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AN AIR REVITALIZATION MODEL (ARM) FOR REGENERATIVE LIFE SUPPORT SYSTEMS (RLSS)

Final Report

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ABSTRACT

The primary objective of the Air Revitalization Model (ARM) is to determine the minimum buffer capacities that would be necessary for long duration space missions. Several observations are supported by the current configuration of ARM. There are at least two factors affecting the buffer sizes: the baseline values for each gas, and the day-to-day or month-to-month fluctuations that are allowed. The baseline values depend on the minimum safety tolerances and the quantities of life support consumables necessary to survive the worst-case scenarios within those tolerances. Most, if not all, of these quantities can easily be determined by ARM once these tolerances are set. The day-to-day fluctuations will also require a command decision. It is already apparent from the current configuration of ARM that the tighter these fluctuations are controlled, the more energy will be used, the more nonregenerable hydrazine will be consumed, and the larger will be the required capacities for the various gas generators. All of these relationships could clearly be quantified by one operational ARM.

INTRODUCTION

Earth is, without a doubt, the most successful known example of a regenerative life support system. Because past and current space missions continue to be of relatively short duration, these life support systems all rely heavily upon expendable materials. Life support systems of many future space missions may try to imitate Earth's own system. One of the major problems encountered with this reproduction is that the amount of buffered air volume on the earth is a great many times larger, per person, than that available on a space mission.

The volume of air available to the life support system can be substantially increased by the use of stored air buffers of each important gas. However, strict mass and volume constraints for extended space missions require that these buffers be kept to a minimum. It will therefore be necessary to use automated physicochemical systems to modify the atmosphere and keep the relative abundance of the various gas constituents in balance.

METHODOLOGY

This investigation involves the development of a computer simulation model that emulates operation of the air revitalization component of an actual regenerative life support system. The added benefit of this procedure is that it also reveals the amount of replenishment from outside sources (e.g. from Earth or locally produced) that would be necessary under various configurations of the system. The particular system that is being modeled is an initially unmanned test bed facility that is now in the earliest stages of development at JSC. This JSC growth chamber is being built in support of NASA's long-duration missions to the moon and Mars. JSC's long-range plans also include design, construction, and operation of a man-rated test bed facility for verification of integrated regenerative life support systems, operations development, and crew-training. The Air Revitalization Model (ARM) is being designed around a built-in facility for evolution to allow it to keep pace with test bed upgrade.

Due to the complexity of this computer model and because of the great danger of undetected errors, it is advisable to approach it's design sequentially. Therefore development of a fully functional ARM has been subdivided into three phases. Of these three phases, the first two have now been essentially completed. Planning is currently under way for the commencement of phase three. It is hoped that phase three can be completed during summer, 1991.

Phase One

In this phase ARM will generate data on a short cyclic interval. The length of each cycle will be set for any value from a fraction of an hour up to a full day or more. ARM will compute the amount of each gas in the storage buffers and then activate the physicochemical systems whenever any controlled amount falls below a baseline, called zero, whose value is unimportant to ARM. In phase one there will be no restriction on the maximum size of any of the buffers. They will be assumed to be extremely large. The controlled atmospheric gases will be nitrogen and oxygen with the possibility of adding a baseline for carbon dioxide at a later date. Also controlled with baseline values will be water and hydrogen with the possibility of adding a baseline for methane at a later date. Available to the system, but with no baseline, will be hydrazine. Hydrazine is nonrenewable and must be resupplied when exhausted. Fortunately, however, hydrazine is often used as fuel and reserve supplies can be transferred to life support systems as needed.

ARM will be provided with a leakage variable. This value will be subtracted from the available amounts in each cycle. The user may choose any rate in either or both of two categories: 1) large leaks consisting of breathable air, or 2) small leaks in which gases are differentiated by molecular size.

Phase Two

This phase consists mainly of internal reorganization and restructuring for greater speed and efficiency. The various baselines will be coordinated and consolidated into a unified structure. This is all necessary as provision for a month-by-month emulation capability for ARM.

All essential documentation will be supplied to ARM. This includes both internal and auxiliary documentation. Many months, even years, of data will be generated by ARM and this data will be thoroughly tested for accuracy, reasonableness, and continuity from month to month.

