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THE CRYOGENICS ANALYSIS PROGRAM FOR APOLLO MISSION PLANNING AND ANALYSIS

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Abstract

The Cryogenics Analysis Program was developed as a simplified tool for use in premission planning operations for the Apollo command-service module. Through a dynamic development effort, the program has been extended to include real-time and postflight analysis capabilities with nominal and contingency planning features. The technical aspects of the program and a comparison of ground-test and mission data with data generated by using the Cryogenics Analysis Program are presented.

By using the electrical power and environmental control systems requirements, computation of the thermodynamic state variables is provided by the program for each of the cryogenic storage tanks of the spacecraft. These calculations are accomplished by combining computations of the equilibrium state variables with a simplified model of the delivery system, including models for heat leak, environmental control system restrictors, and surge tank, check valves, isolation valves, relief valves, and heater/fan pressure-switch logic. Modifications that will permit heater-element temperature computations and will allow for check-valve failures are being incorporated.

The results of the Cryogenics Analysis Program capability to predict flight requirements also are presented. Comparisons of data from the program with data from flight results, from a tank-qualification program, and from various system anomalies that have been encountered are discussed.

Future plans and additional considerations for the program also are included. Among these plans are a three-tank management scheme for hydrogen, venting-profile generation for Skylab, and a capability for

handling two-gas atmospheres. The plan for two-gas atmospheres will involve the addition of the capability to handle nitrogen as well as oxygen and hydrogen.

Introduction

The Cryogenics Analysis Program (CAP) was designed to provide a flexible mission-planning tool in which a fast execution time could be achieved without undue loss of computational accuracy. The CAP can be used for the analysis of the cryogenic oxygen and cryogenic hydrogen systems in any of the configurations proposed for the Apollo command-service module (CSM) by selecting the number of oxygen (O_2) tanks and hydrogen (H_2) tanks in any combination up to a maximum of three each. For systems analyses, tank conditions are computed as a function of time, systems parameters, and environmental control system (ECS) and electrical power system (EPS) flow-rate requirements. In addition to systems analyses, various parametric studies can be performed for individual cryogen tanks operating at specified tank pressures.

The general program philosophy is described in this report, and pertinent mathematical expressions are given. No program is complete until a thorough checkout has been performed. Fortunately, test data were available that provided good information for program verification before the Apollo 14 mission. Postflight data provided a second check on the program.

A dynamic program such as the CAP will undergo continual changes as spacecraft hardware changes are made. These changes and future plans for the program are discussed in the final section of this report.

Program Description

The current CAP is based on the Apollo 14 configuration. A schematic diagram of the system model, which incorporates all system components included in the CAP, is shown in figure 1. A simplified flow diagram of the program logic is presented in figure 2.

Flow Sharing

The CAP uses a simplified flow-sharing model in which pressure drops in the lines, except for the ECS restrictors, are considered to be negligible. The effect of the ECS surge tank on the system flow rate may be either considered or ignored.

Environmental Control System Flow Rate

The pressure drop (in psi) across the ECS restrictors is represented by the cubic equation

$$\Delta P = 51.475\left(\dot{M}_r\right) - 9.911\left(\dot{M}_r\right)^2 + 12.40\left(\dot{M}_r\right)^3 \tag{1}$$

where

$\dot{M}_r = (3.833/\dot{M}_c)\dot{M}_{ECS}$, lb/hr
$\dot{M}_c$ = flow rate for a 750-psi pressure drop, lb/hr
$\dot{M}_{ECS}$ = actual flow rate, lb/hr

If the surge-tank isolation valve is closed, the equations for the two restrictors are solved simultaneously for flow rates so that (1) the sum of the restrictor flow rates is the demanded ECS flow rate, and (2) the restrictor pressure drops lead to the same value for pressure at the downstream junction of the restrictors.

If the surge tank isolation valve is open, the pressure drop across each restrictor is computed by subtracting the surge-tank pressure from the storage-tank pressure. Equation (1) is used to compute the required ECS flow rate for each restrictor. If the total restrictor flow is less than the demanded ECS rate, the oxygen flow from the surge tank is used to make up the difference. If the combined restrictor flow exceeds the ECS usage rate, the excess flow is stored in the surge tank. Thus, the surge tank operates as a buffer for smoothing the ECS flow demands placed on the supply system.

Surge-Tank Model

The surge tank is treated as a pressure vessel in which the pressure, temperature, and density are related by the ideal-gas equation. For constant temperature, the pressure in the surge tank P_s is given by

$$P_s = \frac{900M_s}{M_n} \tag{2}$$

where M_s is the surge tank oxygen mass and M_n is the mass in the surge tank when $P_s = 900$ psi.

Equal-Pressure-Rate Equations

The pressure-change rate is given by the equation

$$\dot{P}_i = A_i\dot{M}_i + B_i\dot{Q}_i \tag{3}$$

where

$\dot{P}_i$ = pressure change rate for the ith tank
$\dot{M}_i$ = mass flow rate for the ith tank
$\dot{Q}_i$ = heat input rate for the ith tank
A_i = density-dependent parameter $\phi\theta/V$ for the ith tank
B_i = density-dependent parameter ϕ/V for the ith tank
ϕ, θ = density-dependent parameters
V = volume

If program logic dictates that the total flow rate M_T must be provided from only one tank, the flow-rate division will be

$$\dot{M}_i = \dot{M}_T = \dot{M}_{EPS} + \dot{M}_{ECS} \tag{4}$$

and

$$\dot{M}_j = \dot{M}_k = 0 \tag{5}$$

where i, j, and k separately assume the values 1, 2, and 3. If tanks i and j are to share the flow (that is, a two-tank operation), the equations become

$$\dot{M}_i = \frac{A_j\dot{M}_T + B_j\dot{Q}_j - B_i\dot{Q}_i}{A_i + A_j} \tag{6}$$

$$\dot{M}_j = \dot{M}_T - \dot{M}_i \tag{7}$$

$$\dot{M}_k = 0 \tag{8}$$

When all three tanks participate, the equations become

$$\dot{M}_i = \frac{A_j A_k \dot{M}_T + A_j\left(B_k\dot{Q}_k - B_i\dot{Q}_i\right) + A_k\left(B_j\dot{Q}_j - B_i\dot{Q}_i\right)}{A_i + A_j + A_k} \tag{9}$$

where $\dot{M}_j$ and $\dot{M}_k$ are given by perturbations of the indices or by using the basic equation (3) to compute the pressure rate for tank i. Then, with this pressure rate for tank i, the flow rates for tanks j and k are computed. In any case,

$$\dot{M}_i + \dot{M}_j + \dot{M}_k = \dot{M}_T \tag{10}$$

for the three-tank flow-sharing situation.

