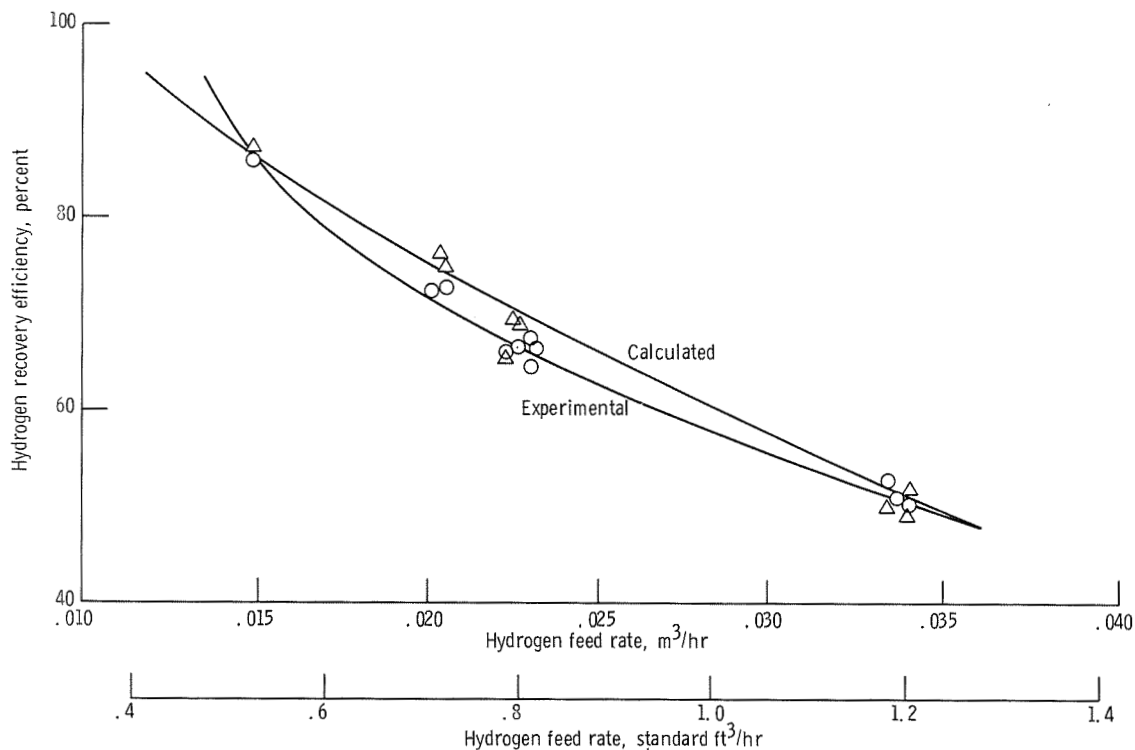
Figure 5. - Hydrogen recovery efficiency as function of gas feed rate. Palladium-silver alloy diffuser.
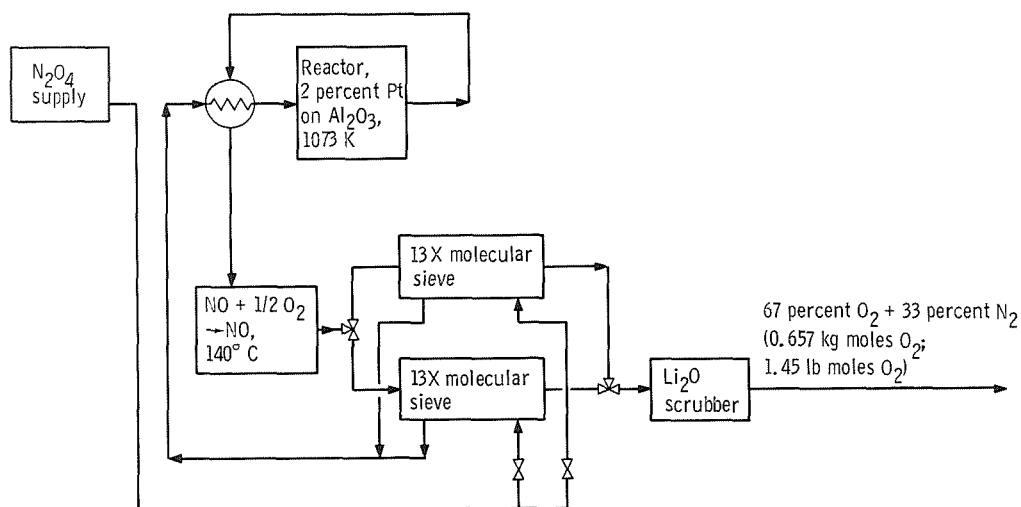
Figure 6. - Nitrogen tetroxide reforming and purification. Reactor feed rate, 40.3 kilograms per day (89 lb/day) of nitrogen tetroxide; nitrogen tetroxide conversion, 80 percent; oxygen yield, 75 percent; estimated subsystem weight, 80.8 kilograms (178 lb) (max); net heat of reaction, -6.21x10^6 joules (-5900 Btu); net heat of addition to sustain reaction, 1.58x10^7 joules per day (15 000 Btu/day); volume, 0.134 cubic meter (4.74 ft^3).