ARM will also be endowed with a table of months and days so that actual monthly data can be emulated rather than only generic months of 30 days each. This is a necessary step before ARM can actually emulate the JSC growth chamber which will be operating on a real-world basis.

Phase Three

This phase will see the addition of maximum baseline values. This will allow ARM to emulate a system with limited storage capacities. By adjusting these variables we can discover the reaction of a regenerative life support system to any variety of reserve storage buffer sizes. Only in this way can we finally determine the minimum safe capacities for these buffers. It also seems possible to provide ARM with two additional aspects of limitation. One would be an absolute lower boundary below the baseline. This lower boundary would represent an empty tank. The other additional limitation would be an absolute upper boundary. This, by analogy, would represent a full tank. These two limitations would open up a whole new realm of possibilities, especially in the absolute minimum. For one thing it would give us insight into the use of emergency air rations and improve our understanding of just how much is really needed for different types of emergencies.

New overlays will be added to ARM to allow year-by-year operation. This will provide insight to the long-term effect of various configurations. The entire structure of ARM would also need to be redesigned to reduce computer memory and storage requirements and enable the program to run on conventional hardware.

When the JSC test bed is completed and in operation, the various model parameters will be adjusted to reflect the actual chamber data. As more data becomes available, a database of various plant growth profiles will be incorporated into ARM to identify different reactions of the environment to the presence of a variety of types of plants.

ARM will be programmed to respond to an assortment of unscheduled "events." The importance of surviving unexpected occurrences will surely increase the minimum buffer sizes. This increase can best be calculated by modeling these events. However, once the values of these increases have been determined, they can be added (moved) below the minimum baseline and need not affect the day-to-day operation of the system.

PARAMETERS

System Constants

These values are well known constants and unless an error is discovered, these constants will not be changed. These are the values used by ARM:

A. Atomic weights
   (Based on IUPAC Atomic Weights of the Elements 1981)
   1. Hydrogen = 1.00794
   2. Carbon = 12.01100
   3. Nitrogen = 14.00670
   4. Oxygen = 15.99940

B. Conversion factors
   (CRC Handbook 1987)
   1. Lbs. to kg = 0.45359237
   2. Ft. to meters = 0.3048

C. Other factors
   (Basic definitions included for exhaustivity)
   1. Percent = 0.01
   2. Total = 100%

D. Physicochemical system formulas
   1. Sabatier $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
   2. Oxygen generation system $2H_2O \rightarrow O_2 + 2H_2$
   3. Nitrogen supply system $N_2H_4 \rightarrow N_2 + 2H_2$
   4. Methane burner $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Controlled Constants

These values can be easily changed as the system may require. The values currently being used by ARM are given here. However, the user should substitute his own constants for the particular system being modeled.

A. Crew Cabin
   1. Crew size = 1
   2. Cabin volume = 30 cubic meters
   3. Air density = 1225 grams/cubic meter
   4. Oxygen conversion = 0.83 kilograms/man/day
   5. Conversion efficiency = 87%
   6. Atmosphere composition
      a. Nitrogen = 77.5%
      b. Oxygen = 21.0%
      c. Water vapor = 1.0%
      d. Carbon Dioxide = 0.5%

B. Plant growth chamber
   1. Plant growth Plots
      a. Length = 1.778 meters
      b. Width = 0.762 meters
      c. Number = 8
   2. Chamber volume = 25 cubic meters
   3. Air density = 1225 grams/cubic meter
   4. CO_2 conversion = 2.5 grams/square meter/hour
   5. Conversion efficiency = 90%
   6. Atmosphere composition
      a. Nitrogen = 76.0%
      b. Oxygen = 18.0%
      c. Water vapor = 3.0%
      d. Carbon Dioxide = 3.0%

C. Time
   1. Time between readings = 8 hours
   2. Plant cycle daylight = 16 hours

D. Physicochemical system efficiencies
   1. Sabatier = 99%

2. Oxygen generation system = 99%
3. Nitrogen supply system = 99%

E. Leakage rates
1. Whole air type = 0.9% per day
2. Permeable membrane type = 0.1% per day

Input Variables

Some variables will often change from one run to the next. These must be chosen by the user depending on the conditions being investigated. They are:

A. Initial quantities of gases in the storage buffers
   1. Nitrogen
   2. Oxygen
   3. Water
   4. Carbon dioxide
   5. Hydrogen
   6. Hydrazine
   7. Methane
B. Leaf Area Index (LAI)
C. Leaf growth rate

DISCUSSION

The graph in figure 1 was generated by ARM. It represents a month, January, in which no plants were growing. Thus the leaf area index has been set to zero. The nitrogen level can be seen to be dropping below an initial, arbitrarily chosen, value of 30 due to an assumed overall leakage rate of 1% per day. The water vapor level is initially decreasing very slowly below 5 because of the low percentage of water vapor contained in the atmosphere. Of course, the gases which are not contained in the atmosphere are not seen to be leaking. See hydrogen, for example, at 15. A peek at the data would reveal that oxygen is leaking by about one third as much as nitrogen. But even the graph shows that the rate at which oxygen is dropping below 10 is greater than the nitrogen decline. This is due to oxygen consumption by the one crew member. This crew member is also responsible for the increase in carbon dioxide. The zero line near the bottom of the graph represents the baseline for each gas in the buffer. It can be seen on the graph that the excess oxygen is depleted on January 10 when the oxygen trace reaches the baseline. At this time the oxygen generation system will begin generating just enough oxygen to keep the oxygen level from dropping below the baseline. The oxygen generation system is also responsible for the hydrogen increase and the greatly accelerated rate of water decline which begins on January 10.

Figure 1.- RLSS/ARM Graph for January

LAI = 0 N2H4 Used = 0.0 Kg 1.0% LEAK

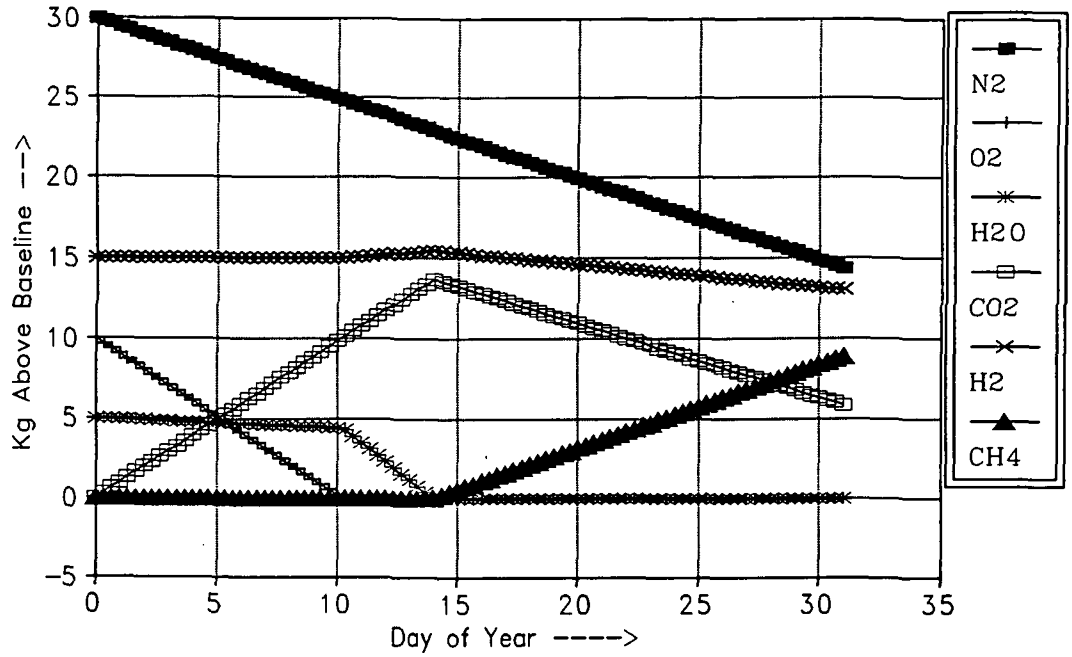
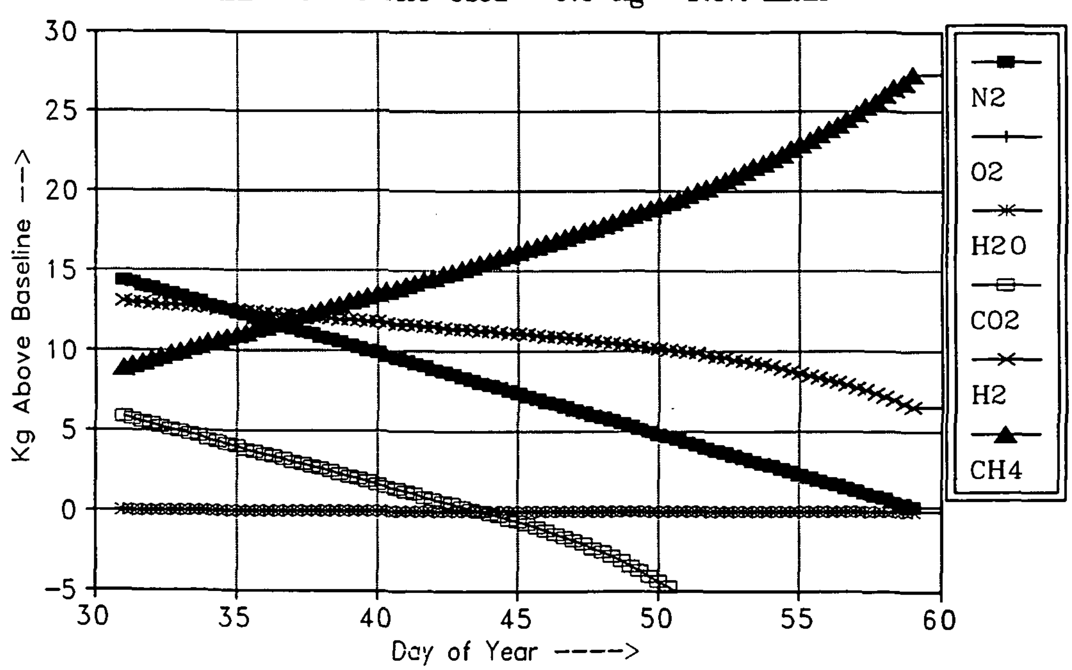


