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APOLLO SOYUZ MISSION

ANOMALY REPORT NO. 1

TOXIC GAS ENTERED CABIN DURING EARTH LANDING SEQUENCE

National Aeronautics and Space Administration

LYNDON B. JOHNSON SPACE CENTER

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STATEMENT

Toxic gas entered the cabin during repressurization for 30 seconds from manual deployment of the drogue parachutes at 18 550 feet (5650 m) to disabling of the reaction control system at 9600 feet (2925 m).

EARTH LANDING SEQUENCE

Nominal Sequence

Nominal operation of the Apollo earth landing sequence for the Apollo Soyuz Test Project was for the crew to arm the sequencer pyrotechnic buses at 50 000 feet (15 240 m) altitude. At 30 000 feet (9145 m), the crew was to arm the automatic earth landing system (ELS) sequencer by positioning the two ELS switches to LOGIC and AUTO. As shown in figure 1, arming the earth landing system applies sense power to the 24 000-foot (7315-m) baroswitches. When the 24 000-foot baroswitches close, the sense power latches the ELS activate relay. This applies power to the reaction control system (RCS) disable relay and the 0.4-, 2.0-, and 14.0-second timers for the apex cover (forward heat shield), drogue parachutes, and main parachutes, respectively. Timeout of the 14-second timer applies power to the 10 000-foot (3050-m) baroswitches. Closure of the 10 000-foot baroswitches releases the drogue parachutes and deploys the main parachutes. Manual switches must be used to disable the reaction control system and deploy the parachutes if the redundant automatic system fails.

Actual Sequence

The crew was about 20 seconds late in arming the pyrotechnic buses, arming them at 37 000 feet (11 280 m) during the time-critical earth landing sequence. The right-seat crewman talked about the two ELS switches that arm the automatic earth landing sequencer at 30 000 feet (9145 m). The left-seat crewman did not acknowledge and the two switches were not thrown until 55 seconds later when the center-seat crewman called them out (fig. 2). Realizing that the drogue parachutes had not deployed automatically, the left-seat crewman switched to cue card backup procedures, manually jettisoning the forward heat shield and manually deploying the drogue parachutes. However, the reaction control system was not disabled manually (a backup function) by placing the RCS CMD switch in the OFF position. The nominal and actual earth landing trajectories and sequences are compared in figure 3.

Spacecraft control had not been returned to the stabilization and control system minimum-impulse mode at 90 000 feet (27 430 m). (In this control mode, the reaction control system responds only to manual commands.) Therefore, the spacecraft motions induced by the deployment of the drogue parachutes caused the guidance and control system to attempt to stabilize the spacecraft by issuing commands to the reaction control system thrusters. The thruster activity was vigorous and lasted for 30 seconds, being terminated when the left-seat crewman finally armed the automatic earth landing sequencer by throwing the ELS switches to LOGIC and AUTO. This action operated the RCS disable relay.

Oxidizer Boiloff

During the 30-second period of high thruster activity, combustion products of monomethyl hydrazine (fuel) and nitrogen tetroxide (oxidizer) were expelled from the thrusters for a period of 7 seconds. These products consist primarily of water with nitrogen oxides and some salts. Then, the CM RCS PRPLNT switches were positioned to OFF by the center-seat crewman at an altitude of about 16 000 feet (4880 m), causing the propellant isolation valves to close. These switches were turned off at approximately the nominal time, as shown in figure 2. Closure of the propellant isolation valves allowed the oxidizer trapped between the valves and the thrusters to boil off (fig. 4) as the thrusters operated for 23 additional seconds before the reaction control system was inhibited by the operation of the RCS disable relay at an altitude of about 9600 feet (2925 m).

The oxidizer boils at pressures below about 15 psia (10.3 N/cm^2) while the fuel boils at pressures below about 1 psia (0.7 N/cm^2). Thus, the oxidizer trapped between the propellant isolation valves and the solenoid valves boiled at the altitudes through which the command module was descending during the 23-second period between closure of the propellant isolation valves and operation of the RCS disable relay. One of the positive roll thrusters was 2 feet (0.6 m) away from the steam vent through which outside air was pulled into the command module after opening of the cabin pressure relief valve (fig. 5). This thruster fired in the direction of the vent and was open for 19 of the 23 seconds. During this time, 1.1 pounds (0.5 kg) of oxidizer was expelled from this thruster. The negative roll engines did not fire during the 23-second period. Each pitch and yaw thruster fired for about 11 of the 23 seconds. Of the total of 9 pounds (4.1 kg) of oxidizer that was trapped in the lines of both reaction control systems, 7.4 pounds (3.4 kg) boiled off during the 23 seconds of high thruster activity.

Toxic Gas in Cabin

The cabin pressure relief valve opened automatically at about 24 500 feet (7470 m) to allow the cabin pressure to equalize with the ambient atmospheric pressure during descent. Thus, during the 30-second period of high thruster activity after drogue parachute deployment, a mixture of air and propellant combustion products followed by a mixture of air and nitrogen tetroxide vapors were sucked into the cabin. Figure 5 shows the flow field and mixing around the command module. The crewmen were exposed to the oxidizer vapors for 4 minutes and 40 seconds, from closure of the reaction control system isolation valves until they were able to don emergency oxygen masks after landing. (The masks were not accessible during descent.)

OXIDIZER CONCENTRATION ANALYSIS

Aerodynamic Analysis

Based on a theory of a periodic shedding of the vortices in the command module wake, it was determined that the gas mixture outside the vent inlet to the cabin would have ranged from 3307 to 4868 mg/m^3 of oxidizer from 16 000 feet (4880 m) to 9600 feet (2925 m). Details of the analysis are presented in the appendix. The principal product of nitrogen tetroxide and air is nitrogen dioxide. With moisture or water, nitric acid is formed. Because of its relative prevalence, stability, and toxicity, nitrogen dioxide is the primary concern for crew exposure. The average of 4100 mg/m^3 of oxidizer is equivalent to 2000 parts of nitrogen dioxide per million parts of air by volume at 1 atmosphere (10.1 N/cm^2).

Environmental Control Analysis

The cabin pressure relief valve allows air to enter the cabin in the left-side lower equipment bay behind a panel 2 feet (0.6 m) from the inlet to the suit loop. As shown in figure 6, the suit loop inlet recirculates cabin air during entry when the crew is unsuited. Cabin total pressure changed from 6.3 to 14.4 psia (4.3 to 9.9 N/cm^2) during the 3 minute and 40 second period from the time the reaction control system isolation valves closed until landing. The suit loop was functioning for 3 minutes and 14 seconds of this time until it was turned off at 800 feet (245 m) altitude prior to landing. Total crew exposure to the toxic oxidizer vapors was for the 4 minutes and 40 seconds from closure of the reaction control system isolation valves until donning of the oxygen masks. The effective free cabin volume for true contaminant diffusion was estimated to be 65 percent of the pressurizable volume, or 207 cubic feet (5.9 m^3).

Fifty percent of the suit loop flow is through the lithium hydroxide canisters. The remainder flows through a hole in the middle of each canister. All the suit loop flow passes through the glycol heat exchanger where the toxic gases not removed by the lithium hydroxide canisters would be converted to nitric acid after reacting with water.

Postflight analysis of the lithium hydroxide canisters showed a thin yellow layer on top with a high nitrogen dioxide content. This layer was less than 1 percent by weight. The next 20 percent had a gray color with a nitrogen dioxide concentration half that of the top layer. The bottom 80 percent was not discolored and had a negligible nitrogen dioxide content.

The lithium hydroxide canisters collected only about 0.5 gram of nitrogen dioxide from a total of 12 grams that was calculated to have entered the cabin. Thus, the suit loop was not the primary mechanism for removal of the oxidizer from the cabin atmosphere.

Color Analysis

Nitrogen tetroxide or nitrogen dioxide is colorless but its intermediate state is nitrogen trioxide which is reddish brown. As the concentration of nitrogen trioxide increases, the color changes from yellow to brown to a brownish-red. Nitrogen tetroxide and air mixtures in 2-inch (5.1-cm) diameter tubes at 1 atmosphere (10.1 N/cm^2) are shown in figure 7. Nitrogen tetroxide reacts in air to form a variety of nitrogen oxides, the principal one being nitrogen dioxide.

The Apollo Commander stated that his first visual observation was a dark reddish-brown cloud very suddenly occupying his entire field of view lasting, perhaps, 20 to 30 seconds. The cloud consisted of clearly discernible suspended particles or droplets. The initial color was closest to that of tube 5 in the figure. Subsequently, there was only a slight haze having a color between those of tubes 2 and 3. The odor and irritants remained and exposure continued until about 1 minute after landing when the oxygen masks were unstowed for each of the crew. The eye-to-panel distance in the spacecraft was estimated by the crew to be about 20 inches (51 cm). Equivalent spacecraft concentrations would be about 1/10th the parts per million shown.

Estimate of Average Crew Exposure

The estimated cabin oxidizer concentration is shown in figure 8. The maximum concentration of toxic gas in the cabin should have been reduced from about 1000 to 700 parts per million of nitrogen dioxide at 1 atmosphere because part of the gas entering the cabin flowed through the suit circuit. The rapid decay shown in the figure assumes reaction of nitrogen dioxide with moisture in the cabin to obtain an average concentration consistent with the lithium hydroxide canister analysis. This results in an estimated average crew exposure of about 250 parts per million of nitrogen dioxide over a period of 4 minutes and 40 seconds.