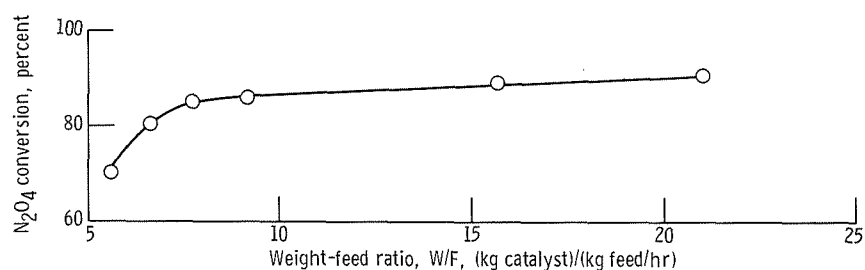
Figure 7. - Nitrogen tetroxide conversion as function of weight-feed ratio at 800° C (MRC data). 2 Percent platinum on aluminum oxide.
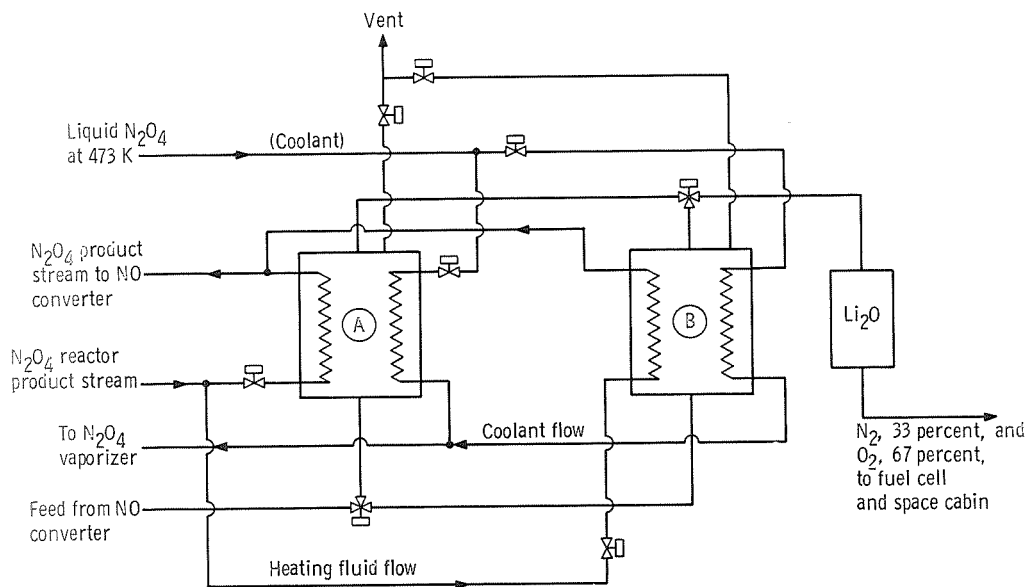
Figure 8. - Proposed molecular sieve nitrogen tetroxide adsorption system.
