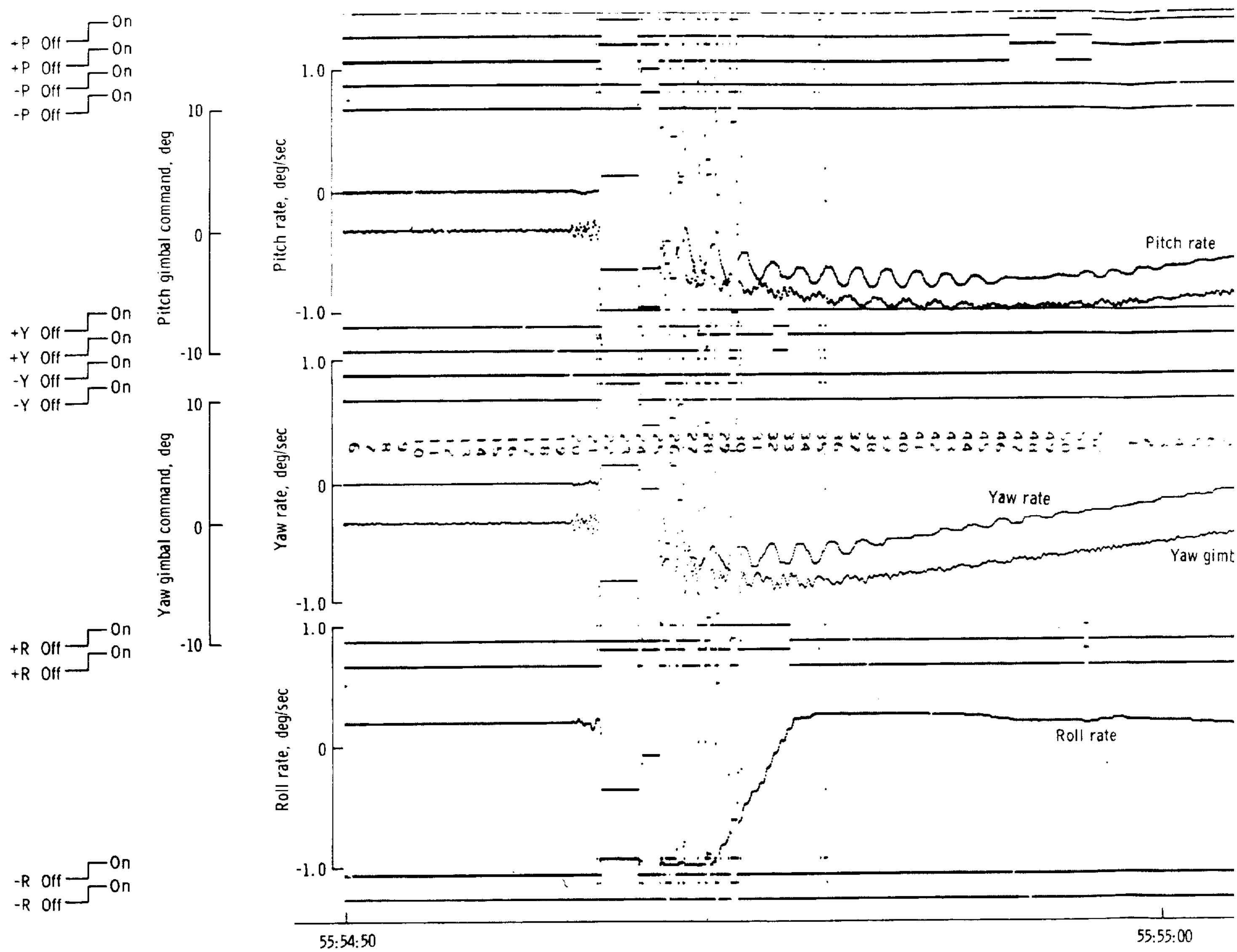
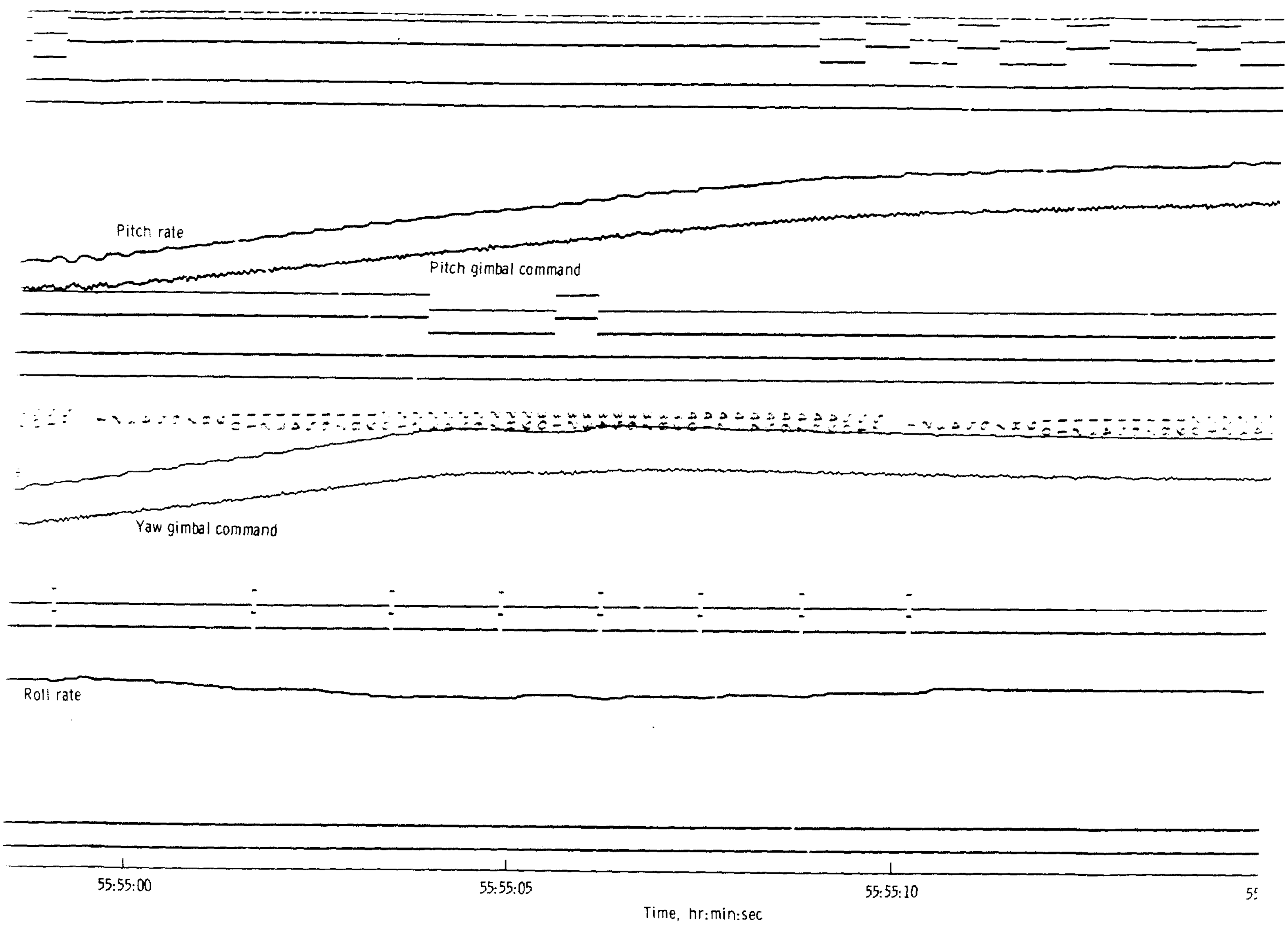


