Conclusion

General expressions are provided that permit the determination during re-entry of the total angle-of-attack $\bar{\delta}$ and the total lateral rate $\bar{s}$ of a vehicle performing nearly circular motion, if the histories of such trajectory parameters as relative velocity, flight path angle, and the pitching moment coefficient slope of the vehicle are known. With certain simplifying assumptions that are reasonable for many high ballistic-coefficient vehicles, approximate solutions are obtained that simulate the nominal behavior of $\bar{\delta}$ and $\bar{s}$ in a satisfactory manner.

References

[1] Lotkin, M., "Determination of Angle of Attack from Rotational Body Rates," *Journal of Spacecraft and Rockets*, Vol. 4, No. 10, Oct. 1967, pp. 1333–1338.

[2] Allen, H. J., "Motion of a Ballistic Missile Angularly Misaligned with the Flight Path Upon Entering the Atmosphere and its Effect Upon Aerodynamic Heating, Aerodynamic Loads, and Miss Distance," TN 4048, Oct. 1957, NACA.

Probability of Rescue in Emergency Return Missions

S. T. Chu* and A. R. Nagy Jr.†
Aerospace Corporation, El Segundo, Calif.

Nomenclature

f_c = specific fuel consumption for aircraft cruising (for round trip from and back to the recovery aircraft station, twice the value of the conventional-cruising specific fuel consumption in lb/hr)
f_L = specific fuel consumption for aircraft loitering
K = kernel function defined in Eq. (10)
p = return probability
p_{SR} = probability of successful rescue operation (assuming unit reliability of pickup)
r = search radius, measured along a great circle arc
r_a = $V_a(t_E + t_1)$
r_{a1} = $V_a(t_E + t_{w1} - t_D)$
r_{a2} = $[V_a f_L/(f_c - f_L)][(w_f/f_L) + t_d - t_E - t_1]$
r' = intersection of $t_{s1}\{r\}$ and $t_{s2}\{r\}$ in which the portion of t_{s1} lying below zero is replaced by $t_{s1} = 0$
R = maximum range of rescue aircraft = $V_a t_{cmx}$
t_1 = allowable in-orbit waiting time
t_c = aircraft cruising time; $t_{cmx} = (w/f_{cf})$
t_d = takeoff delay time of rescue aircraft, time between decision-to-return and aircraft takeoff
t_E = spacecraft reentry time
t_L = aircraft loiter time; $t_{Lmx} = (w_f/f_L)$
t_θ = orbital period
t_s = spacecraft waiting time
t_{s1},t_{s2} = defined in Eqs. (8) and (9), respectively
t_w = water immersion time; t_{w1} = allowable water immersion time of spacecraft
V_a = cruising speed of rescue aircraft
w_f = total fuel available for rescue aircraft for cruising and loitering
θ = orbital inclination

Received January 8, 1970; revision received March 2, 1970. This work was performed for the Space and Missile Systems Organization, Air Force Systems Command, under Contract F04701-69-C-0066.

* Director, Resource and Systems Analysis Office, Systems Planning Division. Associate Fellow AIAA.

† Member of Technical Staff, Resource and Systems Analysis Office, Systems Planning Division. Member AIAA.

Introduction

A successful rescue of spacecraft or an escape capsule requires that the spacecraft returns from orbit to one of the recovery areas and that the rescue aircraft locates the spacecraft and picks up the distressed astronauts at the splash point; i.e., matching a time sequence for the spacecraft with a corresponding time sequence for the rescue aircraft. This Note summarizes a method of analysis[1] that will aid in 1) determining design criteria for spacecraft, 2) tradeoff studies in recovery planning, 3) establishment of requirements for recovery forces, and 4) selection of recovery sites. Sample results are included.