Figure 2.- RLSS/ARM Graph for February

LAI = 0 N2H4 Used = 0.0 Kg 1.0% LEAK



Notice on January 14 that the water level has dropped to zero. At this time the Sabatier process begins operation at exactly the right rate to keep the water level from dropping any further. The Sabatier process causes a decrease in the hydrogen level and the carbon dioxide level on January 14. It is also responsible for the production of methane which is seen to begin on January 14. It should be pointed out that both oxygen and water remain on the baseline for the remainder of January. Also notice, at the top of the graph, the label that indicates that no hydrazine was used during January. All of the traces end on the thirty-first, the last day of January.

The graph in figure 2 was generated by ARM immediately after the previous graph without any user intervention. These are the results for February. It uses the final values at the end of January as the initial values for February. It can be seen that the day numbers at the bottom of the graph are days of the year rather than days of the month, and each day ends at the corresponding mark.

On day 44 the carbon dioxide is depleted. But since there are no plants and since both oxygen and water levels are on the baseline, the carbon dioxide is allowed to go below the baseline rather than use precious oxygen or water to try to stop it.

Nothing noteworthy happens for the remainder of February until February 28, day number 59. On this day the nitrogen is depleted. However, this same situation is duplicated in the next series of graphs and will be illustrated at that time.

There are two very important reasons for studying the operation of ARM with an LAI of 0. Initially, it gives us an opportunity to see this operation without the further complication of input from the biological component of the life support system. This makes it easier to understand and validate ARM. Secondly, this is the mode in which ARM must operate, at least temporarily, if some misfortune destroys all of the plants. This will make it possible to determine the quantities of buffer gases that must be stored for just such contingencies.