+P Off On
+P Off On
-P Off On
-P Off On
+Y Off On
+Y Off On
-Y Off On
-Y Off On
+R Off On
+R Off On
-R Off On
-R Off On
Pitch gimbal command, deg
Yaw gimbal command, deg
Pitch rate, deg/sec
Yaw rate, deg/sec
Roll rate, deg/sec
10
0
-10
1.0
0
-1.0
Pitch rate
Yaw rate
Yaw gimt
Roll rate
55:54:50
55:55:00



Pitch rate
Pitch gimbal command
Yaw gimbal command
Roll rate
55:55:00
55:55:05
55:55:10
Time, hr:min:sec

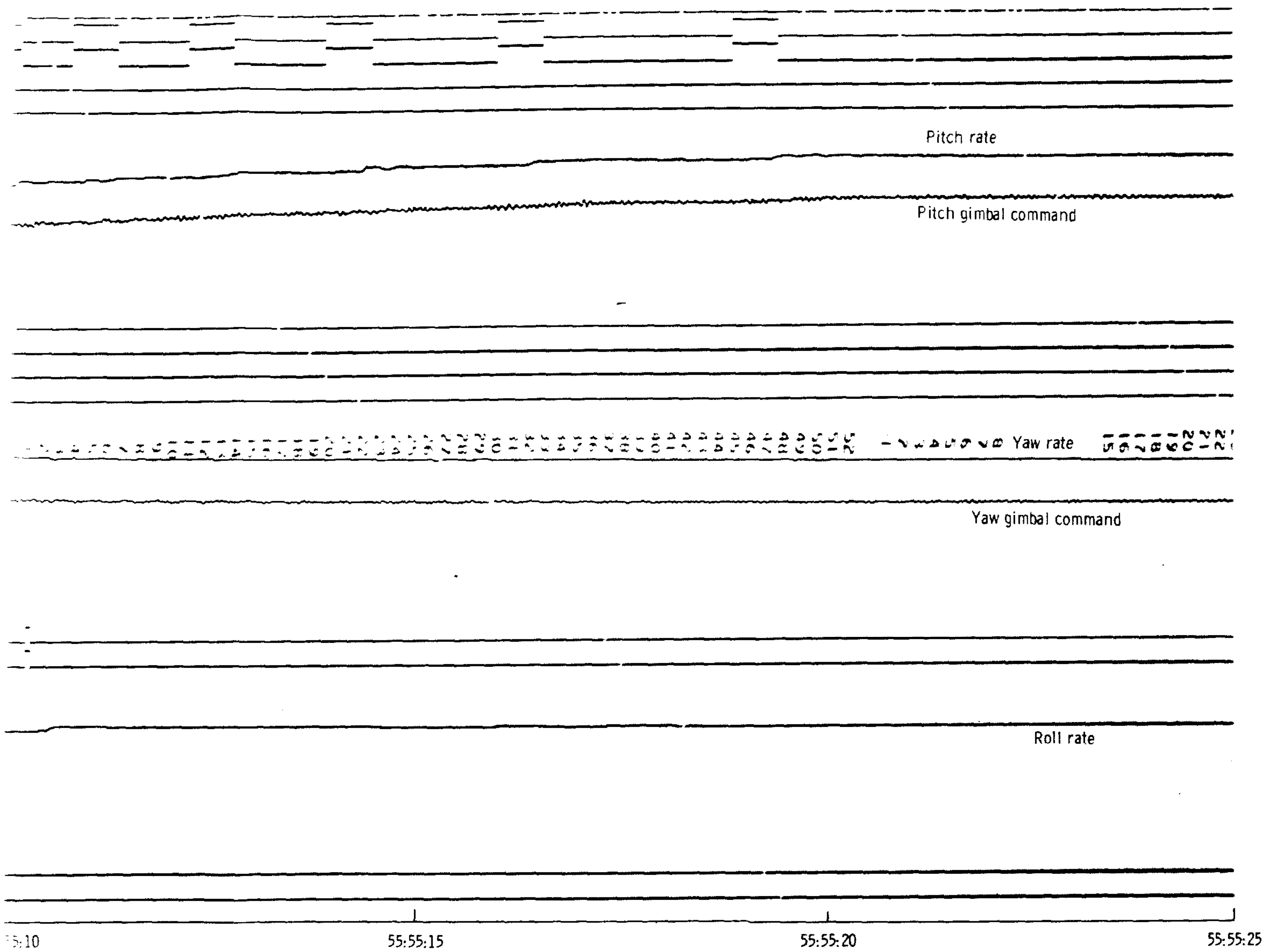


Figure B5-11.- Roll, pitch, and yaw rates.

When transformed from platform coordinates to spacecraft coordinates, this represents a velocity change of 0.4 to 0.6 fps. The uncertainty in this measurement is due to the fact that the PCM system has an increment value of 0.2 fps. The velocity change was combined with the observed roll, pitch, and yaw rates; and a single equivalent impulse acting on the spacecraft calculated. The impulse components are:

X	500 lb-sec
Y	800 lb-sec
Z	-900 lb-sec

This indicates that the force was directed generally normal to the panel covering bay 4 of the service module. The extremely coarse data upon which this calculation is based makes it impossible to better define the force acting upon the spacecraft.

After recovery of data, the integrating accelerometer on the spacecraft stable platform also began to show an abnormal output. Calculations show that the force producing the acceleration amounted to about 60 pounds in