Probability of Rescue Success

Let us consider a ring on the Earth's surface formed by the difference between two concentric recovery circles of radius r and $r + dr$. The return probability of a spacecraft to this ring or a collection of such rings for multiple recovery stations within an allowable in-orbit waiting time, t_1, is given by

$$dp(r,t_1) = p(r + dr,t_1) - p(r,t_1) \tag{1}$$

where r is the limiting recovery radius measured along an Earth great circle arc. This definition implicitly assumes successful deorbit and re-entry. For a specific return operation, the recovery radius will take a value between 0 and r and the actual in-orbit waiting time t_s will lie between 0 and t_1 depending upon the position of the spacecraft at the time of return decision.

The individual elements of a rescue operation and their interactions may best be appreciated by examining a time sequence of the operation; for the spacecraft this sequence includes t_s, the time of re-entry from deorbit to splashdown t_E, and the water immersion time t_w, whereas for the rescue aircraft it includes the delay time t_d, the cruise time t_c, and the loiter time t_L. The re-entry time, t_E, may be considered as a fixed quantity determined by the orbit altitude, spacecraft characteristics, and re-entry conditions, and t_w varies between zero and its allowable t_{w1}; thus,

$$t_E = \text{fixed},\ 0 \le t_s \le t_1,\ 0 \le t_w \le t_{w1} \tag{2}$$

For the rescue aircraft, the t_d may be attributable to the time for sending messages of return decision to the recovery force and the alert time for aircraft takeoff; t_c and t_L are varying quantities and are related to each other through a fixed amount of fuel carried by the aircraft

$$w_f = f_c t_c + f_L t_L = \text{fixed} \tag{3}$$

Since the specific fuel consumption for loitering, f_L, is expected to be smaller than that for cruise, f_c, the limits within which t_c and t_L can vary are, therefore, different and are given by

$$0 \le t_c \le t_{cmx} \qquad 0 \le t_L \le t_{Lmx} \tag{4}$$

where $t_{cmx} = w_f/f_c$ and $t_{Lmx} = w_f/f_L$. For a successful rescue operation, two conditions must be met: the aircraft must arrive at the splash point no later than a fixed t_{w1} hr after the spacecraft splashes into the water and, if the rescue aircraft arrives at the splash point first, it must loiter about this location until the spacecraft splashes down; i.e.,

$$t_c + t_d \le t_s + t_E + t_{w1} \tag{5}$$

$$t_c + t_d + t_L \ge t_s + t_E \tag{6}$$

By using Eq. (3), the inequality of Eq. (6) may be written as

$$t_c + t_d + w_f/f_L - t_c f_c/f_L \ge t_s + t_E \tag{7}$$

Two varying quantities, t_c and t_s, play different roles in the analysis; t_c may be considered as an independent variable, and for a specific value of t_c, the probability of successful

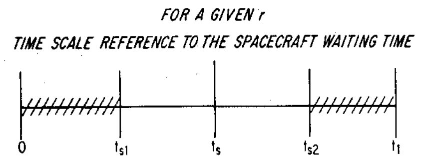

Fig. 1 Time scale reference to the spacecraft waiting time.

rescue operation, p_{SR}, may be determined by spanning t_s over the time interval 0 to t_1 subject to Eqs. (5) and (7), which can be recast as

$$t_s \geq (t_c + t_d - t_E - t_{w1}) \triangleq t_{s1} \tag{8}$$

$$t_s \leq t_c + t_d - t_E + (w_f/f_L) - t_c f_c/f_L \triangleq t_{s2} \tag{9}$$

The probability of return of a spacecraft to the ring areas $(r, r + dr)$ with a successful rescue operation may be represented by

$$dp_{SR}(r,t_1) = K(r,t_1)dp(r,t_1) \tag{10}$$

because the return of spacecraft to the ring areas and the relative arrival time to the splash point of the spacecraft and the rescue aircraft are two independent events. In Eq. (10), $dp(r,t_1)$ is known because $p(r,t_1)$ can be determined.[2] The solution for kernel function $K(r,t_1)$ can be developed by the distribution of successful rescue operations along a time scale with reference to the spacecraft waiting time in orbit.