The specifics for figure 3 are similar to those for figure 1, except that the initial values are set somewhat differently and the leaf area index is set to 4. The slow leakage of water vapor from the atmosphere is more noticeable in this graph than it was in figure 1. The wavy nature of the oxygen trace as well as that of carbon dioxide, and others to a lesser degree, is due to the day and night growth cycle of the plants. The plants cause the oxygen levels to increase and the carbon dioxide levels to decrease until January 25 when the carbon dioxide is exhausted. At this time the emulated methane burner converts just the right amount of methane to hold the carbon dioxide level at

Figure 3.- RLSS/ARM Graph for January

LAI = 4 N2H4 Used = 0.0 Kg 1.0% LEAK

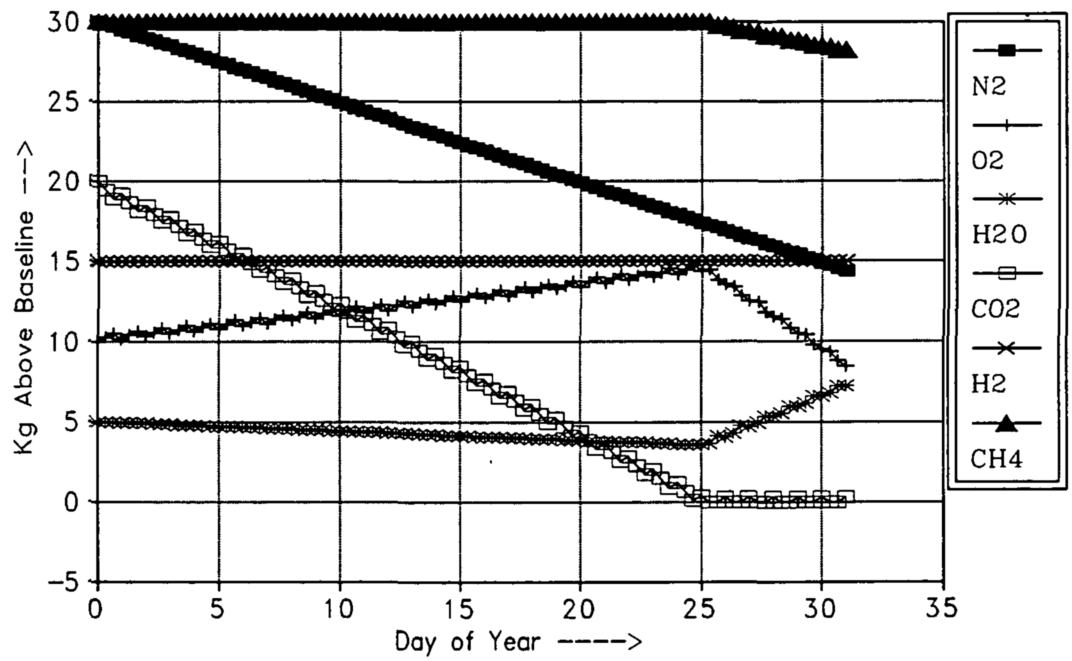
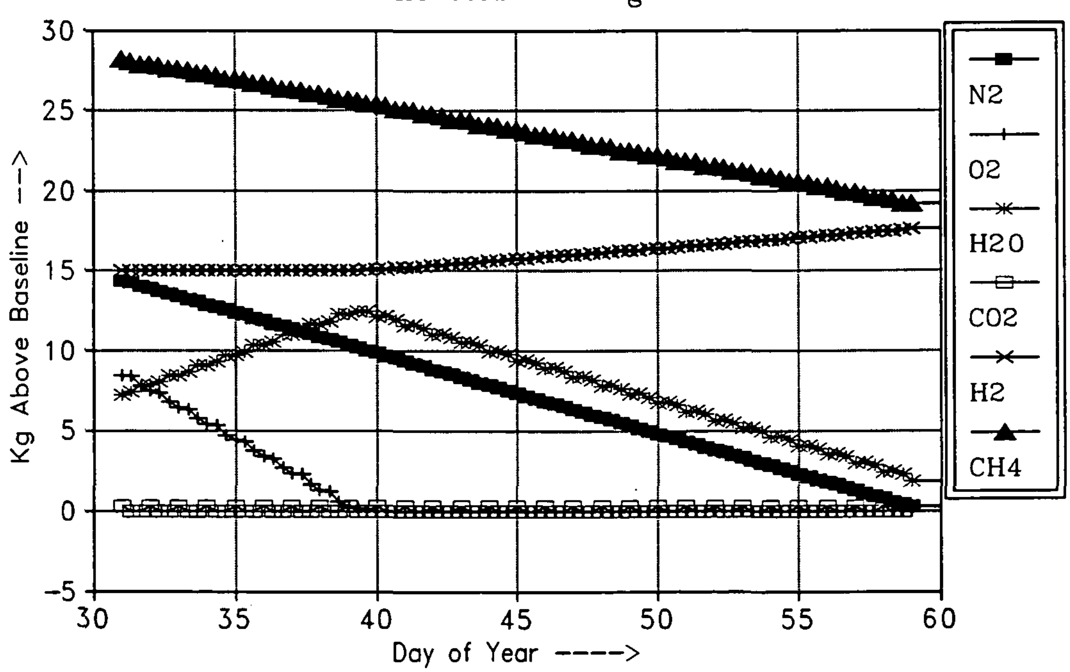