The formation of droplets of the toxic gas, as observed by the Apollo Commander, may have increased the initial maximum local concentration. However, the limited amount of oxidizer available downstream of the isolation valves and the high probability of the droplets reacting with moisture on the damp cabin surfaces would tend to decrease the long-term concentration.

Table I (from ref. 1) presents the effects of nitrogen dioxide on man. The most important factors and conditions that can modify and significantly alter human response to nitrogen dioxide are temperature, predisposing disease, heredity, age, and interactions with other pollutants. The estimated average exposure of about 250 parts per million at 1 atmosphere is compatible with the data in table I. The medical findings support the evidence that the crew was exposed to a high level of oxidizer products and that there were no other toxic compounds such as monomethyl hydrazine. Further information on medical results is presented in reference 2.

POSSIBLE CONTRIBUTING FACTORS TO CREW EXPOSURE

Crew Procedures

Time-critical manual switching.- Time-critical manual switching had been required on early Apollo flights to protect against single-point failures. After redesign, the sequencer pyrotechnic buses were armed prior to entry on Apollo 15 and subsequent flights. However, crew procedures for this mission went back to the pre-Apollo 15 procedure of arming the sequencer pyrotechnic buses at 50 000 feet (15 240 m) during time-critical landing operations. Manual backup capability was used to inhibit a crew-safety automatic sequence during a time-critical operation. As a result, three crucial manual functions were required within the few seconds before reaching 24 000 feet (7315 m) for the automatic sequencer to operate as designed.

Cue card and checklist conflict.- RCS CMD-OFF was listed on the panel 1 (left-seat) entry cue card as a normal function rather than being flagged with asterisks denoting a backup function as on the checklist (fig. 9). In training, the RCS CMD switch was never turned off unless the center seat crewman turned it off when manual backup procedures were used. If there was loss of intercommunications due to noise or when backup manual procedures were required, the left-seat crewman used the panel 1 entry cue card. The cue card and checklist conflict about RCS CMD-OFF may have contributed to the reaction control system not being manually disabled when the left-seat crewman switched to cue card backup procedures.

Differences between training and real-time procedures.- During crew training, the center-seat crewman read the entry checklist and the left-seat crewman repeated the tasks as he accomplished them. The right-seat crewman was not trained to read procedures during entry. The landing cue card on panel 3 was not adequate to do the job because it was simplified 6 months prior to launch, deleting most manual backup tasks including RCS CMD-OFF (fig. 10). During the time-critical earth landing sequence, the right-seat crewman talked about "ELS, LOGIC, AUTO" at 30 000 feet (9145 m). The next mention of these switches was by the center-seat crewman 55 seconds later at 10 000 feet (3050 m). The capability for the right-seat crewman to take over or assist the real-time callout of entry procedures was restricted by the major change to the panel 3 landing cue card deleting RCS CMD-OFF and other backup manual tasks.

Communications

Entry intercommunication procedures for each headset provide individual volume controls for intercommunication, VHF, and S-band, as well as a master volume control. Intercommunication and VHF are amplified for the onboard recorder, bypassing the individual headset volume controls (fig. 11). S-band, as well as any unplanned noises at or above normal listening levels, is also recorded on the onboard recorder due to cross-talk coupling between the headset and the microphone modules.

The crew reported trouble communicating due to noise starting at about 50 000 feet (15 240 m). The onboard tapes revealed an intermittent warbling tone received on the S-band for about 8 to 10 seconds at 90 000 feet (27 430 m). From this time until landing, there was no apparent problem with intercommunications and crew conversation recorded by the onboard recorder was clear with the reaction control system thrusters firing in the background. As on previous missions, high cabin vent noise was present between 24 000 feet (7315 m) and 5000 feet (1525 m).

Emergency Oxygen Masks

Crew exposure to the toxic oxidizer vapors may have been minimized had the emergency oxygen masks been accessible to the crewmen while they were restrained in the seats during entry and landing. The emergency oxygen masks were designed for use as a backup to the suit circuit during unsuited operations in case of smoke or contamination in the cabin, but the stowage location prevented their use during descent.

CONCLUSIONS

Four switches were missed by the crew:

First - Spacecraft control was not returned to the proper mode at 90 000 feet (27 430 m).

Second and third - The two switches which arm the earth landing sequencer were not thrown at 30 000 feet (9145 m). (They were thrown 55 seconds late.)

Fourth - The reaction control system was not disabled manually.

Any one of the three independent missed functions would have prevented the entry of toxic gases.

CORRECTIVE ACTION

Reevaluations of automatic/manual functions of future designs shall be conducted in light of the possibility of crew error for all critical functions.

This anomaly is closed.

TABLE I.- EFFECTS OF NITROGEN DIOXIDE ON MAN[a]

Concentration, ppm	Comment
0.05 (0.1 mg/cu m)	USSR: Maximum allowable concentrations - average during 24 hours
0.15 (0.3 mg/cu m)	USSR: Maximum allowable concentrations - single exposure
0.2	Calculated limit for space travel
0.5	Submarine maximum for 90-day dive
1 to 3	Odor threshold
2.0	Maximum allowable concentration for industry (USSR) as of 1959
5	Ceiling threshold limit value for occupation exposures (average for 8-hour day, 5 days per week)
	Exposure of one asthmatic and one pilocarpinized volunteer for 5 minutes, no effects noted
10	Sixty-minute emergency exposure level for occupational exposure
10	Maximum permitted for 1 hour in submarine
10	Normal volunteer exposed for 60 minutes, interpreted as not showing impairment of pulmonary function
13	Eight volunteers: three of eight had eye irritation; seven of eight had nasal irritation; four of eight had pulmonary discomfort; six of eight had olfactory cognition; two of eight had CNS effects; all predominantly slight
20	Workers in nitric acid recovery plants reputedly exposed to levels averaging up to 20 ppm for up to 18 months showed no ill effects
20	Emergency exposure limit for 30-minute exposure

TABLE I.- EFFECTS OF NITROGEN DIOXIDE ON MAN[a]- Concluded

Concentration, ppm	Comment
25	Emergency exposure limit for 15-minute exposure
25	Seven human volunteers exposed for 5 minutes. Slight or moderate nasal discomfort in five of seven pulmonary discomfort in three of seven; odor detected by six of seven. No consistent changes in expiratory reserve, vital capacity, or MBC
30-35	Workers exposed at 30 to 35 ppm to nitrous fumes over several years; had no ill effects
35	Emergency exposure limit for 5 minutes
50	Seven human volunteers exposed for 1 minute; three of seven had pulmonary discomfort and nasal irritation
64	Moderate irritation of larynx and increase in respiratory rate in volunteers
80	In 3 to 5 minutes, volunteers got tightness of chest
100	Produced rapid, marked irritation of larynx and cough in volunteers
300-400	Few minutes' exposure will cause broncho-pneumonia and death
500	Few minutes' exposure will cause pulmonary edema

[a]Table taken from reference 1. On the basis of these kinds of data, Cooper and Tabershaw recommend that "brief exposures of a general population should not exceed 3 ppm over a period of 1 hour." This is based on the possible potentiation of infections and on the odor thresholds.