Combined Flow-Sharing Logic

The EPS flow-rate demand is computed from the electrical load imposed on the fuel cells. The ECS usage rates are input data. When the surge tank is isolated from the system, the ECS flow-rate demand is the same as the usage rate. When the surge tank is not isolated, the ECS demand placed on the storage tanks is computed as described previously. Then, the system pressures are tested against check-valve pressure dead bands to determine which check valves are permitting flow. When the number of tanks supplying flow has been determined, the total flow rate (EPS demand plus ECS demand) is used in the equal-pressure change-rate flow-sharing equations to compute the anticipated flow rates from each tank. Next, the ECS flow rate required by each restrictor is computed. If the anticipated tank flow rates can meet the ECS demand, these flow rates become the flow rates for the individual tanks. However, the ECS flows must be provided through the restrictors so that pressure considerations are satisfied. If the anticipated flow rates are insufficient to supply the required restrictor flows, the restrictor-flow requirements are met, and the minimum possible adjustment in the anticipated flow from each tank is made. For example, a certain case may call for a 1.5-lb/hr EPS flow rate and a 6.5-lb/hr ECS flow rate or a total flow rate of 8.0 lb/hr. The flow-sharing computations are performed (with the total flow provided from tanks 1 and 3), and anticipated flows of 3.0 lb/hr from tank 1 and 5.0 lb/hr from tank 3 are obtained. The restrictor calculations dictate that the ECS flow must be shared equally by the two tanks; that is, each tank must supply 3.25 lb/hr to the ECS system. The anticipated flow for tank 3 will meet this requirement, but the anticipated flow for tank 1 is insufficient. Thus, the minimum adjustment is made by increasing the flow from tank 1 by 0.25 lb/hr and decreasing the flow from tank 3 by the same amount. Thus, tank 1 will supply 3.25 lb/hr to the ECS system, and the EPS system will receive none. Tank 3 will supply 3.25 lb/hr to the ECS system and the total requirement of 1.5 lb/hr to the EPS system. Instead of having equal pressure rates, the tank 3 pressure will increase relative to the tank 1 pressure. If a 2.9-lb/hr flow was required by restrictor 1 and if a 3.6-lb/hr flow was required by restrictor 2, the anticipated flow rates would be sufficient; each tank would supply the flow to the EPS and the ECS; and the tank pressures would rise or fall together.

Relief-Valve Model

The characteristics of the oxygen and hydrogen overpressure (or vent valves), relief valves supplied by the Propulsion and Power Division of the Manned Spacecraft Center (MSC), are shown in figure 3. Each valve has two distinct modes of operation. The particular parametric values assigned to the various transition points are shown in table I for both the oxygen and the hydrogen valves.

Establishing a model of this relief valve requires a combination of equation (3), which sets forth the pressure rate in terms of flow rate, and the relationships of pressure to flow rate shown in figure 3. The vent-flow rate $\dot{M}_V$ is expressed mathematically by

$$\dot{M}_V = S\left(P - P_R\right) + \dot{M}_R \tag{11}$$

where P is the operating pressure, P_R is the reference pressure, and S is a slope computed according to the particular region of the characteristic curve and depending on whether the pressure is increasing or decreasing. One of the pressures defined by points B, C, D, or E will be P_R; $\dot{M}_R$ is the flow rate corresponding to P_R. This procedure dictates that the pressure increase or decrease will always be directed toward one of the points B, C, D, or E. To make the pressure and average-mass-flow computations independent of step size, an integration of the pressure-rate equation was performed by considering the vent characteristics, and the resulting equations (12) and (13) were programed.

$$P(t) = P\left(t_o\right) + \dot{P}\left(t_o\right)\left(AS\right)^{-1}[\exp(AS\ \Delta t) - 1] \tag{12}$$

$$\Delta M = \dot{M}_T\left(t_o\right)\Delta t + \dot{P}\left(t_o\right)A^{-2}S^{-1}[\exp(AS\ \Delta t) - AS\ \Delta t - 1] \tag{13}$$

where

t_o = time at beginning of time step
t = time at end of time step
$\Delta t = t - t_o$
$P(t)$ = pressure at time t
$P(t_o)$ = pressure at time t_o
$\dot{P}(t_o)$ = pressure rate at time t_o
A = density-dependent parameter $\phi\theta/V$
S = slope of relief valve characteristic
ΔM = total mass lost during time step
$\dot{M}_T(t_o)$ = total flow rate $(\dot{M}_{ECS} + \dot{M}_{EPS} + \dot{M}_V)$ at time t_o

The vent flow rate is used to compute a vent thrust using

$$\text{thrust} = \dot{M}_V\sqrt{\frac{RT_e}{Mg}}\ \frac{(\gamma + 1)}{\sqrt{\gamma}} \tag{14}$$

where

$\dot{M}_V$ = vent flow rate
R = gas constant
T_e = temperature at the exit nozzle
M = molecular weight
g = gravitational acceleration
γ = specific-heat ratio

This equation was derived assuming sonic flow at the exit nozzle.

Heat Leak

Heat-leak calculations are based on the following assumptions.

1. The heat leak into the tank is given by the product of a tank thermal conductivity C_T and the temperature difference between the external temperature T_a and the internal temperature T_T.

2. The C_T is assumed to be constant with temperature.

3. The vapor-cooled-shield effect produces a linear reduction in C_T up to some maximum flow rate.

Standard heat-leak information is built into the program. These data consist of heat-leak values corresponding to minimum and maximum flow rates for a tank temperature TT_R and an ambient temperature TA_R. The reference values may be adjusted for a particular mission by supplying the experimental heat leak $\dot{Q}_{in}$ at minimum dQ/dM tank conditions.

The necessary steps for heat-leak computation are outlined as follows:

1. Compute the flow rate at which the observed heat leak was measured.

2. Compute the reference heat leak corresponding to the computed flow rate, the minimum dQ/dM tank conditions, and the environmental temperature TA_{in}.

3. Take the ratio of $\dot{Q}_{in}$ to the heat leak computed in step 2.

4. Update the value of the tank thermal conductivity by using the ratio in step 3.

The heat leak can be computed by using the updated thermal conductivity and the mission values of tank temperature, environmental temperature, and flow rate.

A detailed discussion of the particular equations involved is considered to be too cumbersome for this discussion. The formal program documentation, scheduled for publication in August 1971, will provide a complete discussion of these equations.

Equations of State

Oxygen

The equation of state used in the CAP is based on R. B. Stewart's dissertation of 1966 (ref. 1). The equation of state and its first-order partials, defined in reference 1, have been coded and have been used in the CAP. Later work by Weber (ref. 2) also was programed, and the results were compared with Stewart's results. The two methods compared very closely for the regions and parameters of interest in the present program. However, Stewart's equation of state is more readily adaptable to computer application at a very slight sacrifice in accuracy.

Hydrogen

At present, no equation of state for hydrogen is used in the CAP. The current basis for the computation of the hydrogen thermodynamic properties is the National Bureau of Standards (NBS) program described in reference 3. The subprogram achieves high speed and a good degree of accuracy by using linear interpolation in a grid of selected data points that define the surface of the returned property. The data used in the program were recorded from laboratory tests performed at the NBS in Boulder, Colorado. The property routines generated by using these data were inserted into the predecessors of the CAP and have been retained during the program development.

Computation of the Program Time Interval

The variable time step used for the program is governed by events that lead to a reconfiguration of the instantaneous cryogen system or by maximum changes that are specified for certain parameters considered by the program. Current calculations limit the time interval to the minimum value of the times required to reach the following events.

1. Hydrogen fan cycling
2. Violation of a pressure-switch limit
3. Violation of the vent-pressure limit
4. Fuel-cell purging
5. Intersection of pressures of two or more tanks
6. Surge-tank pressure-change limit

7. Time for the program-summary print

8. System redefinition (restart or new flow requirement)

The largest time step allowed is 0.5 hour; the smallest time step is 0.03 hour.