the -X direction (retro thrust) over a period of about 8 minutes. At about the same time Commander Lovell reported seeing extensive venting of gases from the service module which definitely was not a normal or expected part of the spacecraft operation at that time. He later described the venting as continuous, looking like, "......a big sheet with the sun shining on it--very heavy--like fine spray from a water hose," unlike gases and liquids vented during other planned spacecraft operations.

The radial velocity of the Apollo spacecraft relative to the Earth can be accurately determined by measuring the doppler shift of the S-band signal transmitted to Earth. Spacecraft velocity components normal to the line between the spacecraft and Earth cannot be determined by this method. The doppler velocity measurement is routinely made every 10 seconds and has an equivalent noise level of 0.015 fps.

Between 55:54:45 and 55:55:05 doppler measurements indicated a radial velocity increment of 0.26 fps. This is shown in figure B5-12. Following this abrupt change in velocity at approximately the time of telemetry loss, additional velocity changes were observed, as shown in figure B5-13. These velocity increments were caused in part by venting from the spacecraft and in part by firings of reaction control system jets.

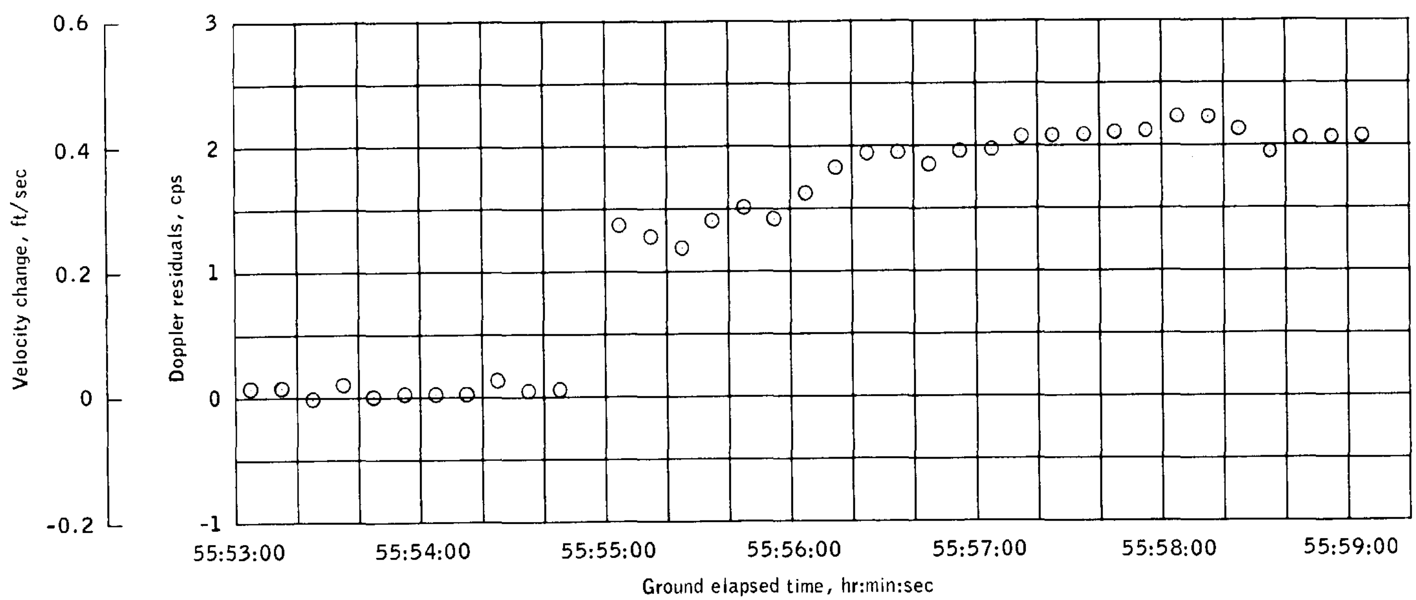


Figure B5-12.- Velocity increment at 55:54:53.