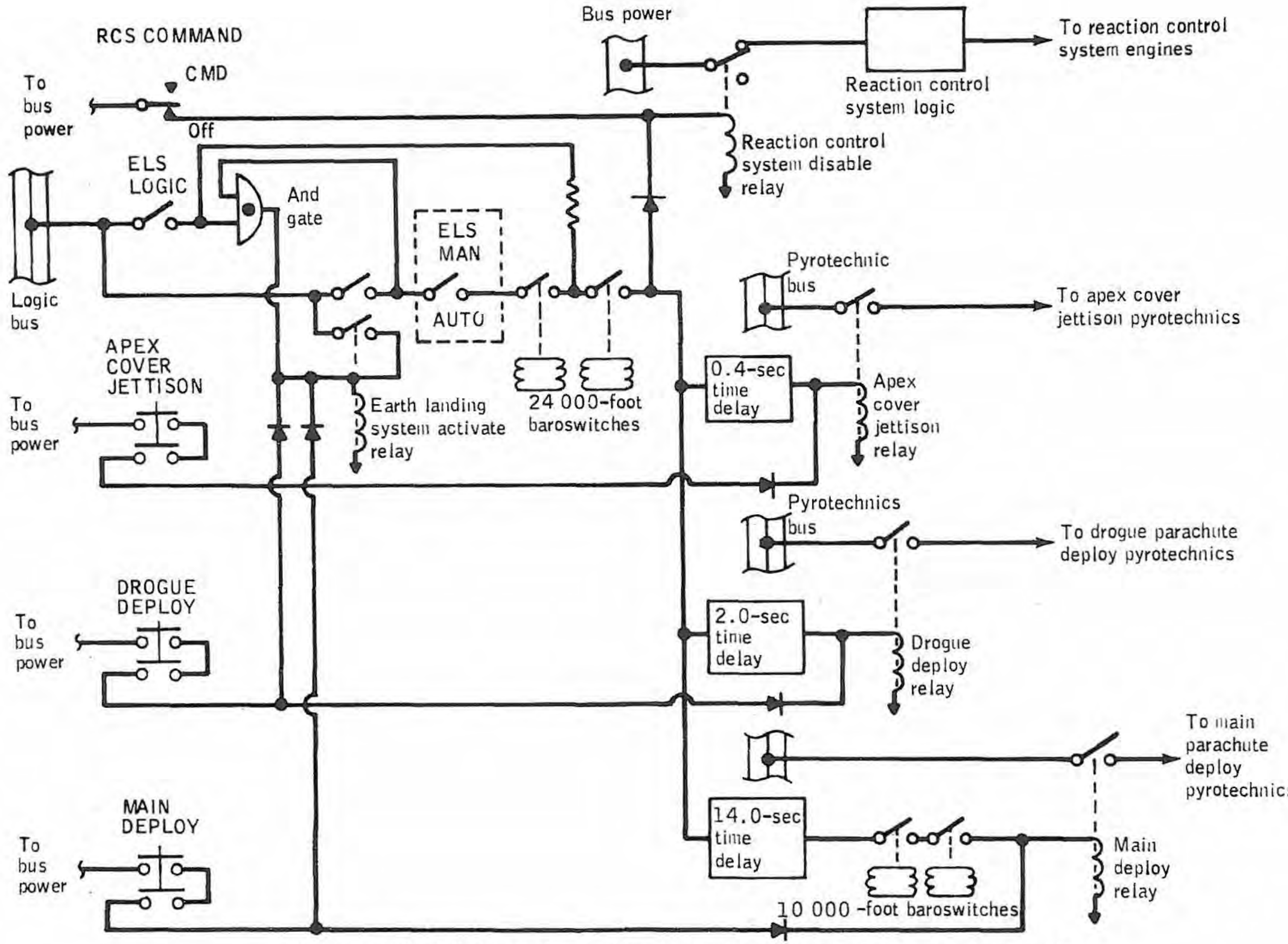


Figure 1.- Simplified manual and automatic circuits of earth landing system (system A).

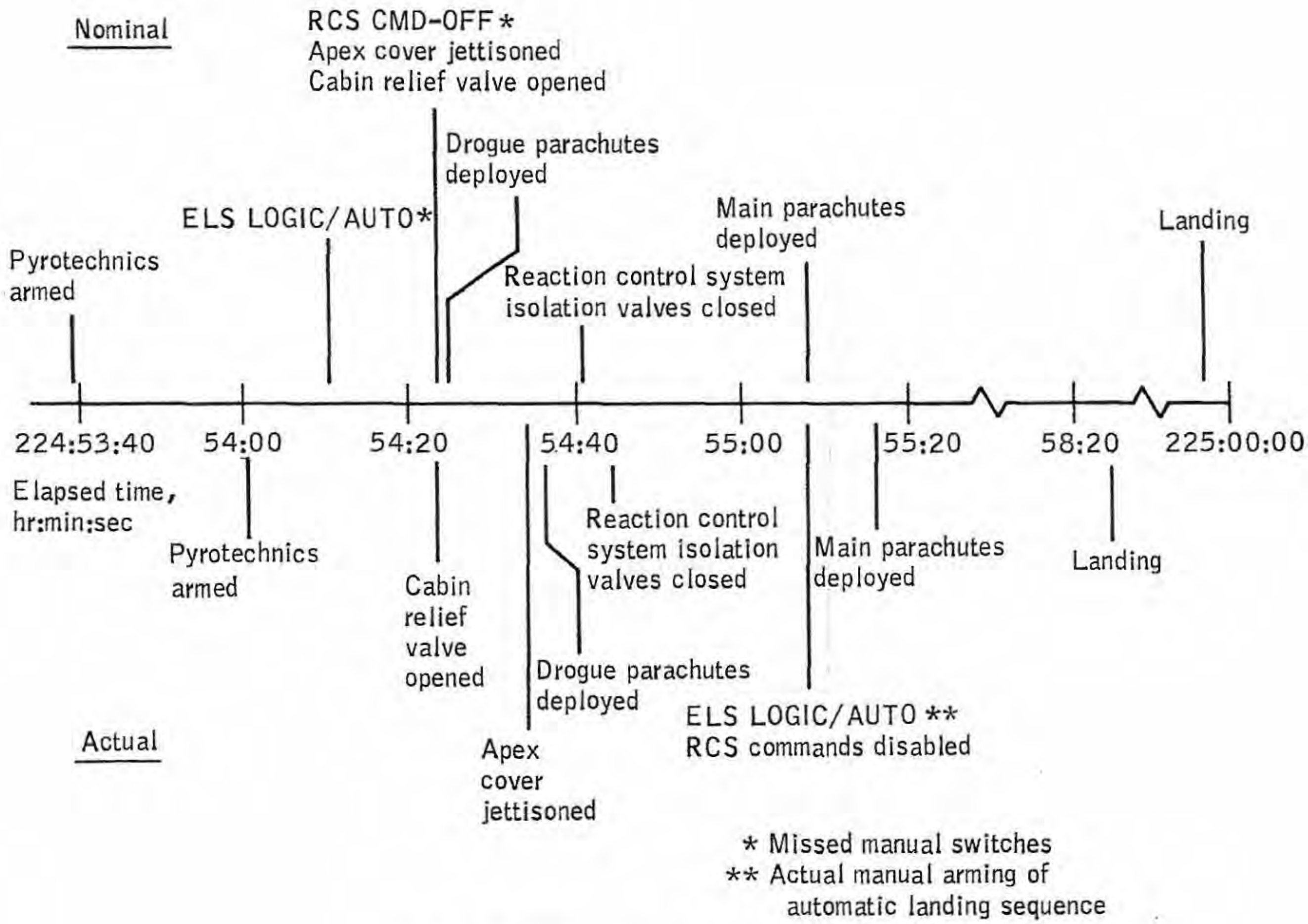


Figure 2.- Landing sequence of events.

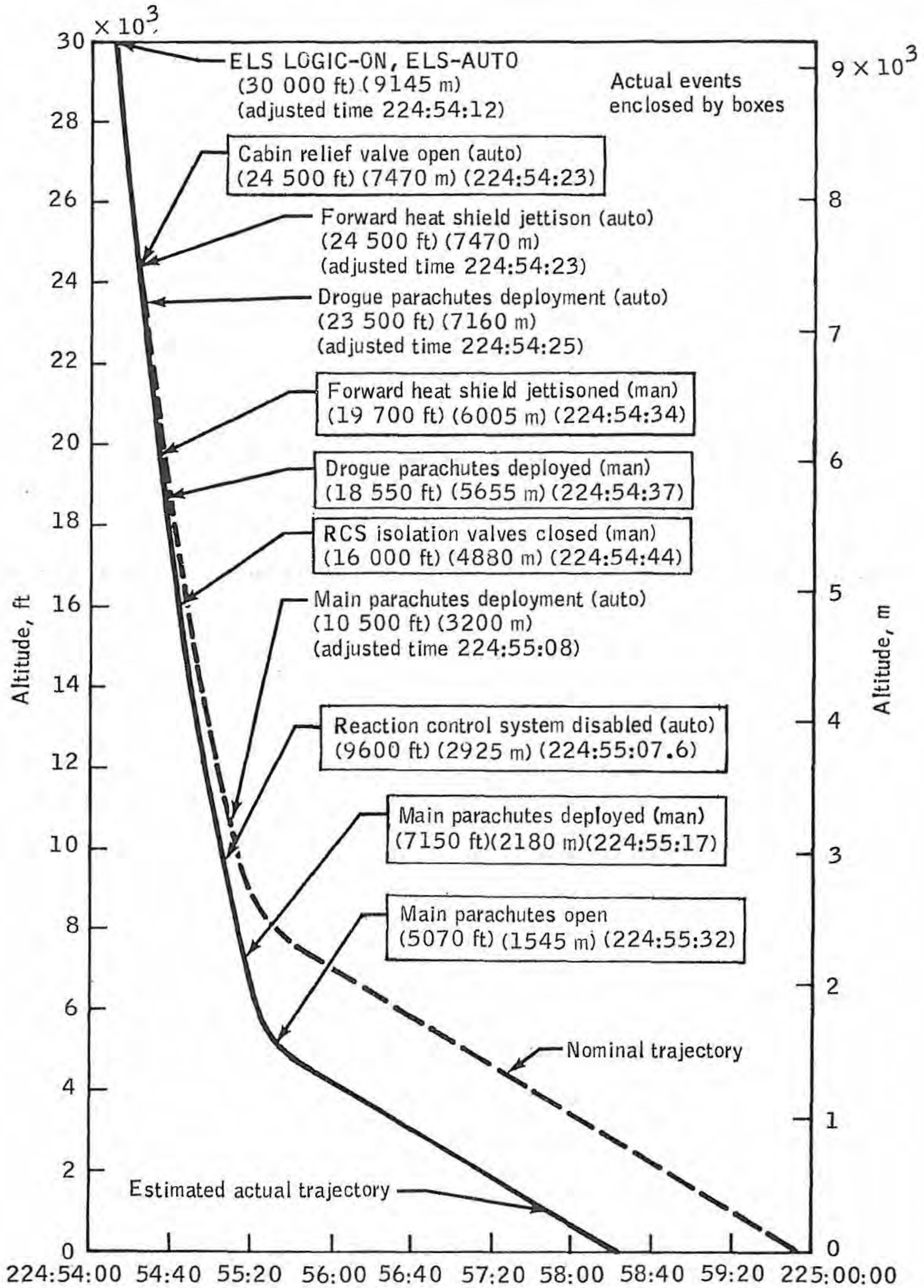


Figure 3.- Comparison of actual and nominal descent sequences.