Updating the Cryogen States

The cryogen state for each tank is updated at the end of each time interval by computing new masses and new pressures according to system operating parameters. The equations of state are used to compute new temperatures. The mass lost from a tank is computed as the product of the tank flow rate and the current time interval. By using the constant tank volume, the density is updated. A new pressure for each tank is computed by using equation (3) with computed flow rates and heat-input rates that are the sums of the heat-leak rate and the heater/fan heat-input rates. Once these values of density and pressure are available, the equations of state are solved to determine the tank temperatures.

Heater-Element Temperature Computations

Heater-element temperature computations are performed by combining parametric data provided by the MSC Structures and Mechanics Division with heater data computed with the CAP. The parametric data consist of node temperature compared with time for various heater-on/heater-off time intervals. Parameters include tank quantities, local g level, and the heat rate supplied by the heaters. The heater on/off times are supplied by the CAP, and an efficient interpolation scheme is used to generate the nodal temperatures for selected nodes.

Analysis is in progress that will permit the previously described parametric data to be used in refined heater calculations that account for heat stored by and released by the heater elements during the appropriate phases of the heater cycles.

Program Checkout

The first exercise performed with the previously described program was that of defining an oxygen-tank-management scheme. Figure 4 shows a simplified schematic of the Apollo 14 oxygen delivery system. The first attempt to manage the system was to use all three tanks during the high-flow periods. It was here that the program first proved to be of value. Results of each computer run indicated a pressure collapse in oxygen tank 1 (fig. 5). First impressions were that an error existed in the program; however, during further analysis, the program was shown to be correct. The spacecraft heater (pressure-switch) logic specifies that the pressure valve of oxygen tanks 1 and 2 must be below approximately 865 psia before the heaters will come on. Oxygen tank 3 operates independently. While tanks 2 and 3 were feeding one restrictor, the tank 2 pressure decay was only one-half as fast as that in tank 1. The heater logic also implies that only one tank (either tank 1 or 2) must be at the cut-off pressure of approximately 925 psia. Thus, with the large pressure drop in tank 1 and only one-half as much pressure drop in tank 2, it is apparent that the tank 1 pressure can never recover in the heater cycle. In fact, the pressure drops lower with each cycle. The solution is to use only oxygen tanks 1 and 2 for the high-flow period and to inhibit the heater in tank 3. This problem was later confirmed by independent investigations.

Manufacturer's Test Study

The next task was to verify the program by attempting to simulate the laboratory tests performed by the tank manufacturer. Set test data and system performance for each tank were provided by the manufacturer. Input parameters such as ambient temperature, flow rates, and tank-management (heater-switching) times were input to the CAP. Tank pressures, temperatures, and quantities were calculated in the program and compared with the test data of the manufacturer. The quantity profiles are shown in figure 6. Note that the correlation is excellent.

The tank management scheme shown in table II was specified in the test procedures. However, analysis of the test data indicated that the actual management scheme was that shown in table III. At two discrete test points (noted in table III with a single asterisk), a quantity balance appeared to have been attempted between oxygen tanks 1 and 2. The test procedure specified an ECS flow of 3.35 lb/hr from 40:55 to 46:36 g.e.t. This specification was determined to be a procedural error because a pressure collapse occurred in tank 1. The CAP simulated this effect. This anomaly, while undesirable in the test, did confirm the CAP prediction that a pressure collapse would happen under similar conditions.

In addition, heater control, as described by the Apollo 14 flight plan, was specified in the test procedures. This specification was based on a heat-leak characteristic similar to that found in the service module (that is, a bay temperature of approximately 70° F). The test by the manufacturer was run at an ambient temperature of 140° F. Because the heater switching is a function of quantity levels and mission time, it became apparent that the increased heat leak, caused by the high ambient temperatures, would force earlier switching times. Again, an accurate calculation of the increased heat-leak function was obtained with the CAP. The results of this detailed comparison study gave a much higher degree of confidence in the overall program and in the capability of the program to support the Apollo 14 mission.

Apollo 14 Premission Analysis

Once the program had simulated the manufacturer's test satisfactorily, production of several profiles for support of the Apollo 14 flight was required. Simulator data for crewmember training, spacecraft consumables analysis, and crew charts for monitoring onboard systems are among the most important support profiles. The crew chart for hydrogen, which was the constraining gas for this mission, is shown in figure 7. Shown on the chart, also, is the hydrogen redline, which is the minimum return quantity based on a tank failure at the critical point in the flight. Critical point is defined as the point at which no return to the primary landing area can be accomplished before the planned nominal time. This point usually is determined by the limitations of the main propulsion system. However, because the Apollo 14 spacecraft was to begin the return to earth as soon as possible after the docking of the lunar module (LM) and the CSM, the critical point occurred during the second lunar surface extravehicular activity. The oxygen crew chart is shown in figure 8. The desired management scheme is reflected by the chart, and the tank-failure capability is retained. For the first time, a cryogen tank for a manned space flight was off-loaded before lift-off. This was required for the demonstration of low-density tank performance, because the Skylab Program will require depleting the tanks.

During the Apollo 14 premission analysis, parametric studies, including the important tank-blowdown analysis, were conducted. The blowdown analysis was performed to verify the capability of the tank 3 enhancement mode. A failure similar to the failure that occurred during the Apollo 13 flight (but without the LM) was assumed for this mode. With the isolation valve closed, no heaters operating in tank 3, and a heat leak approaching zero, proof was required that sufficient oxygen remained to provide ECS oxygen for a return from lunar orbit. Basically, when the heat leak is zero, the cryogen tanks function as high-pressure gas-storage bottles. The tanks will store, without loss, an oxygen quantity at 900 psia that is a function of the ambient temperature. This capability is shown in figure 9. Later tests performed at MSC verified a no-heater blowdown mode capability from a 20-percent quantity level. These tests demonstrated a flow rate equal to (1) an emergency return of a 40-ampere load on the fuel cell plus the ECS requirements and (2) an ECS pressure decay flow.

Flight Support

During the Apollo 14 flight, several profile updates were scheduled to adjust for lift-off values; later, profile updates were to be performed to adjust for heat-leak and pressure-switch shifts. However, early in the flight, it became apparent that a check valve on oxygen tank 2 was not functioning. An analysis was required to determine the effect the failure would have during the rest of the mission. Figure 10 shows the predicted profile based on this failure. The total use, a function of system demands, was not affected, but flow sharing between the tanks was changed. This difference can be observed by comparing the oxygen crew chart to figure 10. The check valve failure significantly impaired the capability to recalculate the heat-leak function; consequently, no further quantity predictions were made.

However, another problem occurred. For Apollo 14 prelaunch and flight operations, the redline on the oxygen tank heater element was set at 200° F. Preliminary analysis had indicated that the peak temperature on oxygen tank 3 (the lowest in density) would exceed the redline only slightly. However, it became obvious that the knowledge of stratification and low-g effects caused by passive thermal control was limited, because the redline was violated before the spacecraft entered lunar orbit. After a new set of thermal tapes had been provided, the heater-on times were recalculated. By processing the thermal tapes, computation of new heater-element temperature limits was possible. This analysis was more realistic than the prelaunch predictions and became the guideline for the balance of the mission.