In Fig. 1, t_{s1} and t_{s2} are functions of t_c as defined in Eqs. (8) and (9). Since t_c is directly related to the aircraft range r by $r = V_a t_c$, the quantities t_{s1} and t_{s2} can also be transformed into linear functions of r. With a given t_c, the rescue operation will be successful when $(t_{s1} \leq t_s \leq t_{s2})$. It can be easily shown that $(t_{s2} - t_{s1})$ represents $(t_{w1} + t_L)$ and therefore is always positive. However, t_{s1} can be larger or smaller than zero, while t_{s2} can be larger or smaller than t_1. Because $0 \leq t_s \leq t_1$, the value of t_{s1} should be replaced by t_1 when it is larger than t_1. Consequently,

$$K(r,t_1) = (\delta_{00}t_{s2} - \delta_0 t_{s1})/t_1 \tag{11}$$

where δ_0 and δ_{00} are kronecker deltas

$$\delta_0 = \begin{cases} 0 \text{ when } t_{s1} \leq 0 \\ 1 \text{ when } t_{s1} > 0 \end{cases} \qquad \delta_{00} = \begin{cases} (t_1/t_{s2}) \text{ when } t_{s2} \geq t_1 \\ 1 \qquad\quad \text{ when } t_{s2} < t_1 \end{cases} \tag{12}$$

The physical meaning of introducing these kronecker deltas is as follows:

a) A negative value of t_{s1} implies that $(t_E + t_{w1}) > (t_c + t_d)$; i.e., the rescue aircraft, with cruising range equal to or smaller than r_{a1}, can always arrive at the splash point within t_{w1} hr after the spacecraft splashdown, where

$$r_{a1} = V_a(t_E + t_{w1} - t_d) \tag{13}$$

is determined by setting $t_{s1} = 0$.

b) When $t_{s2} \geq t_1$, the aircraft with $r \geq r_{a2}$ can always arrive at the splash point first and loiter until the time of rescue operation, where

$$r_{a2} = [V_a f_L/(f_c - f_L)][(w_f/f_L) + t_d - t_E - t_1] \tag{14}$$

Four different forms of $K(r,t_1)$ are possible, depending upon the range of $t_{s1}(r)$ relative to zero and the range of $t_{s2}(r)$ relative to t_1. The expressions of t_{s1} and t_{s2} are defined in Eqs. (8) and (9) as functions of t_c and can be converted into functions of r because $r = V_a t_c$. Of these forms, there are subcases depending upon the relative magnitude of r' and r_{a1}, r' and r_{a2}, r_{a1}, and r_{a2}, where r' denotes the value of r for the intersection of $t_{s1}(r)$ and $t_{s2}(r)$. In determining this intersection, the portion of t_{s1} below zero is replaced by $t_{s1} = 0$. The various forms of K may be classified as in Table 1 and are delineated in Ref. 1. A limitation resulting from the maximum range of the rescue aircraft, R, should be included: K always becomes zero when $r > R$. A typical sample applicable to Case I is given in Fig. 2.

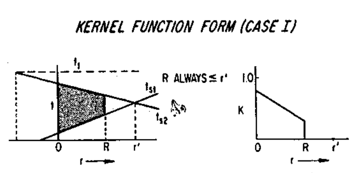

Fig. 2 Kernel function form (case I).

Once the appropriate form of K is selected, the probability of successful rescue operations can be determined by integrating Eq. (10). For Case I, the resulting expressions read

$$p_{SR}(r,t_1) =$$

$$1/t_1 \left\{ Ap(r,t_1) + B\left[rp(r,t_1) - \int_0^r p(r,t_1)dr \right] \right\} \qquad r \leq R$$
$$p_{SR}(r,t_1) = p_{SR}(R,t)_1 \qquad r > R \tag{15}$$

where $A = t_{w1} + (w_f/f_L)$ and $B = -f_c/(V_a f_L)$.