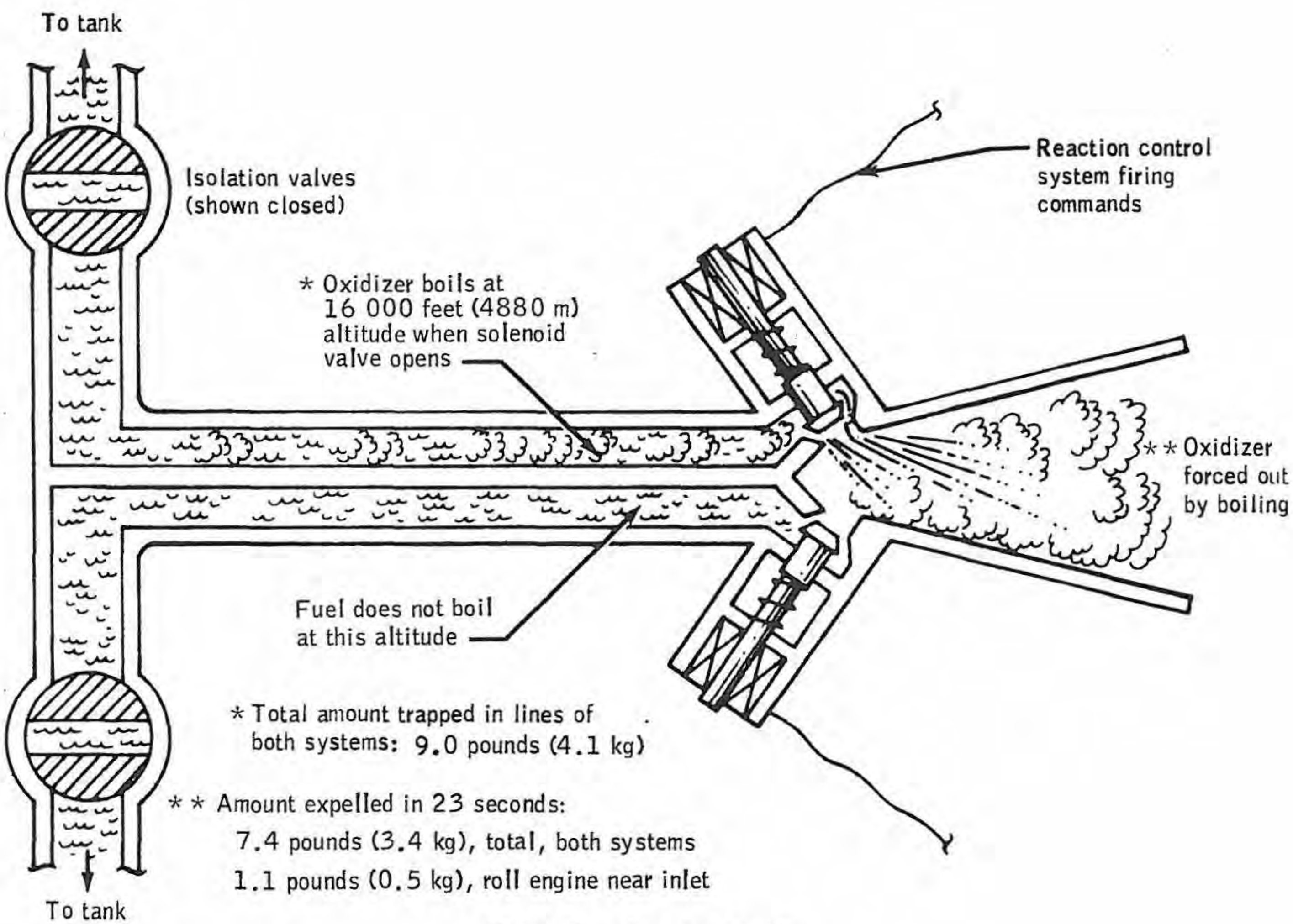


Figure 4.- Oxidizer boiloff.

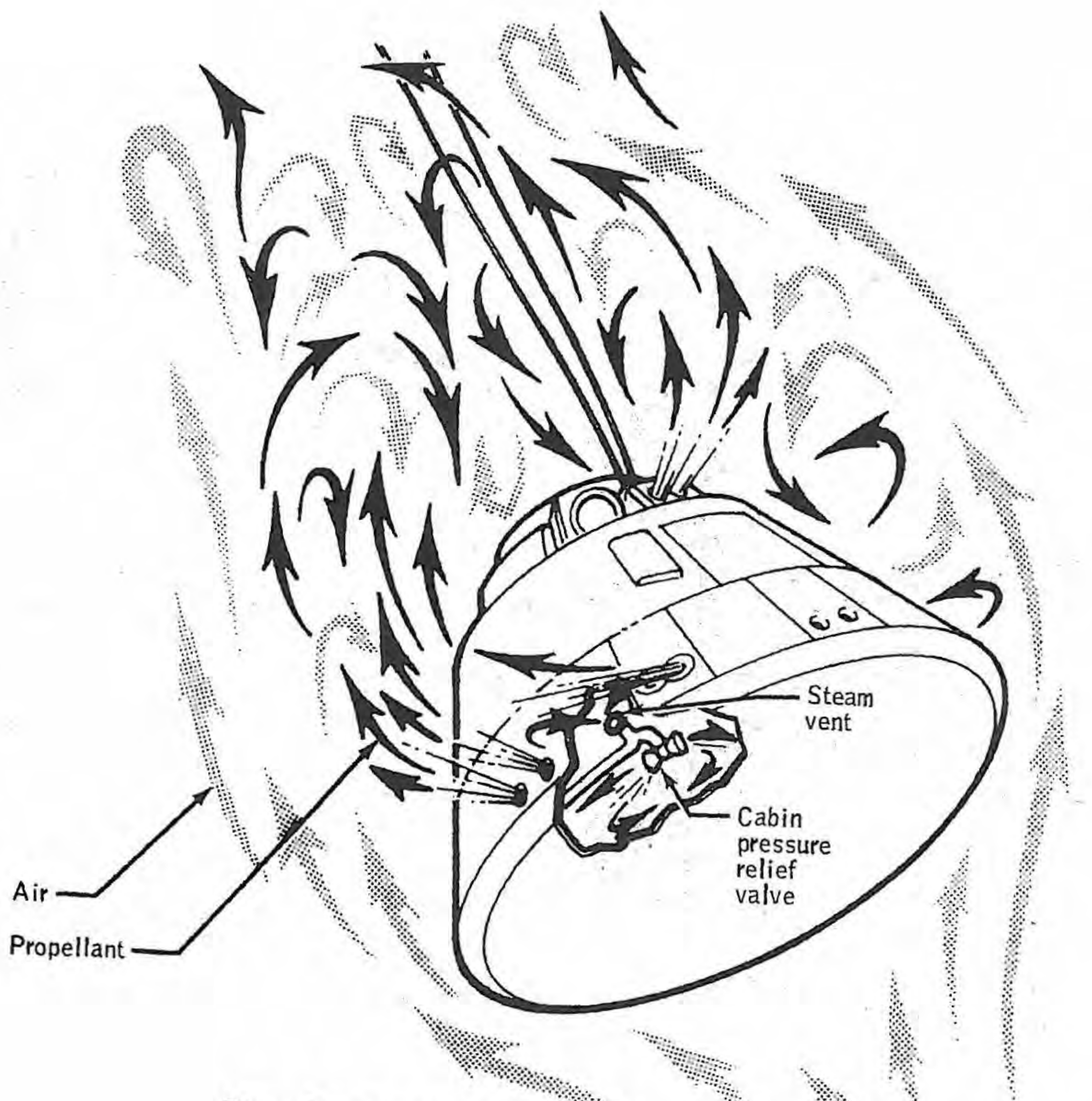


Figure 5.- Flow field mixing around command module at time of incident.