Figure 4.- RLSS/ARM Graph for February

LAI = 4 N2H4 Used = 0.0 Kg 1.0% LEAK



the baseline while the water level begins to rise as a by-product. But, the methane burner also consumes oxygen and this, too, begins to decline on January 25.

In figure 4 we see that the oxygen is exhausted by day number 39. This activates the oxygen supply system which begins using the excess water to produce oxygen and hydrogen. Even though twice as much hydrogen is generated as oxygen, the hydrogen is seen to rise very slowly. This is due to the low mass of hydrogen.

Until now, no hydrazine has been consumed. This is indicated at the top of figures 3 and 4. However, as in figure 2, the nitrogen is depleted on day 59. There are now three gases on the baseline. Since nitrogen reaches the baseline on February 28, we will not see the effects of this until March 1.

In figure 5 we first notice that the Nitrogen Supply System that was activated on February 28 consumes hydrazine and prevents the nitrogen from falling below the baseline. But, of course it has no effect on the water level, which is also falling. Thus, we see the excess water depleted on day 63. At this time we have four gases at the baseline. These four are carbon dioxide, oxygen, nitrogen, and now water. It is clear that these four cannot all be maintained as leakage continues. We have essentially the same problem as seen in figure 2 when carbon dioxide reached the baseline. We also have the same solution. Carbon dioxide is allowed to deteriorate below the baseline. You will notice on the graph of figure 5 that carbon dioxide drops below the baseline just as water is coming onto the baseline on day 63. This leaves water, nitrogen, and oxygen on the baseline. The Nitrogen Supply System continues to generate both nitrogen and hydrogen. But this is not enough to prevent the large drain on the hydrogen supply from using all of the reserve supply of hydrogen. This occurs on day 87. Now the Nitrogen Supply System is called upon to balance the hydrogen drain caused by maintaining the water supply at the baseline. As we saw, the drain on the water supply was caused by a shortage of oxygen. This, in turn, was caused by a lack of carbon dioxide. We will come back to the carbon dioxide in a moment. On day 87, in order for the Nitrogen Supply System to balance the hydrogen, it must also generate huge amounts of nitrogen. This is why the nitrogen level is seen sailing off the top of the graph on day 88.

The system is now in desperate straits. During the month of March the RLSS used 120 kg of hydrazine, mostly in the last few days. During the month of April the system is able to keep hydrogen, oxygen and water at the baseline, but only with a huge consumption of hydrazine as indicated by the label at the top of figure 6, almost 26 metric tons. This indicates that the physicochemical system will do everything it can to maintain the baseline integrity until