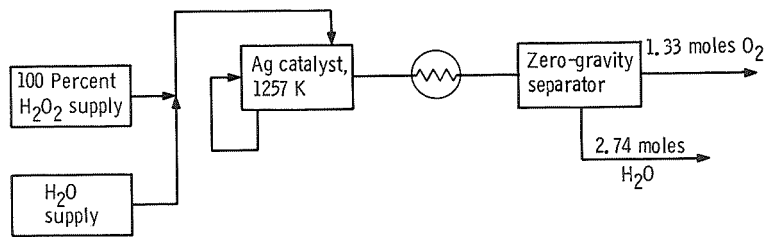
Figure 9. - Hydrogen peroxide reforming process for supplying two-man 2-kilowatt emergency life support system. Reactor feed rate, 41.7 kilograms per day (92 lb/day) of hydrogen peroxide and 4.2 kilograms per day (9.2 lb/day) of water; hydrogen peroxide conversion, >99 percent; oxygen yield, >99 percent; estimated weight of subsystem, 68.0 kilograms (150 lb); net heat of reaction, -1.19×10^8 joules per day (-113 000 Btu/day).
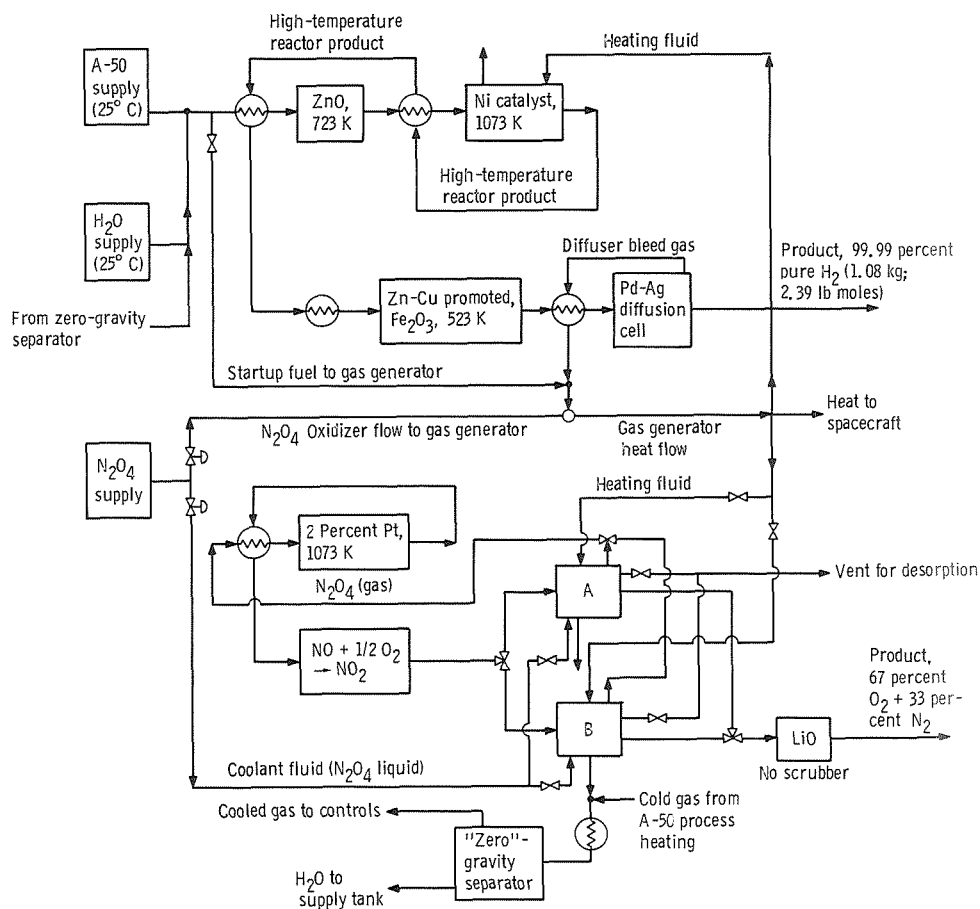
Figure 10. - Process flow for nitrogen tetroxide - Aerozine-50 reforming and purification processes. Reactor feed rate, 17.0 kilograms per day (37.4 lb/day) of Aerozine-50 and 19.5 kilograms per day (43 lb/day) of water.