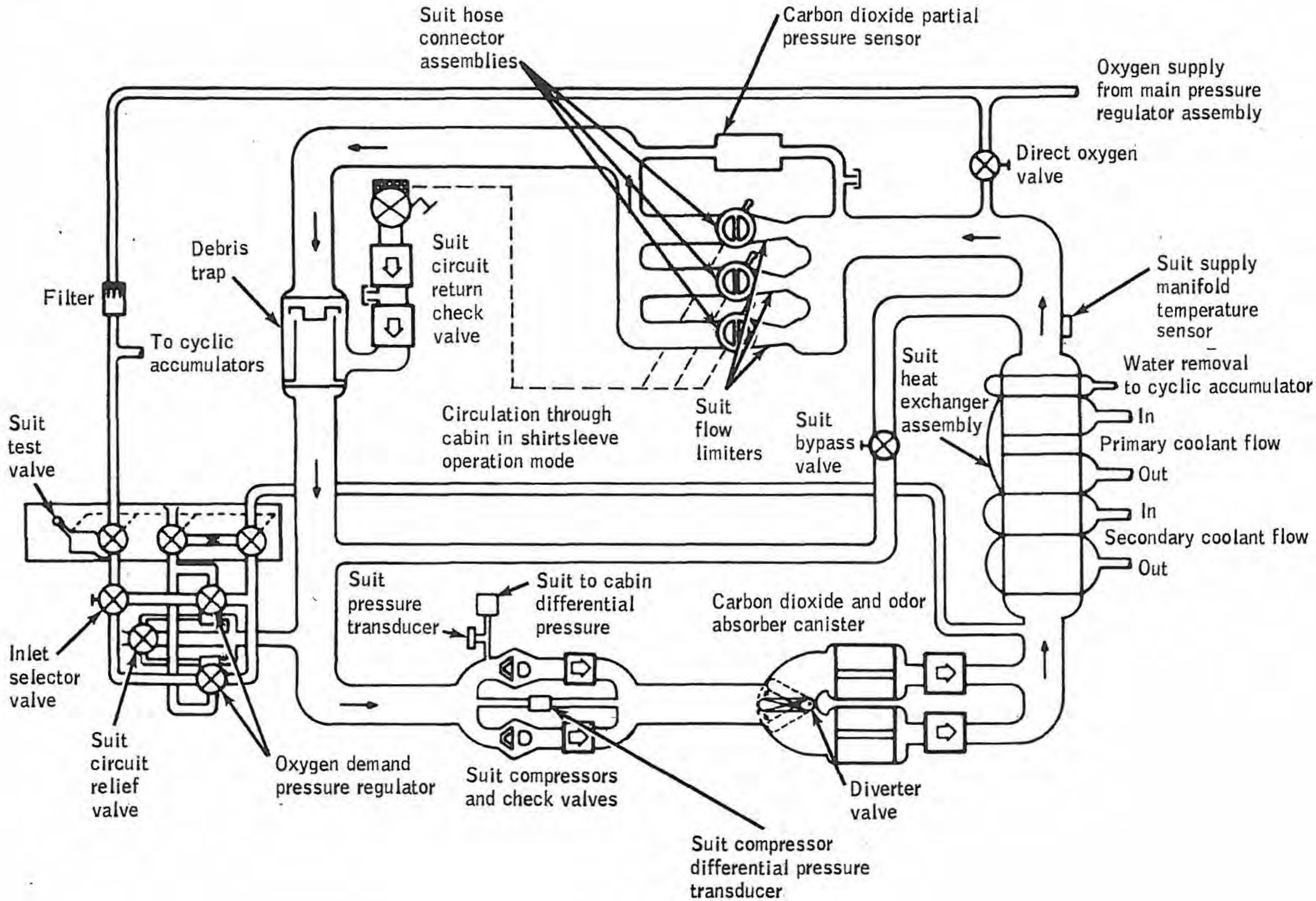


Figure 6.- Pressure suit circuit schematic.

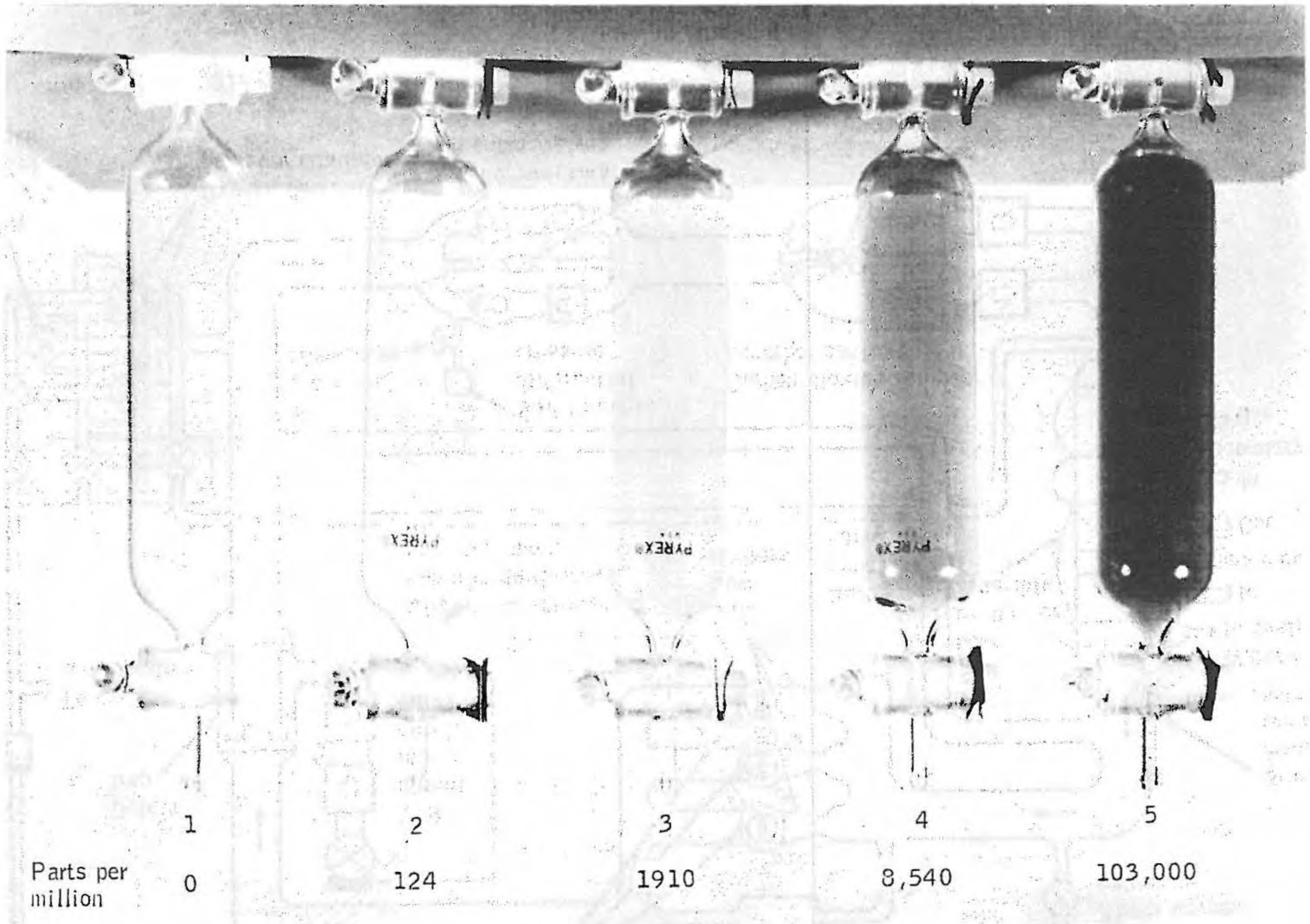


Figure 7.- Comparison of nitrogen tetroxide and air mixtures.