Figure 5.– RLSS/ARM Graph for March

LAI = 4   N2H4 Used = 120.2 Kg   1.0% LEAK

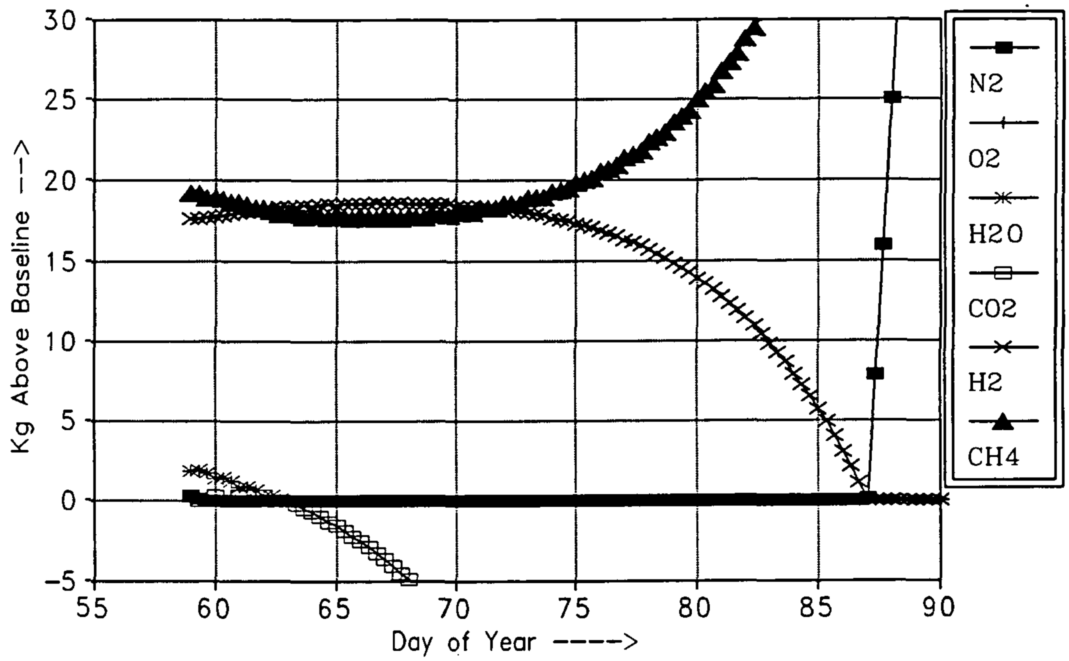
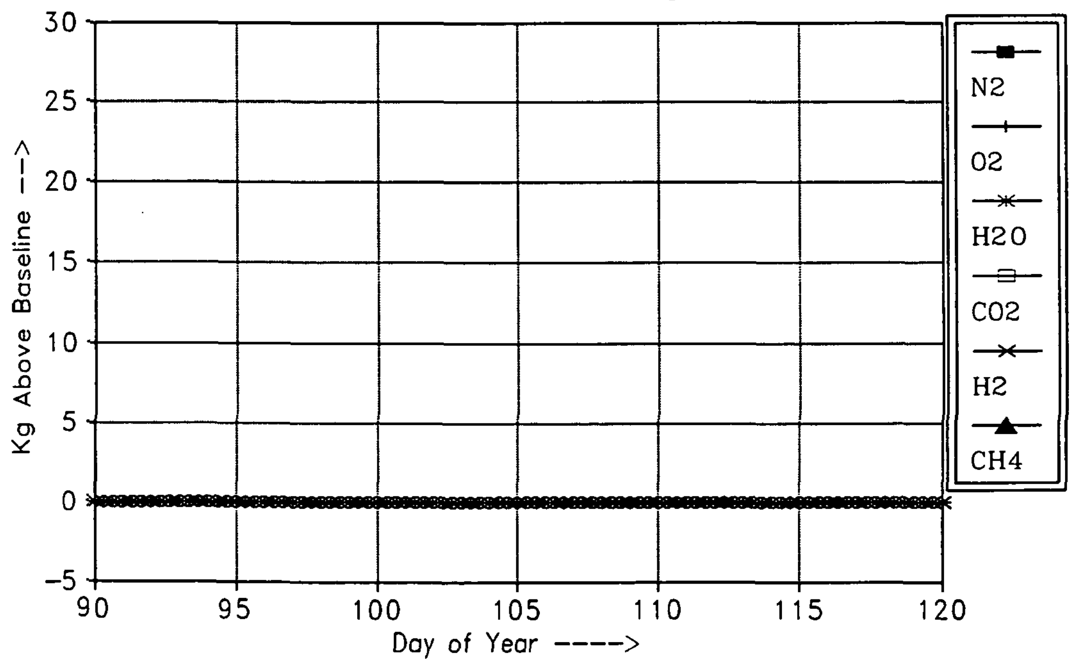


Figure 6.– RLSS/ARM Graph for April

LAI = 4   N2H4 Used = 25959.6 Kg   1.0% LEAK



it totally runs out of resources. We can only hope that never happens.