From the preliminary postflight mission analysis, it is apparent that the predictions made for the Apollo 14 mission were extremely accurate. The results of the preliminary postflight analysis are shown in table IV. Although flow sharing between the tanks deviated slightly from the premission prediction, good correlation existed with the inflight revision. The depletion profile for the Apollo 14 oxygen tank 3 is shown in figure 11. The effect for tanks 1 and 2 is similar to that of tank 3.

Future Plans

Inasmuch as changes are made to the spacecraft, the cryogenic gas storage system, and the delivery system, the CAP must be considered to be changing dynamically as well. Because the program is modular in concept, modification is relatively easy. It has been pointed out previously that any desired tank configuration can be defined, but plumbing changes must be implemented.

In addition to the spacecraft hardware changes, the following items are under investigation.

1. An improvement in the oxygen equation of state

2. Development of an equation of state for hydrogen

3. Addition of the thermodynamic properties of nitrogen for future evaluation of a two-gas atmosphere

The CAP, while certainly not designed for the space shuttle, will provide the basic thermodynamic properties required for the analytical requirements of the shuttle program.

References

1. Stewart, R. B.: The Thermodynamic Properties of Oxygen. Ph. D. Dissertation, Univ. of Iowa, 1966.

2. Weber, L. A.: P-V-T, Thermodynamic and Related Properties of Oxygen from Triple Point to 300 K at Pressures to 33 MN/m^2. J. Res. NBS, vol. 74A, no. 1, Jan.-Feb. 1970, pp. 93-129.

3. Hall, W. J.; McCarty, R. D.; and Roder, H. M.: Computer Programs for Thermodynamic and Transport Properties of Hydrogen. Nat'l. Bureau of Standards Tech. Rept. 9288, Aug. 1967.

TABLE I.- CHARACTERISTIC VALUES FOR THE PRESSURE-RELIEF VALVE

(a) Pressure values

Point	Oxygen pressure, psi	Hydrogen pressure, psi
E	965.0	268.0
D	974.0	270.5
A	983.0	273.0
B	989.8	282.8
C	1010.0	283.0

(b) Flow-rate values

Cryogen	Flow rate, point B, lb/hr	Flow rate, point C, lb/hr
Oxygen	3.0	26.0
Hydrogen	.69	6.0

TABLE II.- HEATER CONTROL ACCORDING TO TEST PROCEDURES

g.e.t., hr:min	Heater control		
	Tank 1	Tank 2	Tank 3
00:00	Automatic	Automatic	Off
11:10	Off	Off	Automatic
59:30	Automatic	Automatic	Off
65:10	Off	Off	Automatic
81:20	Automatic	Automatic	Off
162:10	Automatic	Off	Off
*168:10	Automatic	Off	Automatic
171:40	Off	Off	Automatic
**200:12	Automatic	Automatic	Off
216:12	Off	Off	Off

*Isolation valve to be closed from 168:10 to 171:40 g.e.t.

**This switchover is to occur when tank 3 quantity is 6 percent or less.

TABLE III.- HEATER CONTROL ACCORDING TO TEST DATA

g.e.t., hr:min	Heater control		
	Tank 1	Tank 2	Tank 3
00:00	Automatic	Automatic	Off
11:10	Off	Off	Automatic
59:10	Automatic	Automatic	Off
65:10	Off	Off	Automatic
81:20	Automatic	Automatic	Off
*115:30	Off	Automatic	Off
**133:00	Automatic	Off	Automatic
136:30	Off	Off	Automatic
*149:30	Off	Automatic	Off
181:30	Automatic	Automatic	Off
216:12	Off	Off	Off

*Started tank 1 and 2 quantity balance.

**Isolation valve closed at 133:00 and opened at 136:30 g.e.t.

TABLE IV.- PRELIMINARY POSTMISSION ANALYSIS OF HYDROGEN AND OXYGEN

Cryogen	Premission prediction, lb	Actual remaining, lb
Oxygen	[a]433.1 (1.2)	438.1
Hydrogen	[a]14.8 (3.0)	15.25

[a] Percent deviation, $\frac{P - A}{P}$.

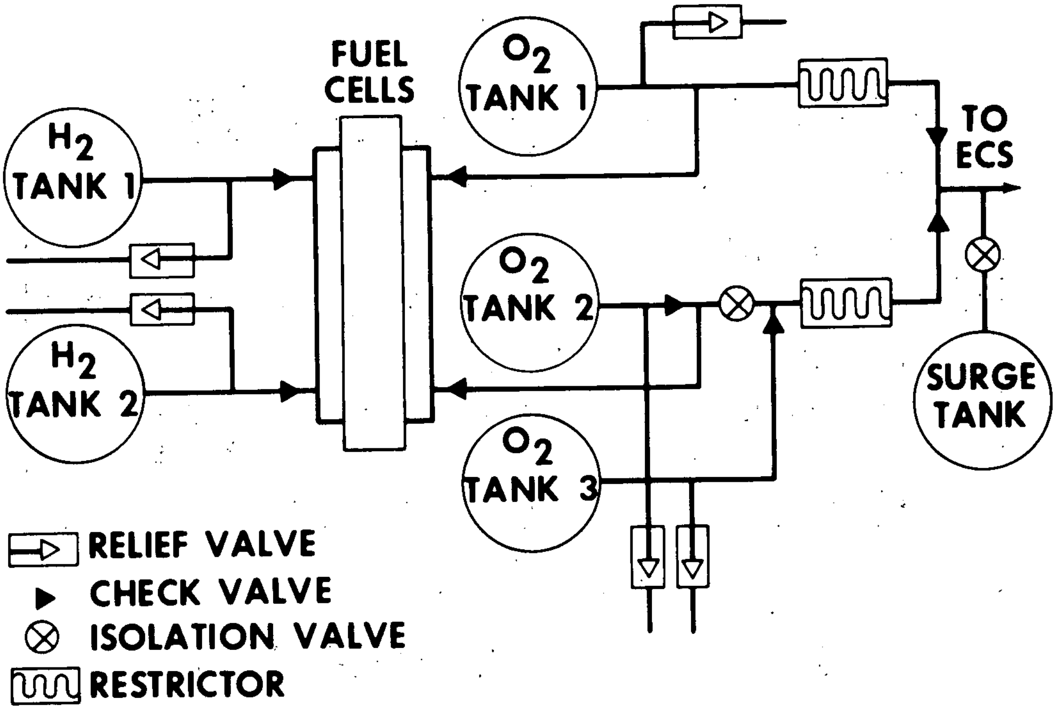


Figure 1.- Apollo 14 storage and delivery system.