One additional consideration is the variable delay provision for the rescue aircraft. In many cases of rescue, an aircraft takeoff delay time t_d is mandatory because of operational limitations. When the waiting time in orbit is long, it is advantageous to employ a variable delay (t_{dv}) concept, in which $t_{dv} \geq t_d$, to increase p_{SR} through a reduction of the required t_L. For spacecraft returning before t_{s1}, the aircraft will still not be able to arrive at the splash point soon enough for a successful rescue; however, if the spacecraft returns after t_{s2}, the aircraft can remain on the ground, conserving fuel which would otherwise be expended in loitering at the splash point. Under this condition, the region between t_{s2} and t_1, as shown in Fig. 1, becomes admissible for successful rescue. Moreover, the K for variable delay can be constructed from that corresponding to a fixed delay by replacing t_{s2} by t_1.

Sample Results

The analysis was applied to a planning study[4] that considered five sites: Hawaii; Tachikawa, Japan; Kindley, Bermuda; Lajes, Azores; and Hamilton Air Force Base, Calif. The orbital altitude was selected as 300 naut miles, while the inclination varied from 30° to 90°. Moreover, the effects of time constraints were assessed by comparing day-night return (24-hr recovery) and return during daylight only. The rescue operations were assumed to be carried out by the ARRS (Aerospace Rescue and Recovery Service) using both the HH-53 helicopter and the HC-130H airplane. For the latter, which in most cases would perform the search and rescue operations, the following are used herein: w_f = 86,270 lb, V_a = 270 knots, f_c = 11,720 lb/hr, f_L = 5200 lb/hr. These characteristics give an R of nearly 2000 naut miles. Other parameters used were: t_E = 0.5 hr, t_d = 0–4 hr, t_{w1} = 0–24 hr.

The HC-130H would cruise to the expected splash point, loiter if necessary, and search for the returned spacecraft.

Table 1 Classification of kernel function

Cases	Conditions		
I	$t_{s1} \geq 0$ and $t_{s2} \leq t_1$		
IIa	$t_{s1} \lesseqgtr 0$ and $t_{s2} \leq t_1$	$r' < r_{a1}$	
IIb		$r' \geq r_{a1}$	
IIIa	$t_{s1} \geq 0$ and $t_{s2} \lesseqgtr t_1$	$r' < r_{a2}$	
IIIb		$r' \geq r_{a2}$	
IVa	$t_{s1} \lesseqgtr 0$ and $t_{s2} \lesseqgtr t_1$	$r_{a2} > r_{a1}$	$r' < r_{a2}$
IVb			$r' \geq r_{a2}$
IVc		$r_{a2} < r_{a1}$	$r' < r_{a2}$
IVd			$r' \geq r_{a2}$