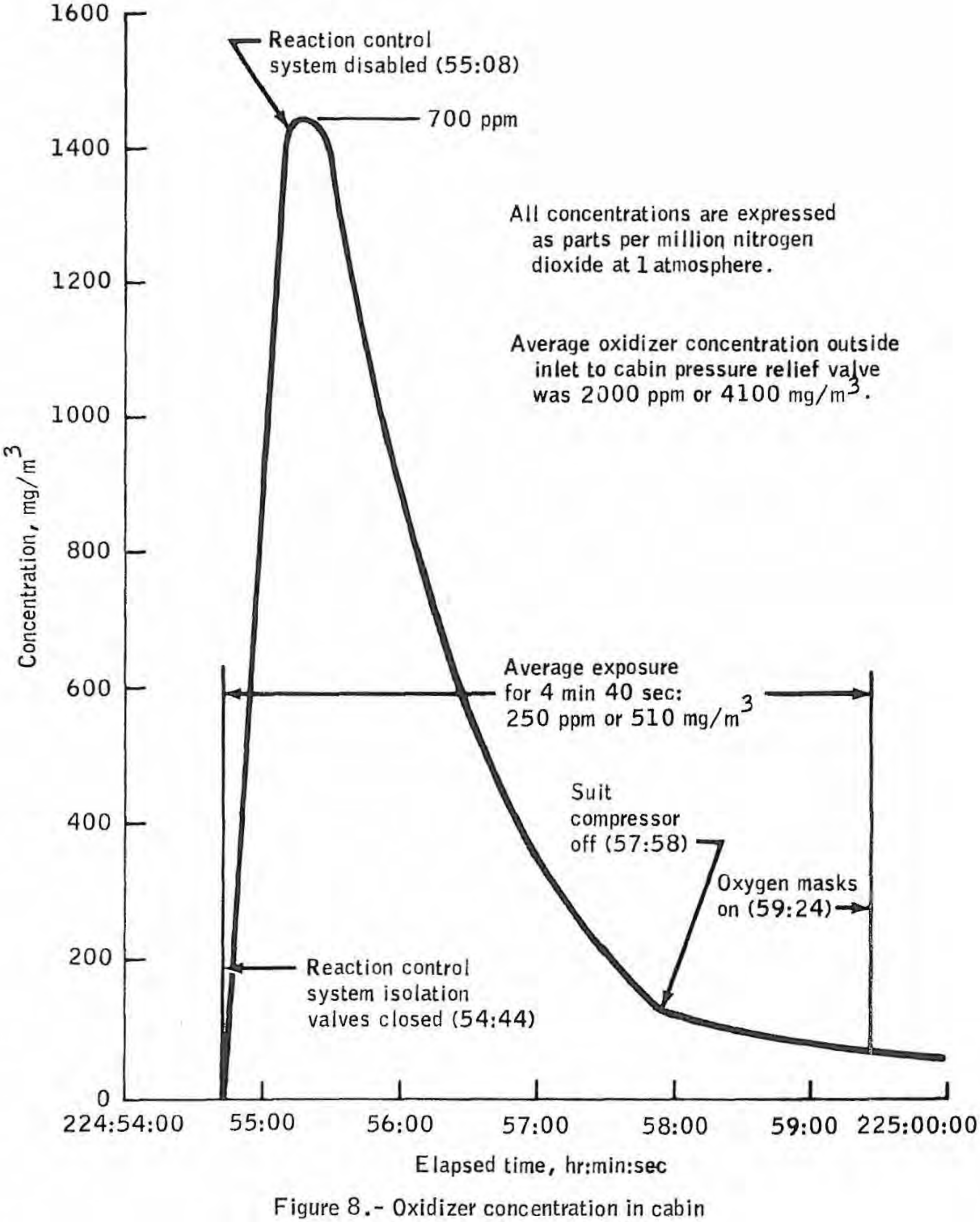


Figure 8.- Oxidizer concentration in cabin

EARTH/POST LANDING

RET		Watch
50K'(__:__)	CABIN PRESS REL vlv (2) - BOOST/ENTRY	(00:50)
	SECS PYRO ARM (2) - on (up)	
	Check altimeter	
40K'(__:__)	*If CM unstable: *	(01:04)
	* *	
	* RCS CMD - OFF *	
	* 40K' APEX COVER JETT pb - push *	
	* DROGUE DEPLOY pb - push *	
	* (2 sec after apex cover jett) *	
30K'	ELS LOGIC - on (up) ELS - AUTO	(01:23)
24K'(__:__)	RCS disable (auto)	Start DAC (01:36)
(May be 23K')	*RCS CMD - OFF*	
	Apex cover jett (auto) *APEX COVER JETT pb - push* (Wait 2 sec)	
	Drogue parachutes deployed (auto) *DROGUE DEPLOY pb - push*	
	*If both drogues fail: *	
	* *	
	* ELS - MAN *	
	* Stabilize CM (direct RCS) *	
	* 5K' MAIN DPLY pb - push *	
	* ELS - AUTO *	
23.5K'	Cabin pressure increasing	
	*If not increasing by 17K': *	
	* *	
	*CABIN PRESS REL vlv (RH) - DUMP *	
	or side hatch vlv open - close at zero	
	CM RCS PRPLNT (2) - OFF	

(a) Checklist

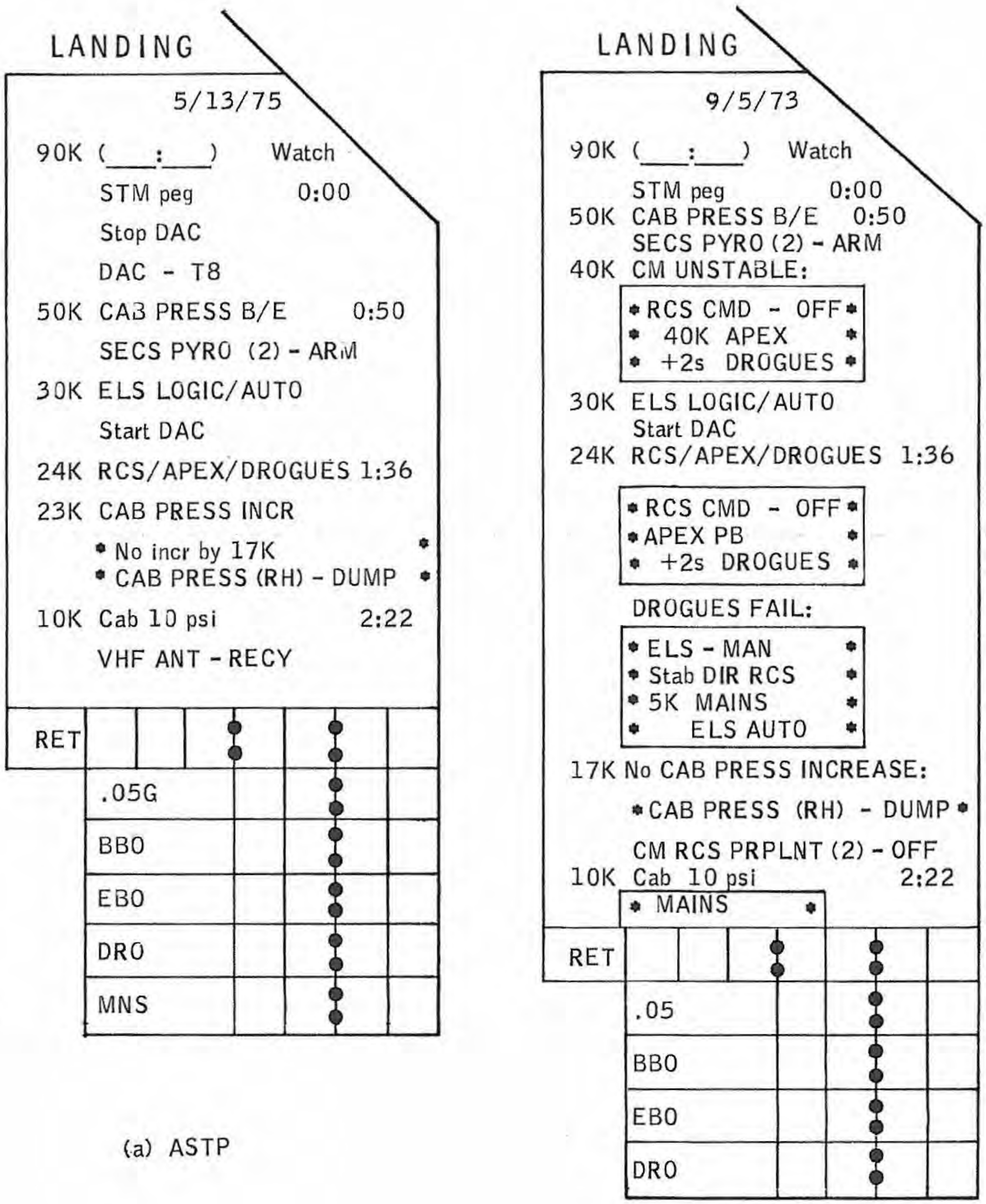
ENTRY 6/27/75

DEORBIT BURN COMPLETE
V82E, PRO, 00E, V66E
CM RCS CK
BMAGS - 1/2
YAW ____ to ____°

50K	BOOST/ENTRY PYRO ARM
30K	ELS LOGIC/AUTO
	RET DRO ____:____
24K	RCS CMD - OFF *If DROGUES FAIL: * * ELS - MAN * * 5K MAINS, ELS AUTO*
	✓ CAB PRESS INCR by 17K CM RCS PRPLNT (2) - OFF
10K	MAINS, RET ____ ____
.8K	CAB PRESS - CLOSE DIR O2 - OPEN (Suited) BUS TIES - OFF

(b) Cue card

Figure 9.- ASTP landing checklist and panel 1 entry cue card.



(a) ASTP

(b) Skylab third visit

Figure 10.- ASTP and Skylab landing cue cards for panel 3.