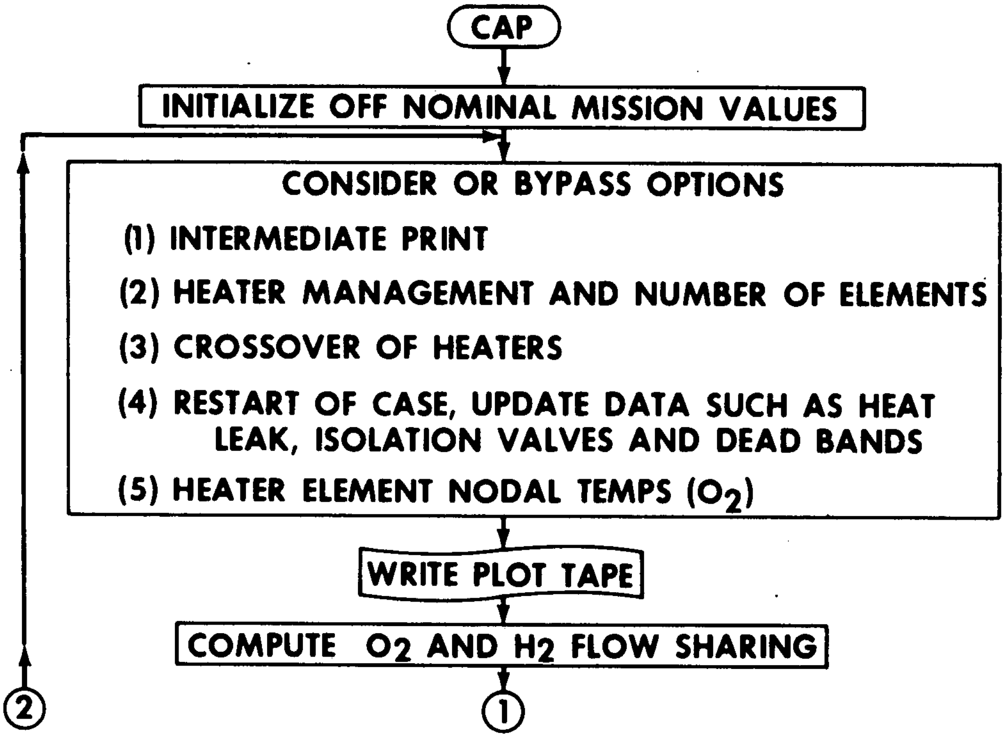


Figure 2.- Simplified flow diagram of the CAP logic.

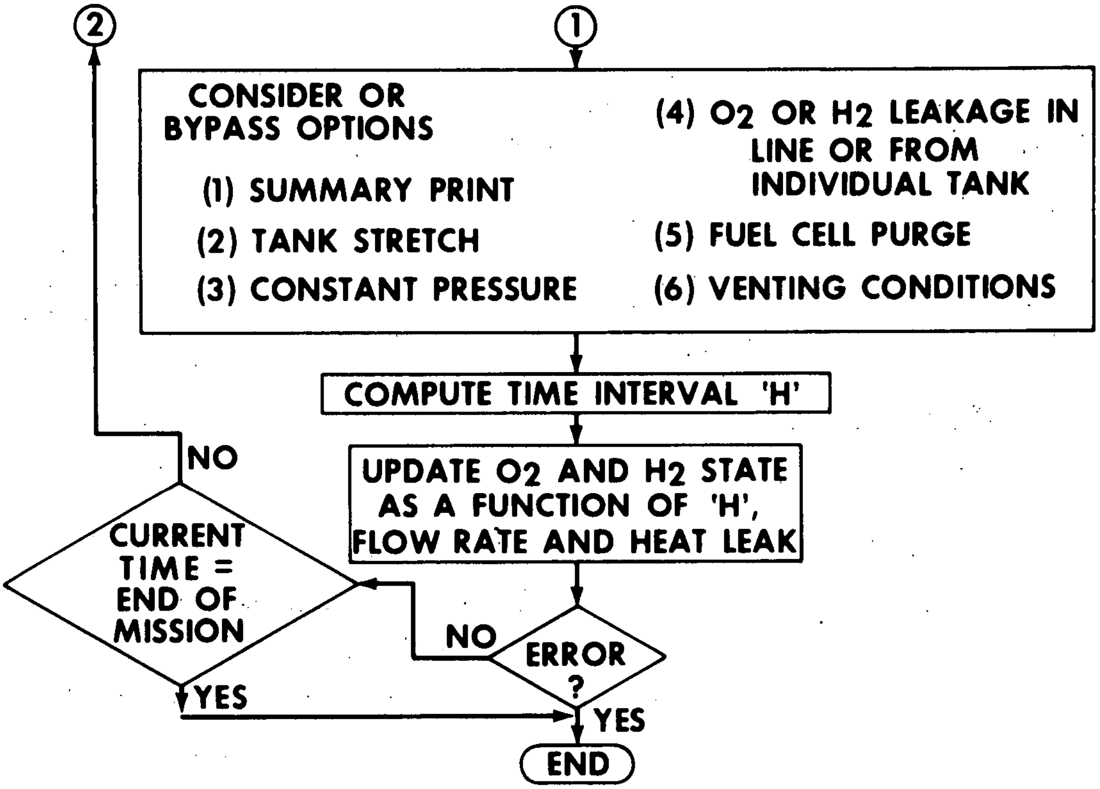


Figure 2.- Concluded.

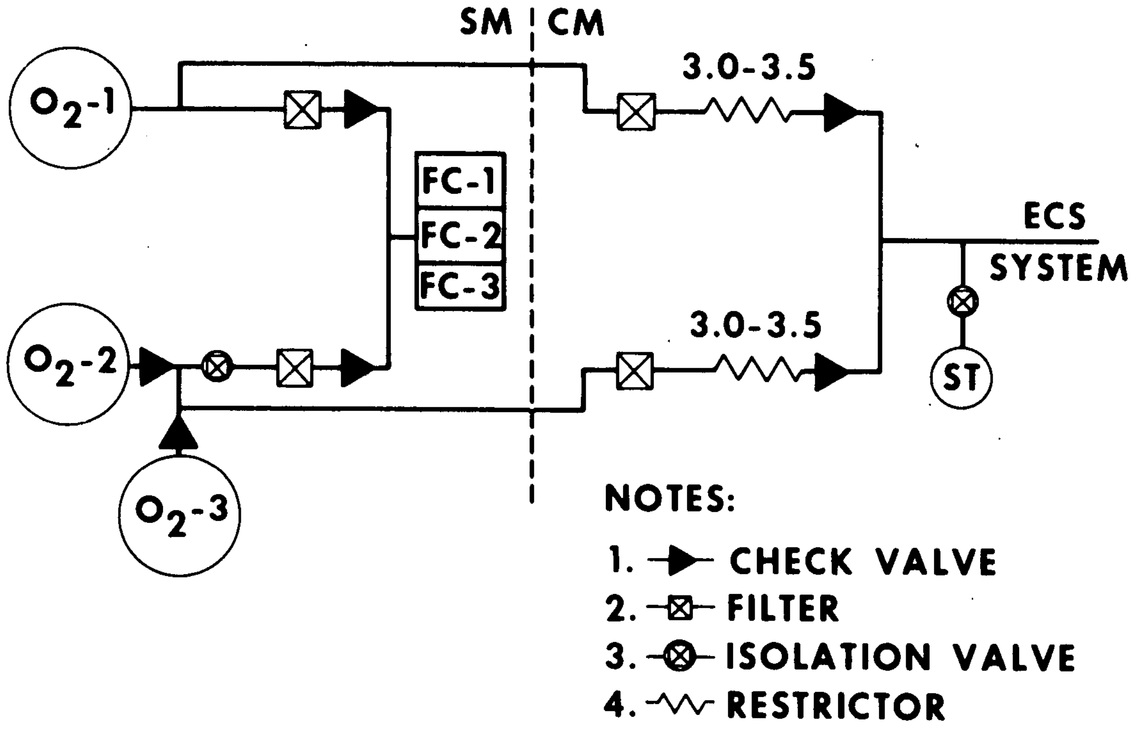


Figure 3.- Simplified oxygen delivery system.