Now, returning to the carbon dioxide. We have seen that this whole breakdown of the system was first initiated by the shortage of carbon dioxide. There are auxiliary sources of carbon dioxide that can prevent the system from running down once they are utilized. This includes the recycling of waste and the eating and digesting of food which will likely be resupplied from Earth. If these factors are figured in, we will see a totally different end result. It is therefore very likely that a future version of ARM will include these features.

Important Discovery

This procedure is probably known, but it was a challenge for me. In order to keep the RLSS in balance it is quite important to poll the different gas supply systems in an appropriate sequence. So far, I have found only one sequence that works. This is an important understanding, not only for a simulation model, but also for a computer control system. The sequence used by ARM is given in table 1. Ceiling checks will not be done by ARM until it reaches phase three. They are included here for reference only. If the value in the floor check is negative, the corresponding system will be used to bring it up to the baseline. If the value in the ceiling check is above established maximums it will be consumed until brought below the ceiling. It should be understood that these systems can run simultaneously, but in three shifts. Systems 1 through 4 can run together as long as each knows the results of all previous systems and stops polling in sequence. Systems 5 through 7 and then systems 8 and 9 can repeat the process. There should, however, be no time lapse between the three shifts, especially if the leakage rate is high.

It can be seen from this table that the only products which can be generated above its ceiling will be methane, water, and nitrogen. Excess water can be stored in liquid form and excess nitrogen can be used to increase atmospheric volume or pressure to some degree. Excess methane beyond storage capacity could be vented or used as fuel.

The only products which can run short are water, carbon dioxide and hydrazine. Hydrazine is nonrenewable and must be resupplied from sources beyond RLSS domain, anyway. Similarly, resupplied food, to supplement the edible biomass provided by the plants, will help alleviate the shortages of both carbon dioxide and water when the resupplied food is digested by the crew.

TABLE 1.- SEQUENCE OF OPERATION

#	Name*	Floor Check	Ceiling Check	Byproduct	Requisite
1.	NSS	N_2 <0		H_2	N_2H_4
2.	S	H_2O<0	CO_2>Max	CH_4	CO_2 & H_2
3.	MB	CO_2<0	O_2 >Max	H_2O	CH_4 & O_2
4.	OGS	O_2 <0	H_2O>Max	H_2	H_2O
5.	S	H_2O<0	H_2 >Max	CH_4	CO_2 & H_2
6.	MB	CO_2<0 and H_2O>0 or O_2>0	CH_4>Max	H_2O	CH_4 & O_2
7.	OGS	O_2 <0	H_2O>Max	H_2	H_2O
8.	S	CH_4<0	H_2 >Max	H_2O	CO_2 & H_2
9.	NSS	H_2 <0		N_2	N_2H_4

*NSS = Nitrogen Supply System
S = Sabatier System
MB = Methane Burner
OGS = Oxygen Generation System

CONCLUSIONS

The Air Revitalization Model (ARM) seems to indicate, on the basis of minimum baseline constraints only, that Regenerative Life Support Systems (RLSS) can be held on or above all of the minimum baselines for very long periods, months or even years. If this feat can be duplicated for maximum baselines, then only very small buffer storage would be necessary except that which may be required for recovery from catastrophic events. However, there is a price. This model does not track the energy requirements, but it does show a need for a continuous resupply from outside sources, such as from Earth or from local resource extraction. Under the present configuration of ARM, resupply would be required only for carbon dioxide, water and hydrazine. The carbon dioxide and water could, of course be supplied in the form of food stock, and the hydrazine does not differ from hydrazine fuel.

Under this configuration, ARM also indicates that the only large storage buffers beyond those necessary for the baseline amounts would be for storage of excess methane, water and nitrogen. However, these storage requirements are diminished if resupply is reliable.

It remains for future enhancements of ARM to determine the effects of additional constraints on the operation of RLSS. Some future enhancements which may be considered for annexation to ARM include:

1) maximum baseline constraints
2) absolute minimum constraints
3) absolute maximum constraints
4) year-to-year overlays
5) plant profiles
6) unscheduled "event" scenarios
7) resupply schedules
8) waste oxidation
9) liquid water recycling
10) tracking of gas production
11) tracking of gas usage totals
12) tracking of energy usage totals

It would seem that there is still much to be done.