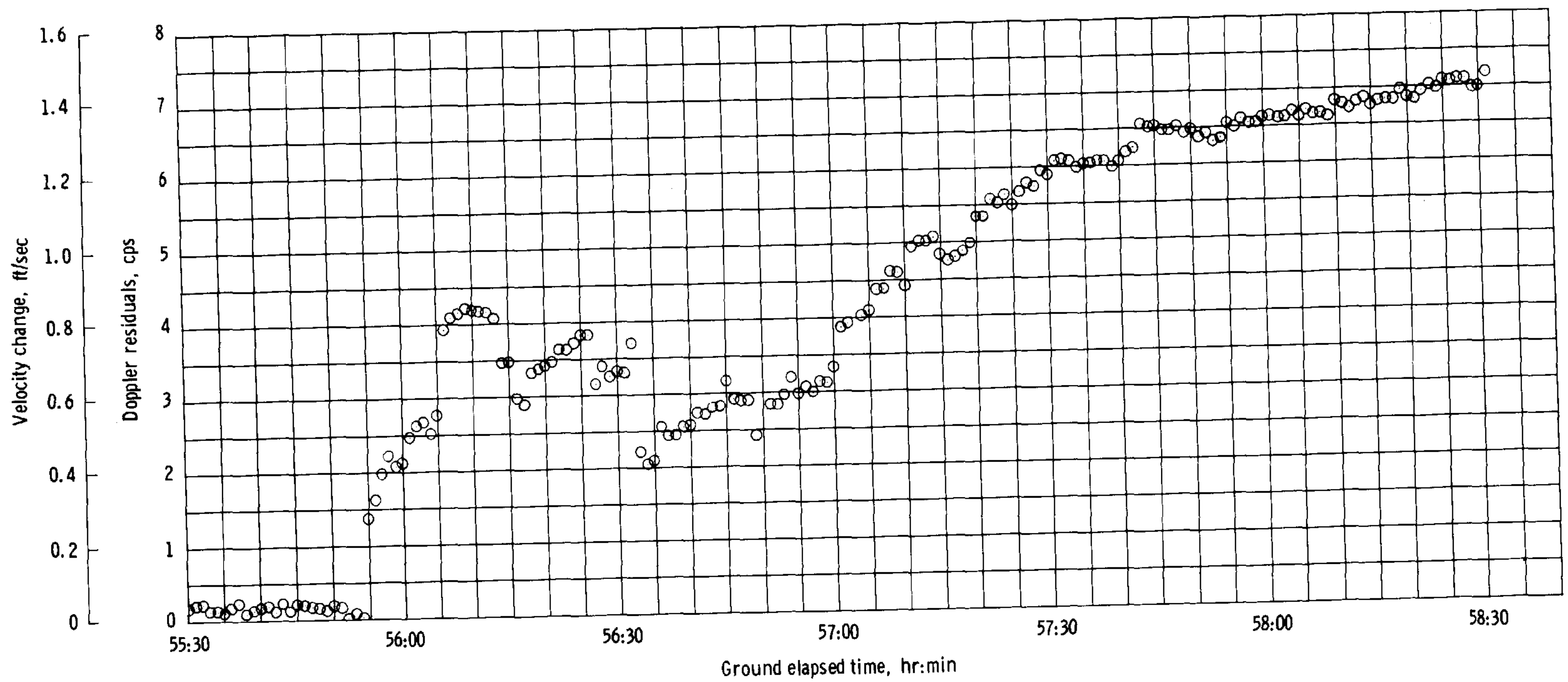


Figure B5-13.- Doppler tracking data.

The jet firings caused velocity increments rather than pure rotation rate changes because the jets did not always fire in opposed pairs. This resulted from the power system configuration in the spacecraft and closure of the quad C valves. (See Part B6 of this Appendix.)

TEMPERATURE CHANGES OBSERVED IN SERVICE MODULE

Following the recovery of telemetry data there were a number of temperature changes observed at various locations in the service module. The locations of all temperature sensors in the service module are shown in figure B5-14, and telemetered records from these sensors for the time period of 55:53:40 to 55:56:10 are shown in figure B5-15. From these temperature records the following conclusions can be drawn:

1. Both temperature measurements in bay 3, the bay adjacent to bay 4, increased after 55:54:55, whereas they had been steady prior to that time.