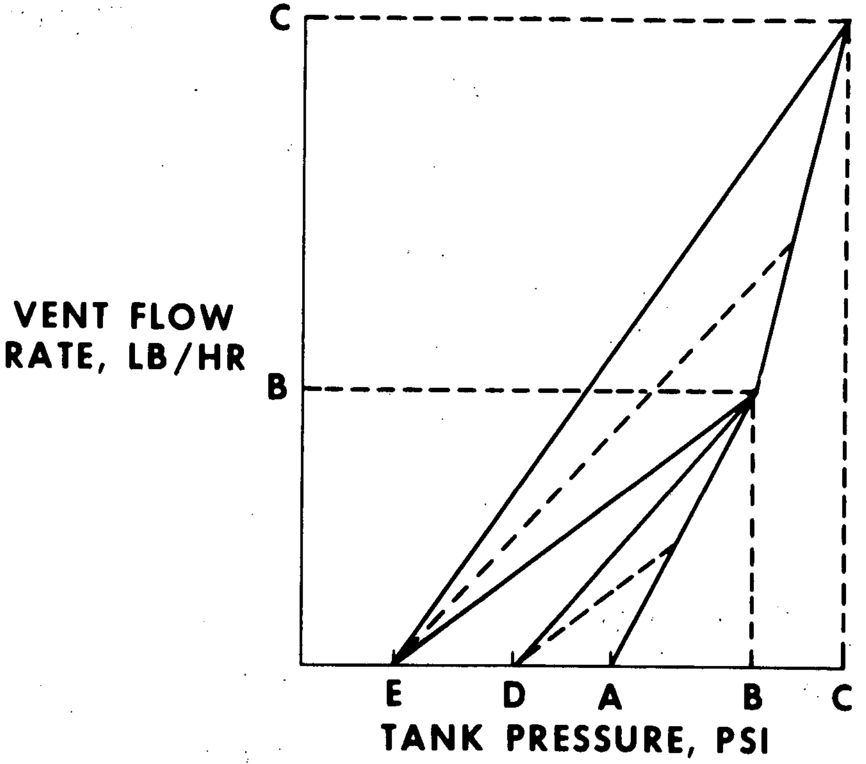
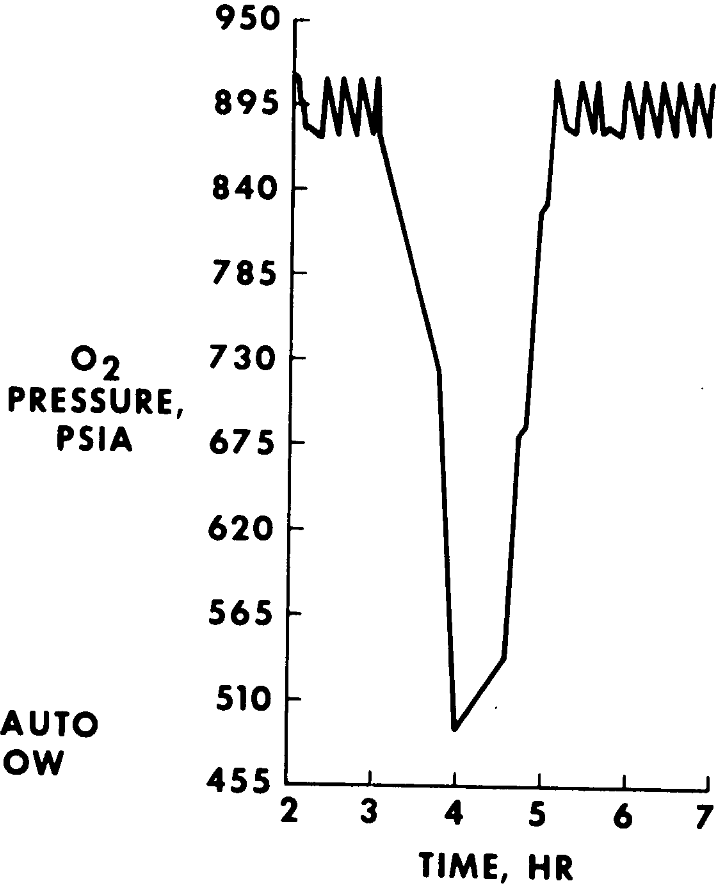


Figure 4.- Apollo CSM vent-valve characteristics.



NOTE:
ALL TANKS IN AUTO
(3-4 HR) ECS FLOW
6.5 LB/HR

Figure 5.- Oxygen tank 1 pressure collapse.

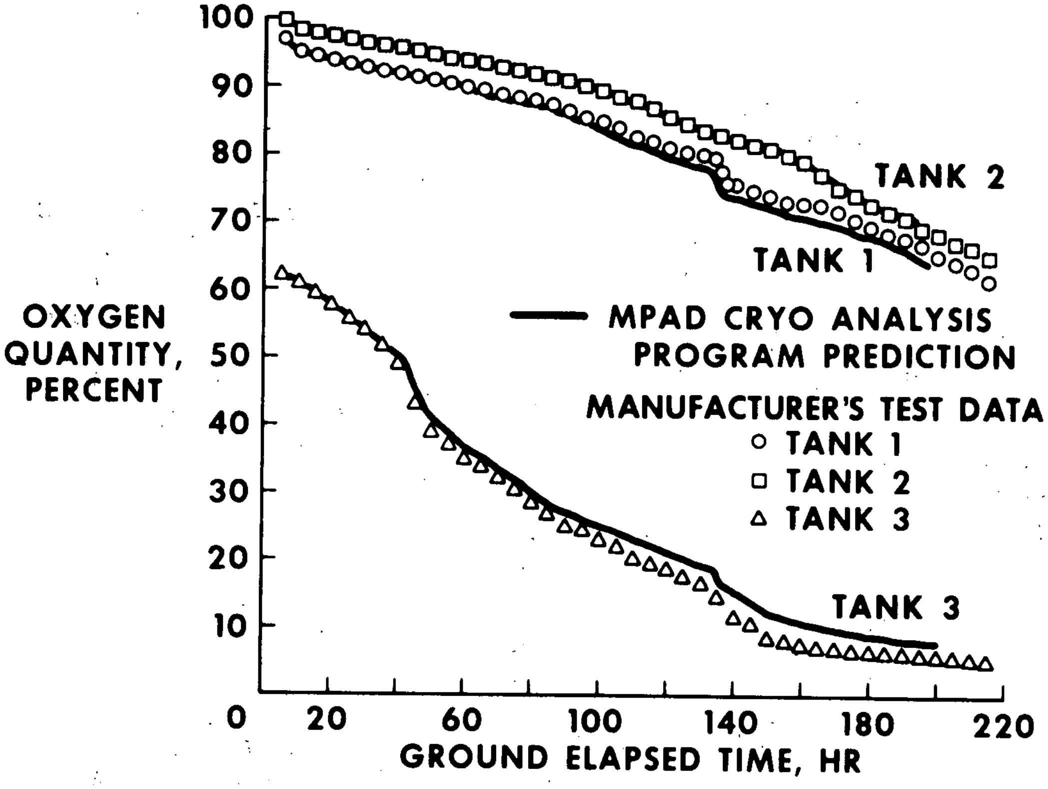


Figure 6.- Comparison of manufacturer test data to the CAP computer prediction model.