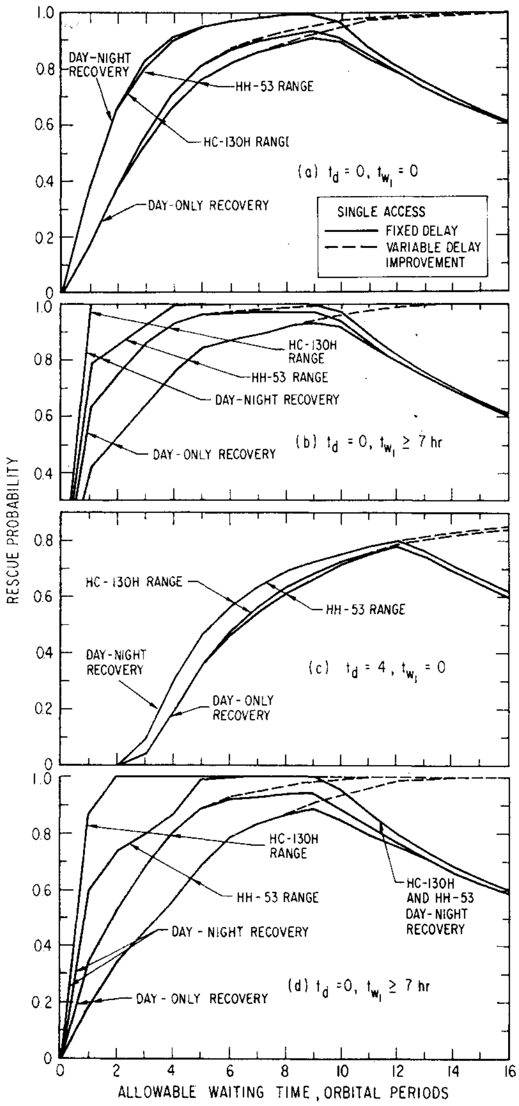

Fig. 3 Recsue probabilities ($\theta = 30°$).

Once it is located, paramedics with survival gear would drop into the water by parachute. The rescue will be assumed to be complete as soon as the paramedics have access to the astronauts. Two modes of astronaut retrieval are possible. The first would involve transfer of the astronauts to the HC-130H by a surface-to-air snatch with the Fulton gear. This mode is the least preferred, because it may not be applicable to an injured astronaut. The second mode would be to retrieve the astronauts with an HH-53 helicopter which would follow the HC-130H. However, the unrefueled range of the helicopter is limited, requiring that it be refueled with an HC-130P tanker. Since the search in both modes is performed by the HC-130H, the use of the helicopter affects the problem only by reducing R from that corresponding to the HC-130H (2000 naut miles) to about 900 naut miles. This latter figure was obtained by examining the maximum fuel load of the HC-130P tanker and the duty time for the crew of the HH-53.

Extensive training has been conducted by the ARRS in search and rescue with the HC-130H and considerable experience has been gained in the recovery operations for the Mercury, Gemini, and Apollo programs; therefore, a very high operational reliability can be assumed. The over-all success of an emergency return mission with water recovery can be considered to be most strongly affected by a rescue probability. An important consideration which eases the rescue operations is to have the search aircraft at the expected splash point prior to spacecraft impact. This, of course, corresponds to the case of $t_{w1} = 0$ in the rescue operation.

Sample results are given in Fig. 3. Significant differences in p_{SR} between day-night and day-only recovery are obvious. The p_{SR} for HC-130H retrieval is greater than or equal to that for helicopter HH-53 retrieval; their curves diverge after a few waiting orbits but eventually converge at a longer allowable waiting time when the return probability becomes unity for the maximum radius related to helicopter retrieval. The more significant difference between the two retrieval modes (day-only vs day-night) occurs for long t_{w1}, which permits the HC-130H to use more effectively the potential recovery areas near the maximum search radius, because sufficient t_c is available.

Figure 3a was constructed for $t_d = 0$ and $t_{w1} = 0$. If the HH-53 is to be used for day-night retrieval of the astronauts, an in-orbit waiting time t_l of 4 orbital periods ($4t_0$) must be allowed to achieve 90% probability of early aircraft arrivals, whereas $t_l = 9t_0$ must be allowed for day-only retrieval under otherwise identical constraints.

Figure 3b is for the same conditions as Fig. 3a except that t_{w1} is permitted to reach its asymptotic maximum. If an assured rescue by HH-53 is desired ($p_{SR} = 1.0$), t_l's of $5t_0$ and $13t_0$, respectively, must be allowed for day-night retrieval and day-only retrieval. Moreover, variable delay of aircraft takeoff is necessary for the day-only recovery for assured rescue. In comparison, the curves in Fig. 3c for $t_d = 4$, $t_{w1} = 0$, are significantly lower than the other cases. A wait of 4 hr not only eliminates the possibility of rescue during the first two orbits but also reduces the possibility of rescuing the crew of spacecraft for longer allowable waiting times. Consequently, p_{SR} does not even approach 90% after an allowable waiting of 16 orbits.