2. The corresponding temperature measurements in bay 5 showed much smaller increases. Bay 5 is adjacent to bay 4.

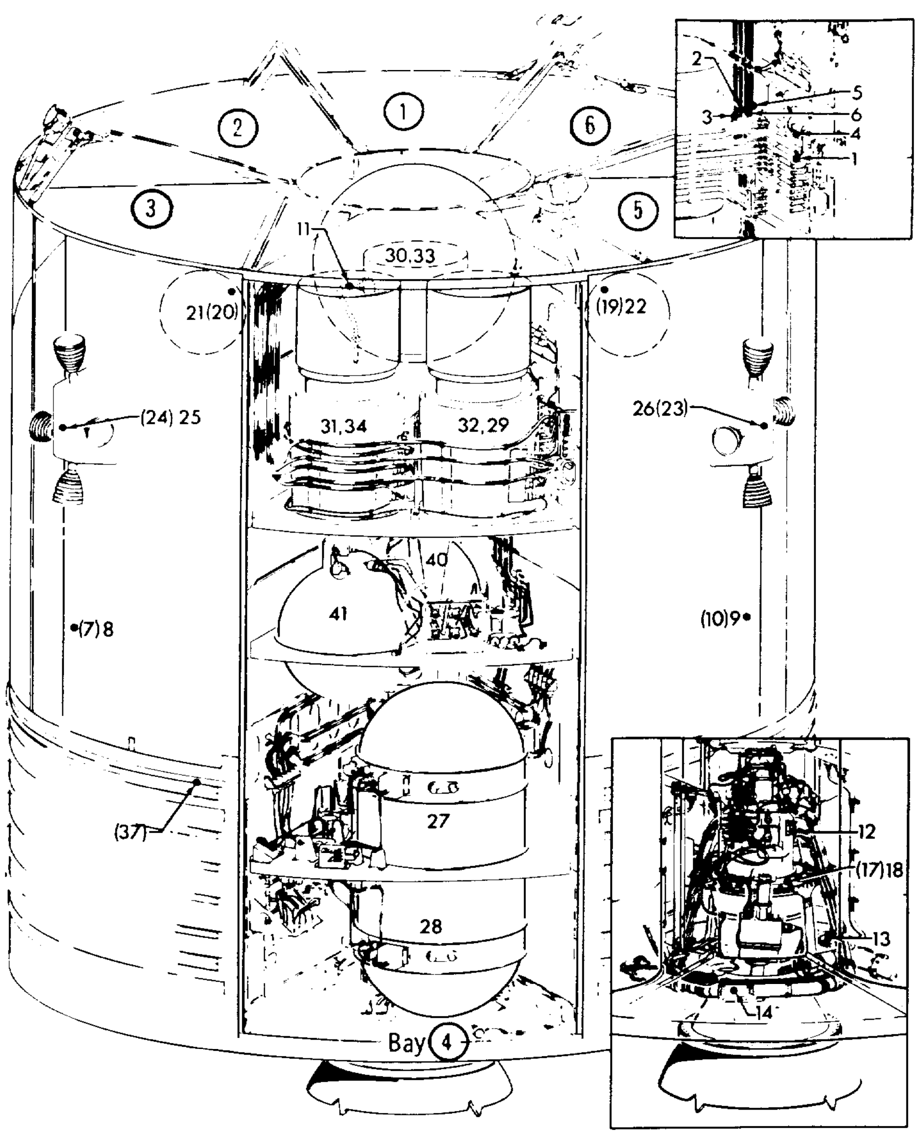
3. A change was observed in the service propulsion valve body temperature. This sensor, unlike many temperature sensors in the lower part of the service module, is not covered by multiple layers of insulation.

4. Four sensors located in close proximity on the separator between bay 4 and bay 5 showed rapid temperature rises of small magnitude immediately after the recovery of telemetry data. These sensors measure the temperatures of fuel cells 1 and 3 radiator inlets and outlets.

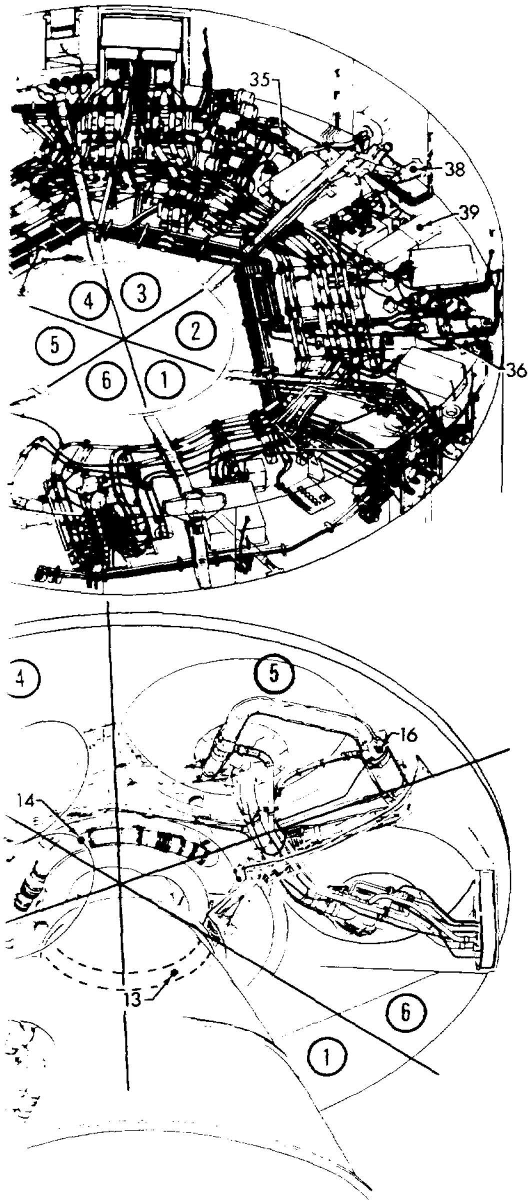
5. The temperature of quad C and D reaction control engines continued the same rate of rise after data loss as before data loss.

FAILURE OF CRYOGENIC OXYGEN SYSTEM

The telemetered quantities from cryogenic oxygen tank no. 2 were all off-scale following the recovery of telemetry at 55:54:55. Since no accurate assessment of the damage to this tank has been possible, the readings of the sensors within it are in doubt. The temperature was reading full-scale high and continued this way until 55:55:49, This page left blank intentionally.