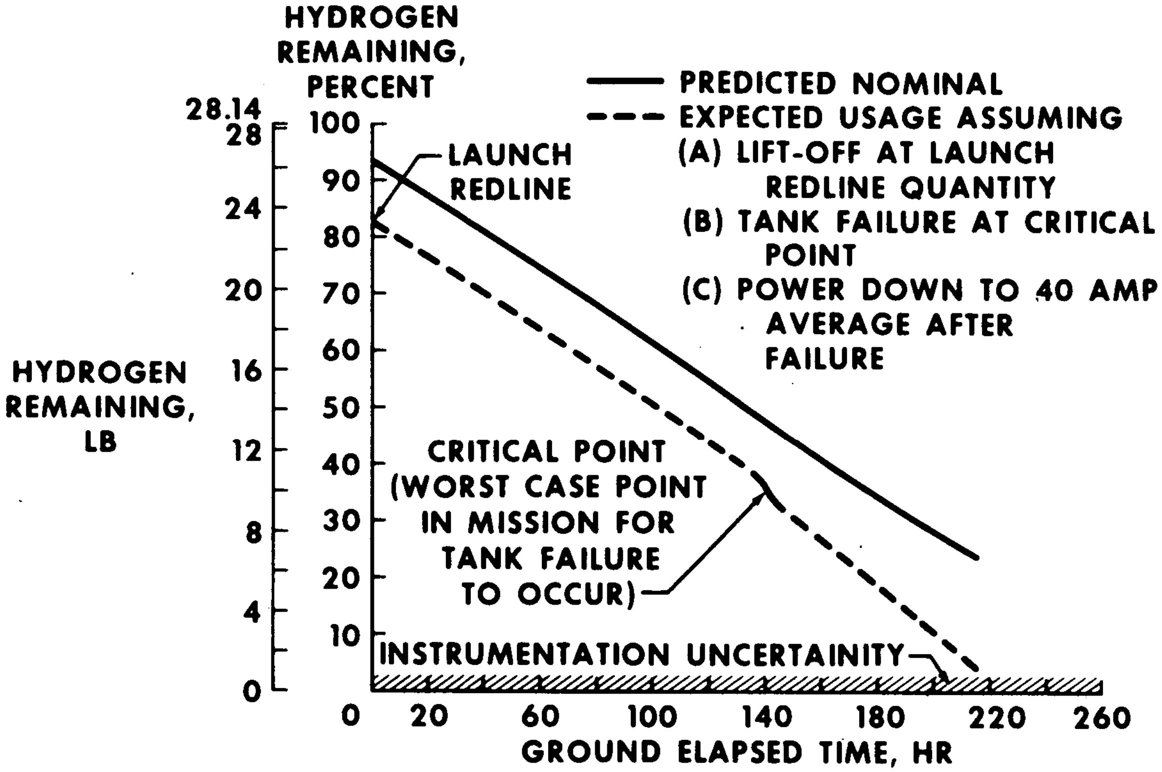


Figure 7.- Hydrogen remaining in one tank of the CSM.

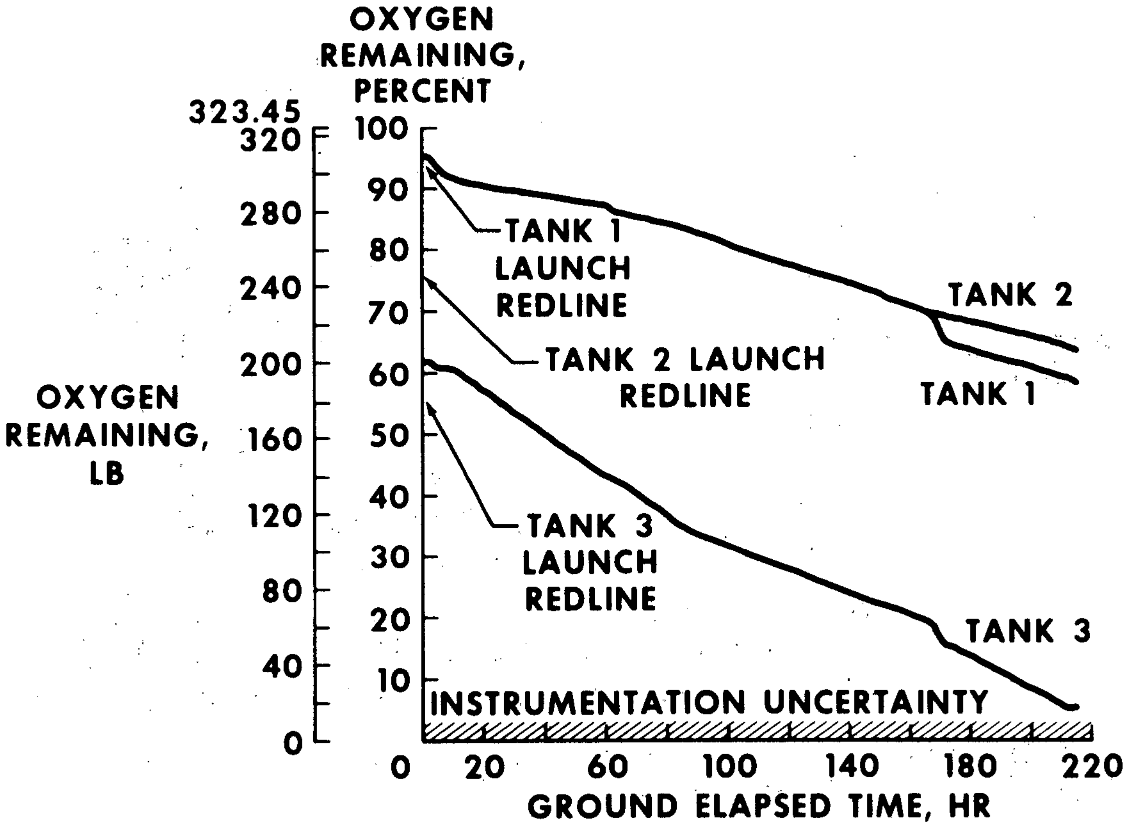
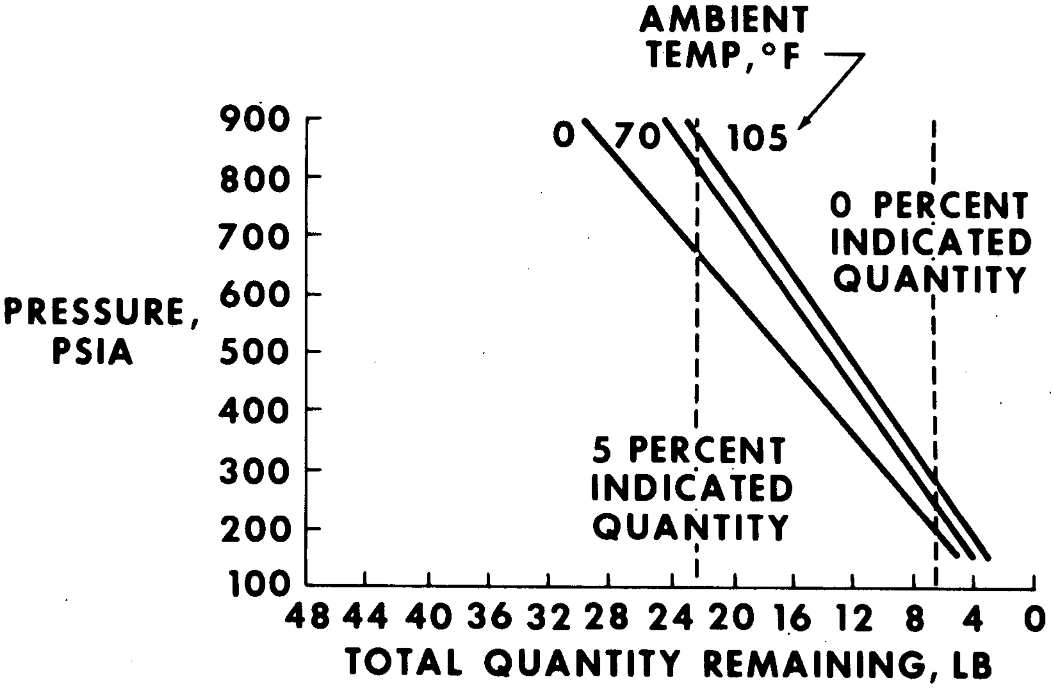