If $t_d = 4$ hr were imposed on the rescue recovery operations because of system constraints, a more efficient approach would be to require the spacecraft to remain in orbit during the 4 hr and not permit deorbit until the t_d has lapsed. The curve of rescue probability could be constructed from the results for $t_d = 0$ by adding 4 hr, i.e., 2.5 orbits, to the abscissa. A comparison of Figs. 3a and 3c indicates that the rescue probability can be greatly enhanced by this approach.

Although the results discussed so far are restricted to single access in which the spacecraft would return to the first accessible site, the possibility of adverse weather or sea states suggest that provision be made to include these possibilities in planning studies. Consequently, results of p_{SR} for the second-degree redundant access are shown in Fig. 3d for $t_d = 0$, $t_{w1} \geq 7$ hr. The difference from Fig. 3b is chiefly an effect of return probability. The rescue probability, as expected, is lower than for the corresponding case of single access. When day-only recovery is considered, the redundant case is more affected by the retrieval method than the single access case.

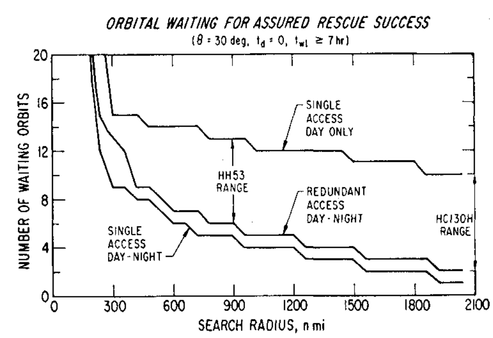

Fig. 4 Orbital waiting for assured rescue success.

An apparent anomaly is visible in Fig. 3d at the point where $t_1 = 5t_0$; the curve takes an uneven jump because of the particular locations of the recovery sites used. These recovery sites generate belts[2] which are almost coincidently overlapping on the fifth waiting orbit. For example, the belts of the fifth waiting orbit of Tachikawa, Hawaii, and Hamilton fall on the belts of the first waiting orbit of Hamilton, Kindley, and Lajes, respectively, thus resulting in a big jump in p and p_{SR} for redundant access.

An assured rescue represents a desired goal of all rescue operations. The required t_1 for this condition is shown in Fig. 4 as a monotonically decreasing function of the increasing search radius. The results of assured rescue for the case of single access and day-night retrieval are given by the lower curve. As shown by the middle curve, the penalty of redundant access is found to be relatively modest, amounting to one or two additional waiting orbits for any search radius larger than 400 naut miles. The penalty of day-only retrieval, on the other hand, is much larger as shown by the upper curve. The day-only retrieval is based on an average December day which imposes the most severe local time constraint among all the months in a year.

Concluding Remarks

The results of this analysis as presented in this Note and the more extensive ones in Refs. 1 and 4, lead to a number of significant observations:

1) Since the reliability of water recovery operations can be expected to be high, the over-all rescue success is very strongly affected by the rescue probability p_{SR} as defined in this analysis.

2) Although the more preferred means of retrieval from the standpoint of astronaut comfort and safety may be with the refueled HH-53 helicopter, a significant reduction in p_{SR} may occur.

3) A significant difference in p_{SR} exists between day-only and day-night recovery. Adverse weather or sea states can reduce the p_{SR} as evidenced by the difference between single and redundant access. For assured rescue, the penalty of redundant access amounts to an additional one or two waiting orbits.

4) The provision for a variable takeoff delay can improve p_{SR}, but only if t_1 is greater than 6 orbital periods. An aircraft takeoff delay, during which the spacecraft is permitted to deorbit, can cause very serious reductions in p_{SR}. A more desirable approach would be to provide for an intentional deorbit lag to compensate for the time of aircraft takeoff delay, t_d.