1
2
3
5
6
2
3
5
6
4
1
11
30,33
21(20)
(19)22
(24) 25
26(23)
31,34
32,29
40
41
(7)8
(10)9
(37)
27
28
12
(17)18
13
14
Bay 4

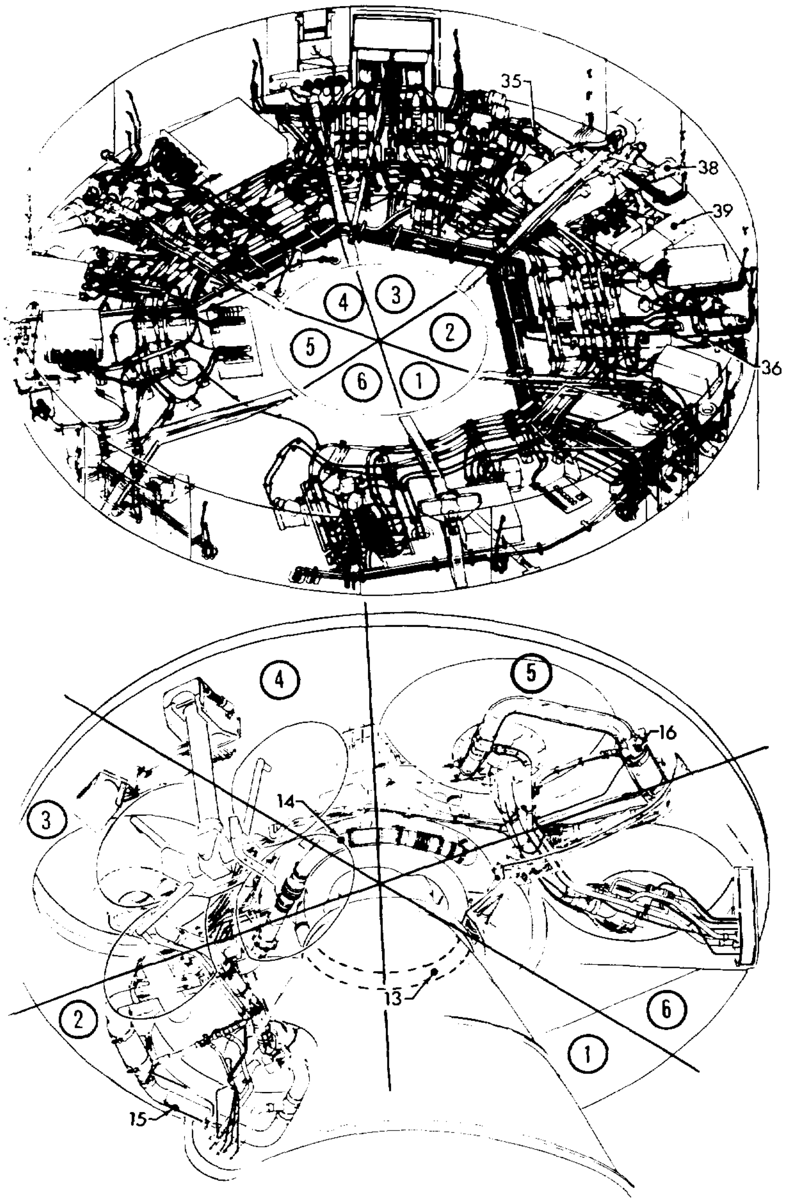

3
2
15



Service module temperature measurements			
Number	Measurement number	Title	Remarks
1	SC2090	Fuel cell 1 radiator inlet	
2	SC2091	Fuel cell 2 radiator inlet	
3	SC2092	Fuel cell 3 radiator inlet	
4	SC2087	Fuel cell 1 radiator outlet	
5	SC2088	Fuel cell 2 radiator outlet	
6	SC2089	Fuel cell 3 radiator outlet	
7[a]	SA2377	Bay 2 oxidizer tank surface	Opposite 9
8	SA2378	Bay 3 oxidizer tank surface	
9	SA2379	Bay 5 fuel tank surface	
10[a]	SA2380	Bay 6 fuel tank surface	Opposite 8
11	SP0002	Helium tank	
12	SP0045	Service propulsion valve body	
13	SP0048	Service propulsion fuel feed line	
14	SP0049	Service propulsion oxidizer feed line	
15	SP0054	Service propulsion oxidizer line	
16	SP0057	Service propulsion fuel line	
17[a]	SP0061	Service propulsion injector flange 1	Opposite 18 on flange
18	SP0062	Service propulsion injector flange 2	
19[a]	SR5013	Reaction control helium tank quad A	Bay 6 opposite 21
20[a]	SR5014	Reaction control helium tank quad B	Bay 2 opposite 22
21	SR5015	Reaction control helium tank quad C	Bay 3
22	SR5016	Reaction control helium tank quad D	Bay 5
23[a]	SR5065	Reaction control engine package quad A	Bay 6 opposite 25
24[a]	SR5066	Reaction control engine package quad B	Bay 2 opposite 26
25	SR5067	Reaction control engine package quad C	Bay 3
26	SR5068	Reaction control engine package quad D	Bay 5
27	SC0043	Hydrogen tank 1	
28	SC0044	Hydrogen tank 2	
29	SC2084	Fuel cell 1 skin	Internal
30	SC2085	Fuel cell 2 skin	Internal
31	SC2086	Fuel cell 3 skin	Internal
32	SC2081	Fuel cell 1 condenser exhaust	Internal
33	SC2082	Fuel cell 2 condenser exhaust	Internal
34	SC2083	Fuel cell 3 condenser exhaust	Internal
35	SF0260	Environmental control primary radiator inlet	
36	SF0262	Environmental control secondary radiator inlet	
37[a]	SF0263	Environmental control secondary radiator outlet	Bay 6 opposite
38	ST0840	Nuclear particle detector	
39	ST0841	Nuclear particle analyzer	
40	SC0041	Oxygen tank 1	
41	SC0042	Oxygen tank 2	

[a] Located on opposite side of vehicle and not shown in the view.