Figure 8.- Oxygen remaining in the CSM.



TANK TEMPERATURE = AMBIENT AT 900 PSI
HEAT LEAK = 0 Btu/HR
NO HEATERS

Figure 9.- Oxygen blowdown capability.

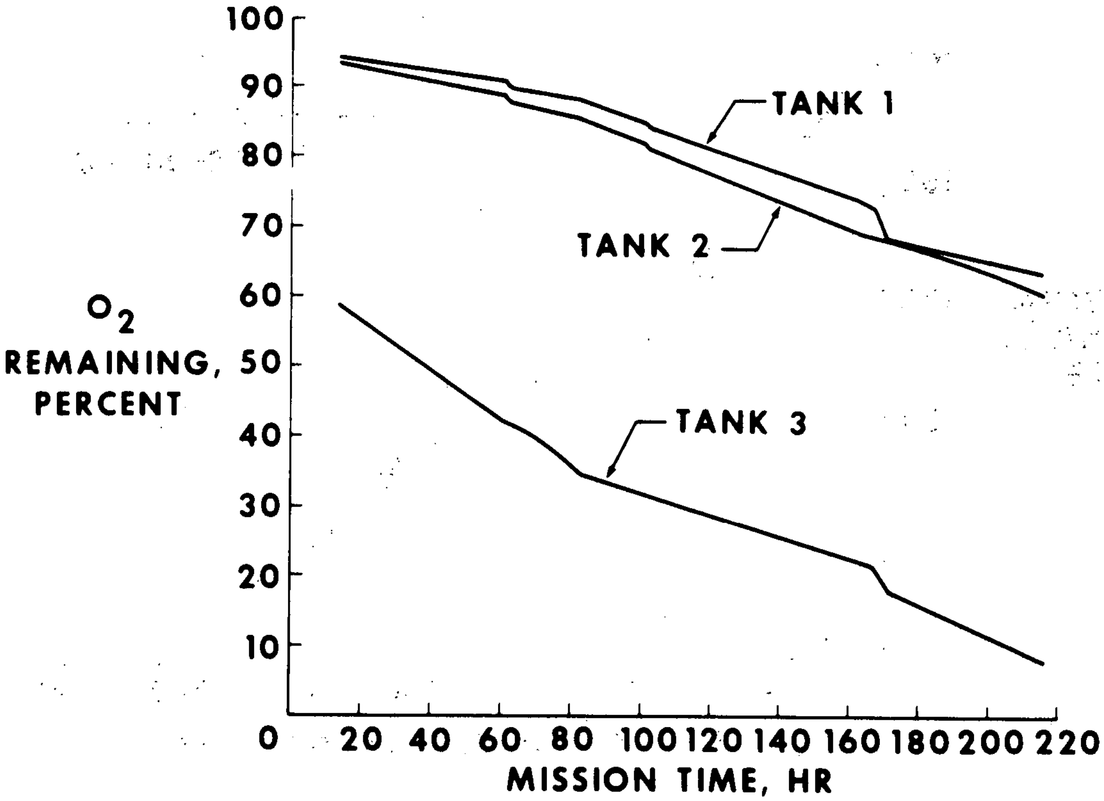


Figure 10.- Oxygen remaining in tanks 1, 2, and 3 of the Apollo 14 spacecraft.

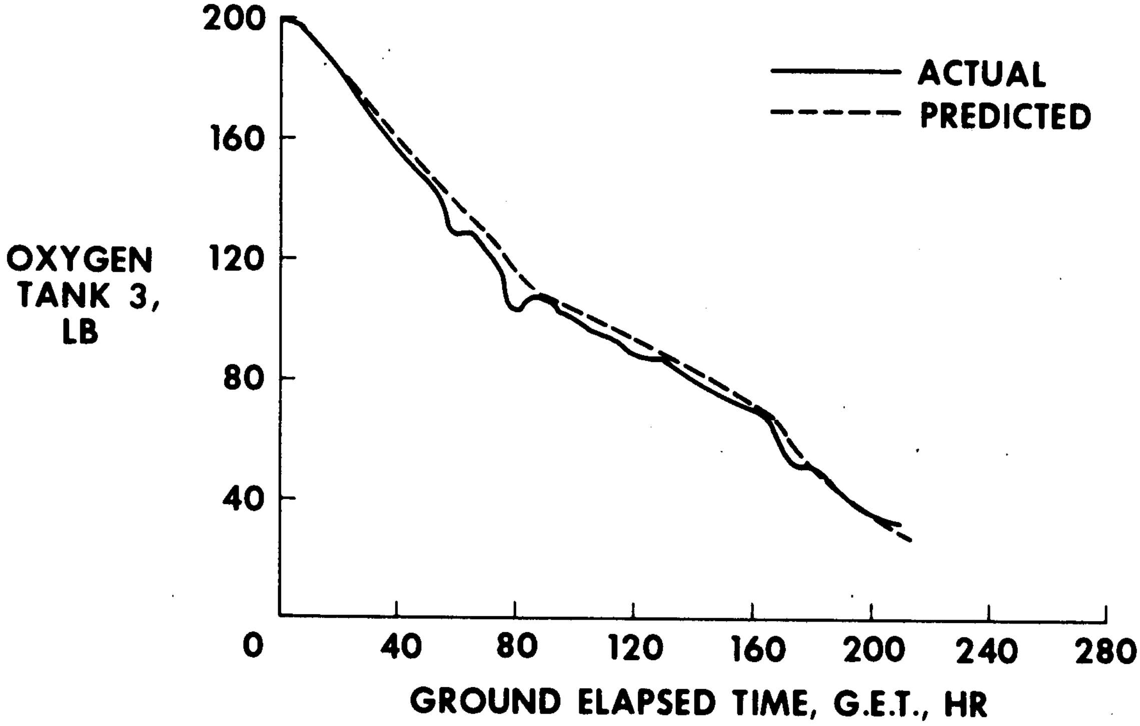


Figure 11.- Depletion profile for Apollo 14 oxygen tank 3.