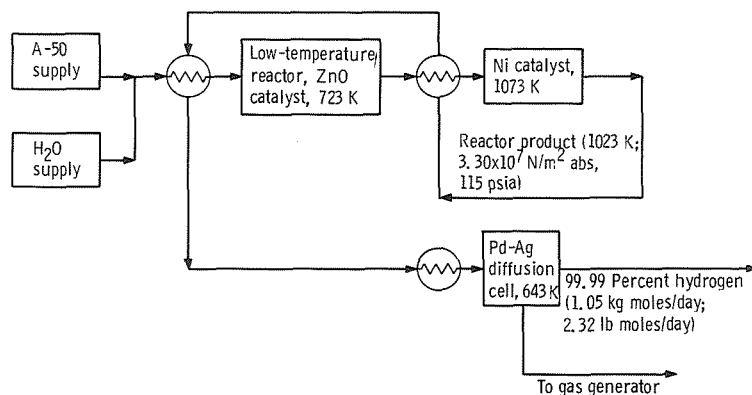
Figure 11. - Aerozine-50 reforming process with dual-reactor chain. Reactor feed rate, 19.5 kilograms per day (43 lb/day) of Aerozine-50 and 22.7 kilograms per day (50 lb/day) of water; hydrogen conversion, 87 percent; hydrogen yield, 61 percent, 99.99 percent pure hydrogen; estimated weight of subsystem, 63.0 kilograms (134 lb)(max); net heat of reaction, 6.69×10^7 joules (63 500 Btu); net head addition to sustain reaction, 1.25×10^8 joules per day (119 000 Btu/day); volume, 0.096 cubic meter (3.2 ft^3).
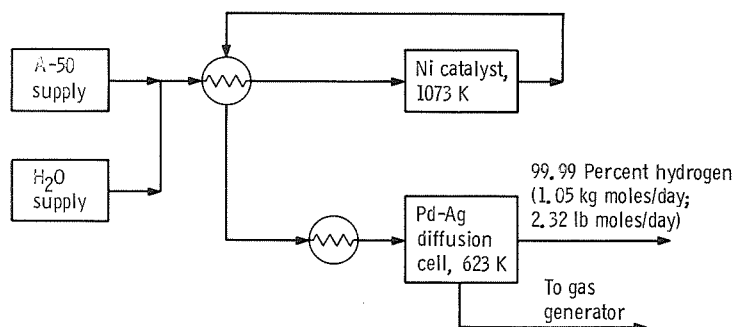
Figure 12. - Aerozine-50 reforming process with single-reactor chain. Reactor feed rate, 29.5 kilograms per day (65 lb/day) of Aerozine-50 and 34.5 kilograms per day (76 lb/day) of water; hydrogen conversion, 55 percent; hydrogen yield, 40 percent, 99.99-percent-pure hydrogen; estimated weight of subsystem, 61.1 kilograms (135 lb)(max); net heat of reaction, 6.32×10^7 joules (60 000 Btu); net heat addition to sustain reaction, 1.16×10^8 joules per day (110 000 Btu/day); volume, 0.0792 cubic meter (2.8 ft^3).
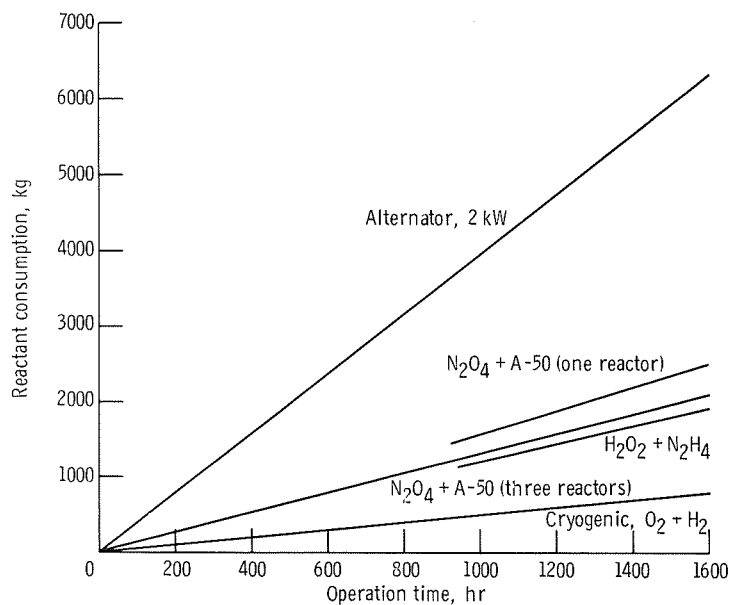

Figure 13. - Reactant consumption in various emergency life support systems for two-man - 2-kilowatt system.

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