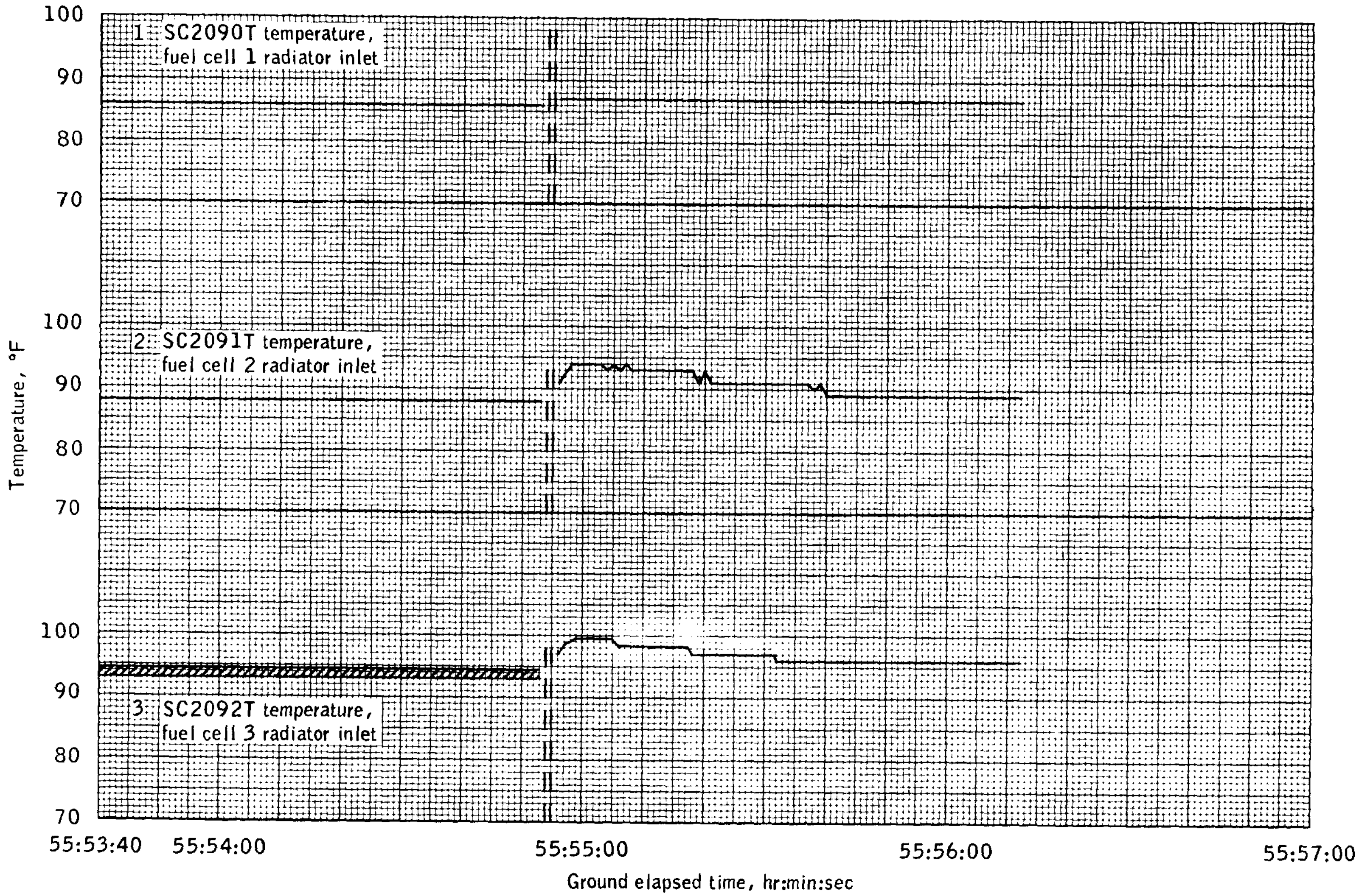
Figure B5-14.- Temperature sensor location in Apollo service module.