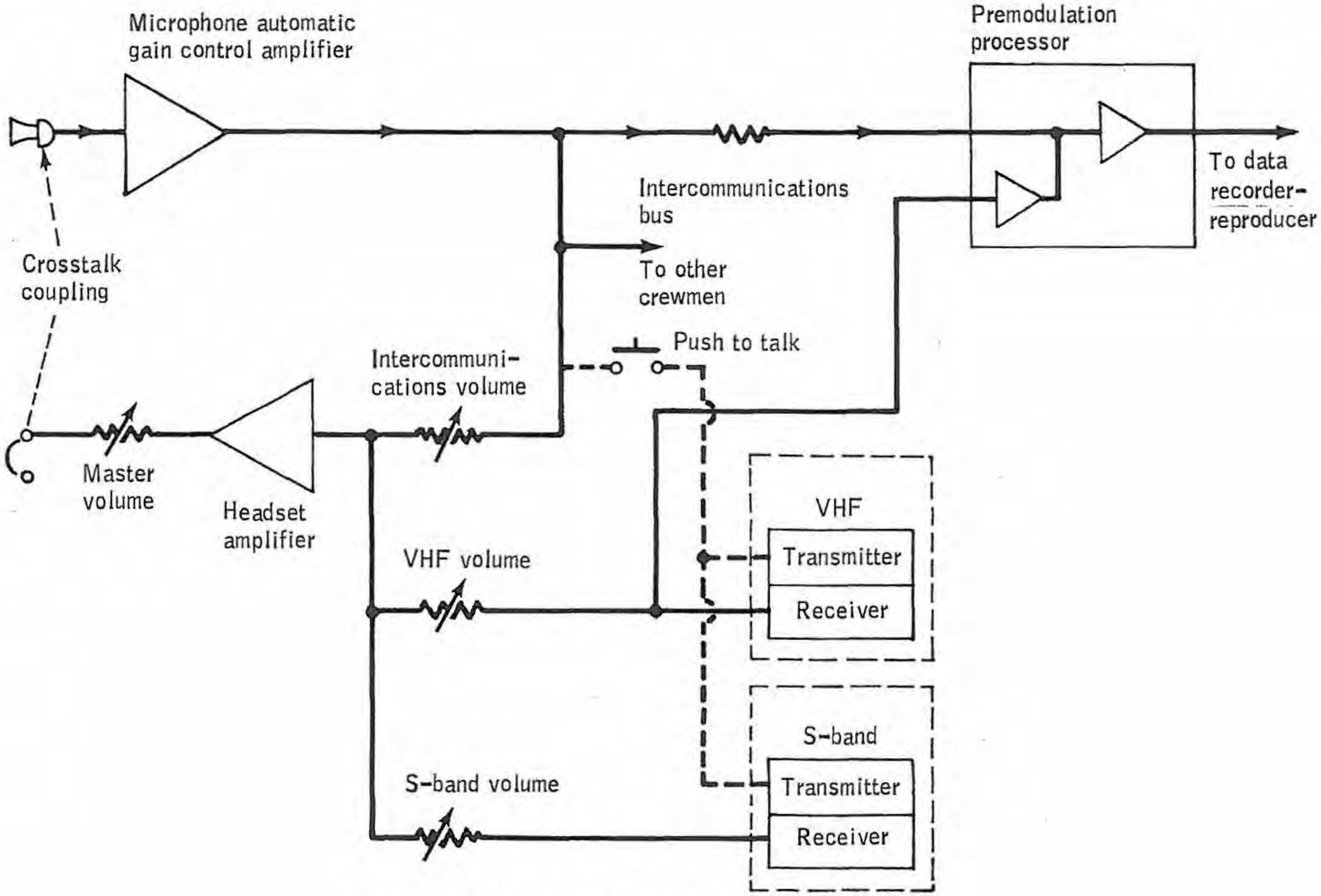


Figure 11.- Simplified audio functional diagram.

REFERENCES

1. Cooper, W. C. and Tabershaw, I. R. Biological effects of nitrogen dioxide in relation to air quality standards. Arch. Environ. Health 12:522-530, April 1966.

2. Johnson Space Center. ASTP Life Sciences Medical Report. (Planned for publication by Life Sciences Directorate in 1975.)

APPENDIX

ESTIMATE OF NITROGEN TETROXIDE CONCENTRATION INGESTED INTO COMMAND MODULE CABIN DURING APOLLO SOYUZ MISSION

INTRODUCTION

A study was made to determine the possible concentration of oxidizer which could have entered the command module cabin near the conclusion of the Apollo Soyuz mission. The probable mechanism which would allow this influx was vortex mixing in the near wake of the command module.

ANALYSIS

As the command module descends, the wake region is bounded by the command module conical afterbody and by a cylinder having the same diameter as the command module. Vortices exist in this wake region which provide the mechanism for mixing of the air and oxidizer prior to the mixture ingestion.

Two descent events were considered in the analysis: manual operation of switches to close the reaction control system isolation valves at 224 hours 54 minutes 44 seconds (7 seconds after deployment of the drogue parachutes) and automatic disabling of the reaction control system firing commands at 224 hours 55 minutes 7.6 seconds (approximately 30 seconds after deployment of the drogue parachutes). The approximate command module velocities at the times of these events were 373 ft/sec (114 m/sec) and 253 ft/sec (77.1 m/sec), respectively, and the altitudes were 16 000 feet (4880 m) and 9600 feet (2925 m), respectively. The reaction control system roll thruster that was emitting oxidizer for the majority of the 30-second interval was 4.5 inches (11.4 cm) downstream, 22.5 inches (57.2 cm) cross-stream, and was angled in the direction of the steam vent (the opening to the cabin pressure relief valve). The oxidizer flowing from this thruster was taken as the only source that entered the cabin.

The turbulent near wake of the command module is a three-dimensional phenomenon (even though the command module is essentially axially symmetrical) including both downstream and cross-stream components of circulation. For simplicity, the mixing may be represented as shown in figure A-1. Between the separation streamline and the command module afterbody (cone), vortices are periodically growing and shedding. As a vortex grows to its maximum size, the efflux of the roll thruster is contained by the vortex, mixed, and ingested through the steam vent. The vortex is shed and the process continues. The frequency of the shedding as well as the volume of the mixture directly influence the concentration of the oxidizer.

The Strouhal number may be used to describe the frequency of this shedding and is defined as nd/V where n is the frequency, d is the diameter and V is the freestream velocity. For bluff bodies such as the command module, a Strouhal number of approximately 0.2 may be used. In order to substantiate this concept, photographs from a drop test of the command module were evaluated. This test occurred April 4, 1968, and was designated "Apollo Block II Drop Test 85-1." Still photographs of the movie documenting this test were reviewed. Of interest to this analysis is the flow field visualization provided by the smoke from the mortar used to deploy the forward heat shield. The periodic nature of the vortices shed is clearly evident. Furthermore, an approximation of the Strouhal number is possible. The time markings on the right of the film strip occur every 0.1 second, indicating a camera speed of approximately 70 frames per second. The vortices are shed at a frequency of from six to seven per second, yielding a Strouhal number of approximately 0.2 based on a velocity of 370 ft/sec (113 m/sec). The distance through which mixing occurs appears to be as long as a command module diameter downstream, although the smoke appears to be concentrated closer to the separation point (the maximum diameter, d).

The volume of the vortex which was considered in this study was determined as bounded by a cylinder of diameter d, a cone frustum of 33 degrees (0.576 radian) half-angle with the forward heat shield removed, and a peripheral angle of 30 degrees (0.524 radian) each side of the cabin relief vent. This volume includes the reaction control system roll thruster and steam vent but excludes the yaw and pitch thrusters. The mixing length was chosen as 65 inches (165 cm), yielding from figure A-2 a volume of 50 cubic feet (1.42 m^3).

From previous data, it is seen that the roll thruster oxidizer valve was open most of the time; for this analysis, the thruster was considered to have emitted oxidizer continuously. As a result, the concentration of the mixture that could have entered the cabin is only a function of the mixing volume and the command module velocity. Detailed calculations of the two cases considered follow.

Case I.-

$V = 373$ ft/sec (114 m/sec)

$d = 154$ in. (3.91 m)

$h = 16\ 000$ ft (4880 m)

Strouhal number $= 0.2 = \frac{nd}{V}$

$$n = \frac{0.2\ V}{d} = \frac{0.2\ (373)}{154/12} = 5.813 \text{ per second}$$

$$M = 0.0272 \text{ kg/sec} \times \frac{(\text{sec})}{5.813} = 0.00468 \text{ kg}$$

Volume of mixture = 50 ft^3 (1.416 m^3)

$\frac{M}{V}$ = oxidizer concentration

$$\frac{M}{V} = \frac{0.00468 \text{ kg}}{1.416 \text{ m}^3} \times \frac{10^6 \text{ mg}}{\text{kg}}$$

$$\frac{M}{V} = 3307 \text{ mg/m}^3$$

Conversion to parts per million:

Nitrogen dioxide: 14.008 g/gram mole
32.000
46.008 g/gram mole

$$\frac{46.008}{22.414} \quad \frac{\text{g/gram mole}}{\text{liters/gram mole}} \quad \frac{\times 10^3 \text{ mg/g}}{\times 10^{-3} \text{ m}^3\text{/liter}} = 2.053 \times 10^6 \text{ mg/m}^3$$

$3307/2.053 \times 10^6 = 1611$ ppm nitrogen dioxide at 1 atmosphere (standard temperature and pressure)

Case II.-

$V = 253$ ft/sec (77.1 m/sec)

$d = 154$ in. (3.91 m)

$h = 9500$ ft (2900 m)

Strouhal number $= 0.2 = \frac{nd}{V}$

$$n = \frac{0.2\ V}{d} = \frac{0.2\ (253)}{154/12} = 3.943 \text{ per second}$$

$$M = 0.0272 \text{ kg/sec} \times \frac{(\text{sec})}{3.943} = 0.00690 \text{ kg}$$

$$\frac{M}{V} = \frac{0.00690 \text{ kg}}{1.416 \text{ m}^3} \times \frac{10^6 \text{ mg}}{\text{kg}}$$

$$\frac{M}{V} = 4876 \text{ mg/m}^3$$

Conversion to parts per million:

$$\frac{4876 \text{ mg/m}^3}{2.053 \times 10^6 \text{ mg/m}^3} = 2375 \text{ ppm nitrogen dioxide at 1 atmosphere}$$
(standard temperature and pressure)

Average of cases I and II.-

$$\begin{array}{l} 3307 \text{ mg/m}^3 \\ \underline{4876} \\ 8183 \text{ mg/m}^3 \end{array} \qquad 8183/2 = 4091 \text{ mg/m}^3$$

$4091 \text{ mg/m}^3 \sim 4100 \text{ mg/m}^3$

$4100/2.053 \times 10^6 = 1993 \sim 2000$ ppm nitrogen dioxide at 1 atmosphere (standard temperature and pressure)

RESULTS

Table I-A lists velocity, altitude, and oxidizer concentration in the wake of the spacecraft versus time for 24 seconds starting at 16 000 feet (4880 m) altitude.

At the beginning of the oxidizer influx, the calculations yield a concentration of 3307 mg/m^3 of oxidizer; at the end of the influx, the concentration was calculated to be 4868 mg/m^3. These results were based on an assumed maximum vortex volume of 50 cubic feet (1.42 m^3). Since the concentration is essentially inversely proportional to the volume of the vortex, these results are a direct function of this assumption.