5) The lower extreme of allowable water immersion time, $t_{w1} = 0$, refers to the case in which the search aircraft must be at the expected splash point before the spacecraft. This is a necessary requirement for a successful rescue being made by the air-pickup mode. Although this condition may not be necessary for the water pickup mode, the chances of personnel on-board the aircraft visually locating the returning spacecraft are improved. The second extreme of $(t_{w1} - t_d) = R/V_a$ hr refers to a t_{w1} that will increase p_{SR} to its maximum. Increasing t_{w1} beyond this point does not increase p_{SR}.

6) Sufficient t_{w1} and t_1 must be provided in the design of spacecraft for an assured rescue ($p_{SR} = 1.0$). In addition, a high p_{SR} for $t_{w1} = 0$ is very desirable.

References

[1] Chu, S. T. and Nagy, A. R., Jr., "Probability of Rescue Success of Emergency Return of Spacecraft," TR-0066(5758-06)-1, (in preparation), Aerospace Corp., El Segundo, Calif.

[2] Chu, S. T. and Davis, K. S., "Multiple Site Return Probability of Spacecraft from Circular and Elliptical Orbits," *Journal of Spacecraft and Rockets*, Vol. 5, No. 4, April 1968, pp. 419–424.

[3] Chu, S. T. and Nagy, Jr., A. R., "Inclusion of Time Constraints and Redundant Access on Spacecraft Return Probabilities by the Concept of Borel Set," *Journal of Spacecraft and Rockets*, Vol. 6, No. 6, June, 1969, pp. 667–772.

[4] Nagy, Jr., A. R., "Orbital Return Probabilities of Escape Spacecraft," TOR-0200(4525-04)-2, Feb. 1969, Aerospace Corp., El Segundo, Calif.

Effects of Simulated Venusian Atmosphere on Polymeric Materials

S. H. KALFAYAN* AND R. H. SILVER†
Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, Calif.

POLYMERIC materials (plastics and rubbers) serve as electrical and thermal insulators, protective and structural materials, vibration dampeners, adhesives, etc., on spacecraft and planetary landing probes. In 1967, Venera 4 entered Venus's atmosphere and sent back information about temperature, pressure, and atmospheric composition, as it descended to the surface,[1,2] and Mariner V flew by Venus and reported back atmospheric data, among other information.[3] This Note reports results of exposure of polymeric materials to a simulation of the Venusian atmosphere, which was reported to be composed as follows, in weight percentages: CO_2, 90 ± 10 (probably >90); O_2, 0.4–1.6 (probably ~1); N_2, <7 (probably <2.5); and H_2O, 0.1–0.7. The effects of the simulated "Venus" atmosphere, also are compared with those of air and nitrogen at 550°F and ca. 18 atm.

Experimental

The simulation chamber was a 10-in.-diam by 12-in.-long stainless steel, cylindrical tank. Ports on each side of the cylinder served as gas inlet and outlet. Stainless-steel sheathed, copper-constantan thermocouples were inserted near each port. The front cover plate, as originally supplied by the manufacturer, had an asbestos-graphite gasket seal which proved inadequate and was replaced by a ⅛-in. thick Teflon disk with the same diameter as the cover plate. The disk could be used for several runs at the test conditions, without significant distortion or deterioration. Test specimens of polymeric materials were placed on two stainless steel shelves within the cylindrical tank.

The simulator was placed in a Conrad environmental chamber capable of heating it to the desired temperature and holding the temperature within the specified tolerance. It was then evacuated three successive times and purged with the test gas to eliminate residual air. During the fourth and final purging the gas pressure was brought to 50% of the required value, using the following mixture (wt %): CO_2, 96.7–99.5; H_2O, 0.1–0.7; O_2, 0.4–1.6; and N_2,

Received January 19, 1970; revision received February 18, 1970. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif., under Contract NAS7-100, sponsored by NASA.

* Group Supervisor, Polymer Section.
† Engineer, Polymer Section.