The resulting probable concentration average value was found to be about 4100 mg/m^3 of oxidizer or 2000 parts of nitrogen dioxide per million parts of air at 1 atmosphere.

TABLE I-A.- OXIDIZER CONCENTRATION IN SPACECRAFT WAKE

Time, sec	Velocity		Altitude		Oxidizer, mg/m^3
	ft/sec	m/sec	feet	meters	
0	373	114	16 000	4880	3307
1	355	108	15 675	4780	3475
2	339	103	15 375	4685	3639
3	323	98	15 075	4595	3819
4	313	95	14 750	4495	3941
5	303	92	14 425	4395	4071
6	296	90	14 100	4295	4167
7	290	88	13 825	4210	4253
8	286	87	13 550	4130	4313
9	282	86	13 300	4050	4374
10	278	85	13 025	3970	4437
11	274	84	12 750	3885	4501
12	272	83	12 500	3810	4535
13	269	82	12 250	3730	4586
14	267	81	12 000	3655	4620
15	265	81	11 750	3580	4655
16	263	80	11 500	3505	4690
17	262	80	11 250	3430	4708
18	260	79	11 000	3350	4744
19	259	79	10 725	3270	4763
20	257	78	10 475	3190	4800
21	256	78	10 225	3115	4818
22	255	77	10 000	3050	4837
23	254	77	9 750	2970	4856
23.6	253.4	77	9 600	2925	4868
24	253	77	9 500	2900	4876

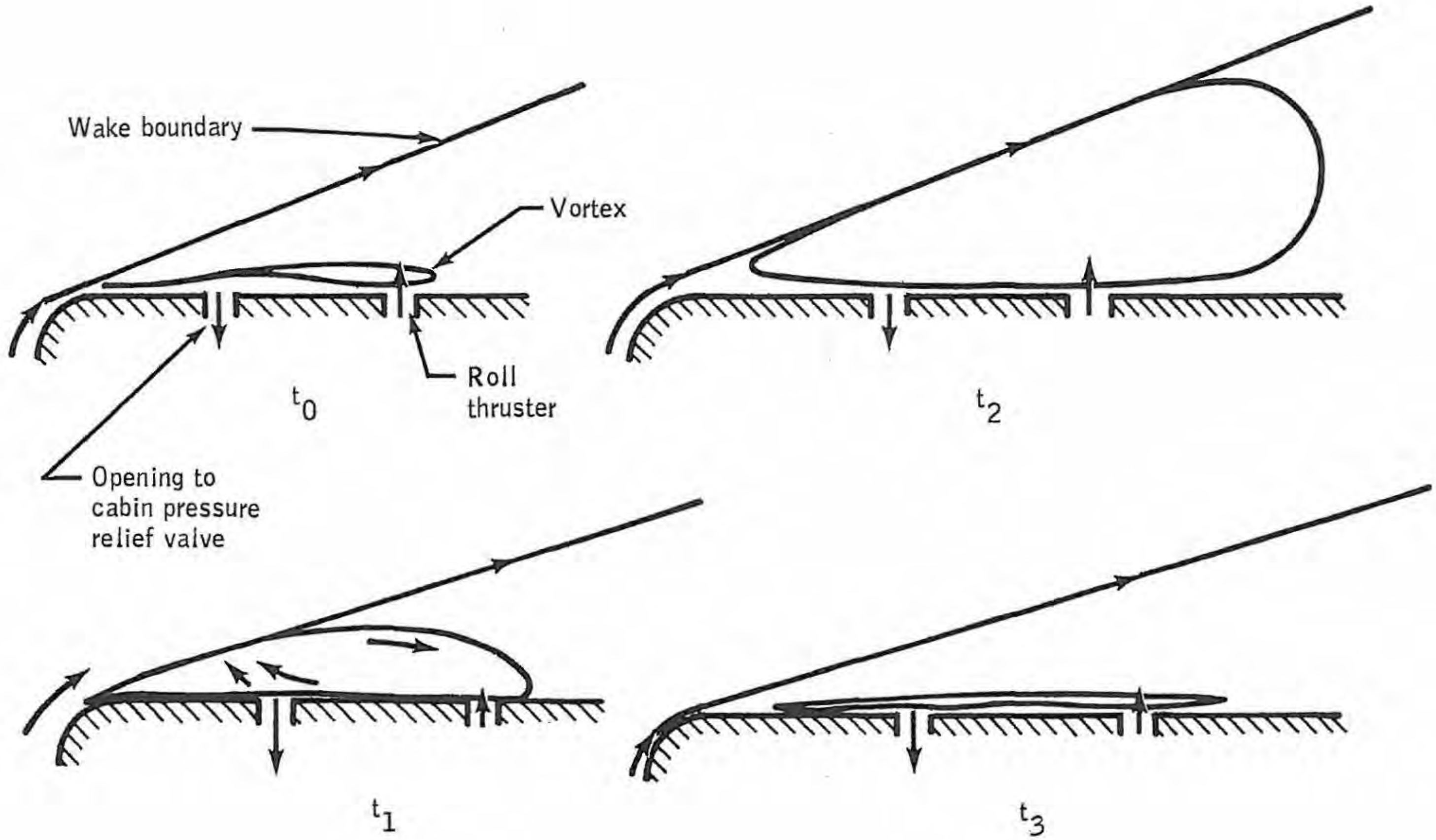


Figure A-1.- Flow field in the region of the roll thruster and cabin pressure relief valve opening as a function of time.

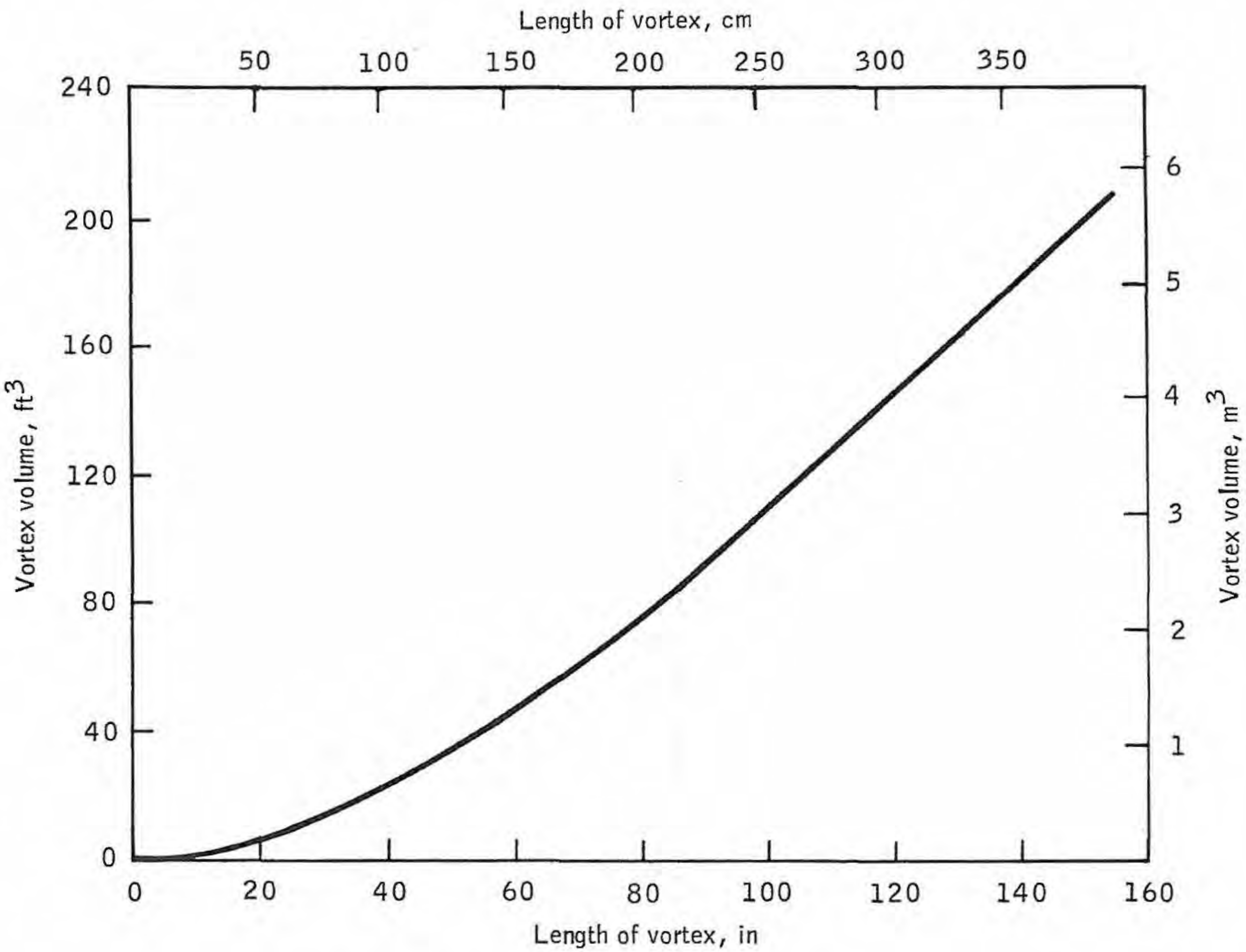


Figure A-2.- Vortex volume verses vortex length.