Service module temperature measurements			
Number	Measurement number	Title	
1	SC2090	Fuel cell 1 radiator inlet	
2	SC2091	Fuel cell 2 radiator inlet	
3	SC2092	Fuel cell 3 radiator inlet	
4	SC2087	Fuel cell 1 radiator outlet	
5	SC2088	Fuel cell 2 radiator outlet	
6	SC2089	Fuel cell 3 radiator outlet	
7[a]	SA2377	Bay 2 oxidizer tank surface	Opposi
8	SA2378	Bay 3 oxidizer tank surface	
9	SA2379	Bay 5 fuel tank surface	
10[a]	SA2380	Bay 6 fuel tank surface	Opposi
11	SP0002	Helium tank	
12	SP0045	Service propulsion valve body	
13	SP0048	Service propulsion fuel feed line	
14	SP0049	Service propulsion oxidizer feed line	
15	SP0054	Service propulsion oxidizer line	
16	SP0057	Service propulsion fuel line	
17[a]	SP0061	Service propulsion injector flange 1	Opposi
18	SP0062	Service propulsion injector flange 2	
19[a]	SR5013	Reaction control helium tank quad A	Bay 6
20[a]	SR5014	Reaction control helium tank quad B	Bay 2
21	SR5015	Reaction control helium tank quad C	Bay 3
22	SR5016	Reaction control helium tank quad D	Bay 5
23[a]	SR5065	Reaction control engine package quad A	Bay 6
24[a]	SR5066	Reaction control engine package quad B	Bay 2
25	SR5067	Reaction control engine package quad C	Bay 3
26	SR5068	Reaction control engine package quad D	Bay 5
27	SC0043	Hydrogen tank 1	
28	SC0044	Hydrogen tank 2	
29	SC2084	Fuel cell 1 skin	Intern
30	SC2085	Fuel cell 2 skin	Intern
31	SC2086	Fuel cell 3 skin	Intern
32	SC2081	Fuel cell 1 condenser exhaust	Intern
33	SC2082	Fuel cell 2 condenser exhaust	Intern
34	SC2083	Fuel cell 3 condenser exhaust	Intern
35	SF0260	Environmental control primary radiator inlet	
36	SF0262	Environmental control secondary radiator inlet	
37[a]	SF0263	Environmental control secondary radiator outlet	Bay (
38	ST0840	Nuclear particle detector	
39	ST0841	Nuclear particle analyzer	
40	SC0041	Oxygen tank 1	
41	SC0042	Oxygen tank 2	

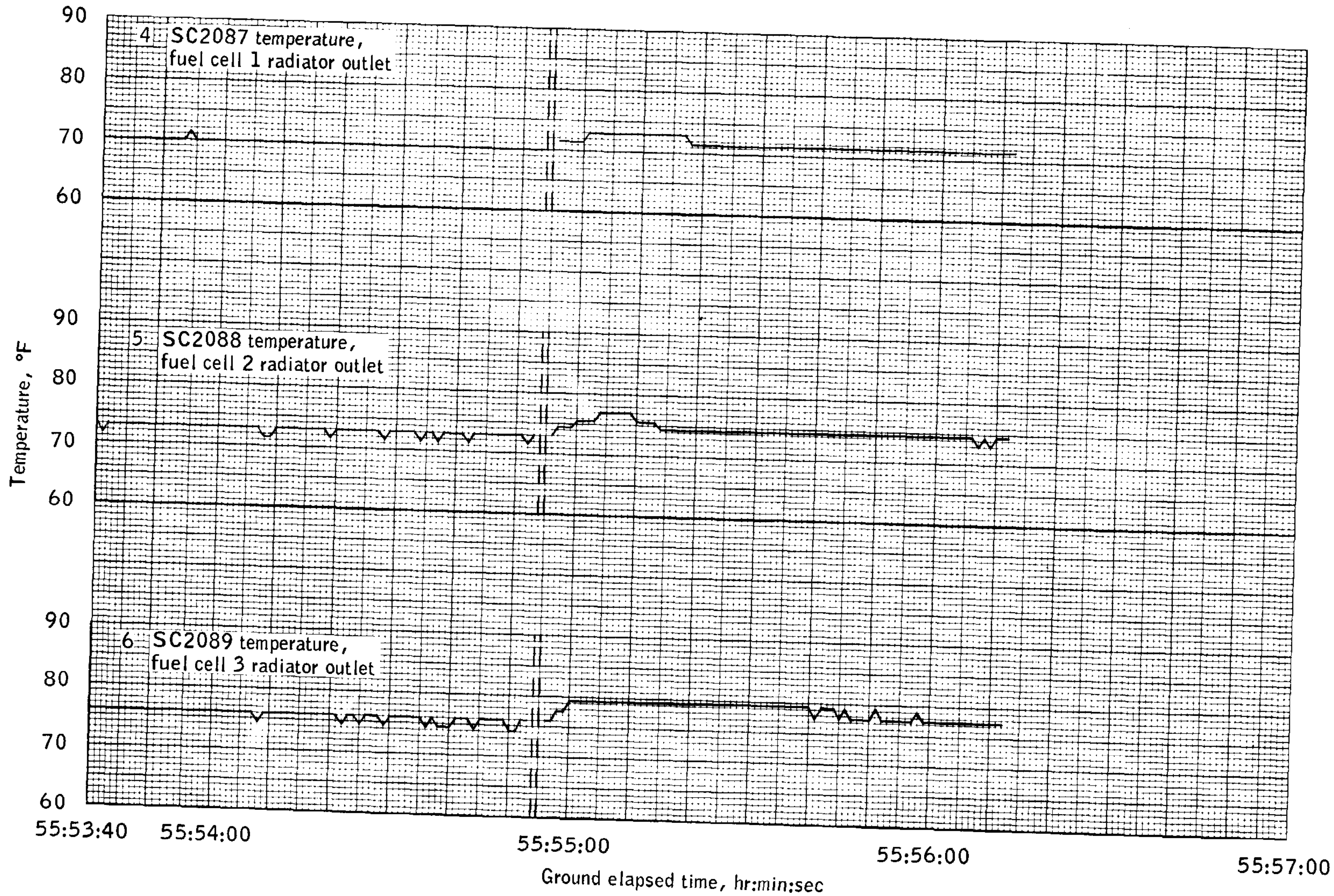
[a] Located on opposite side of vehicle and not shown in the view.

Figure B5-14.- Temperature sensor location in Apollo s



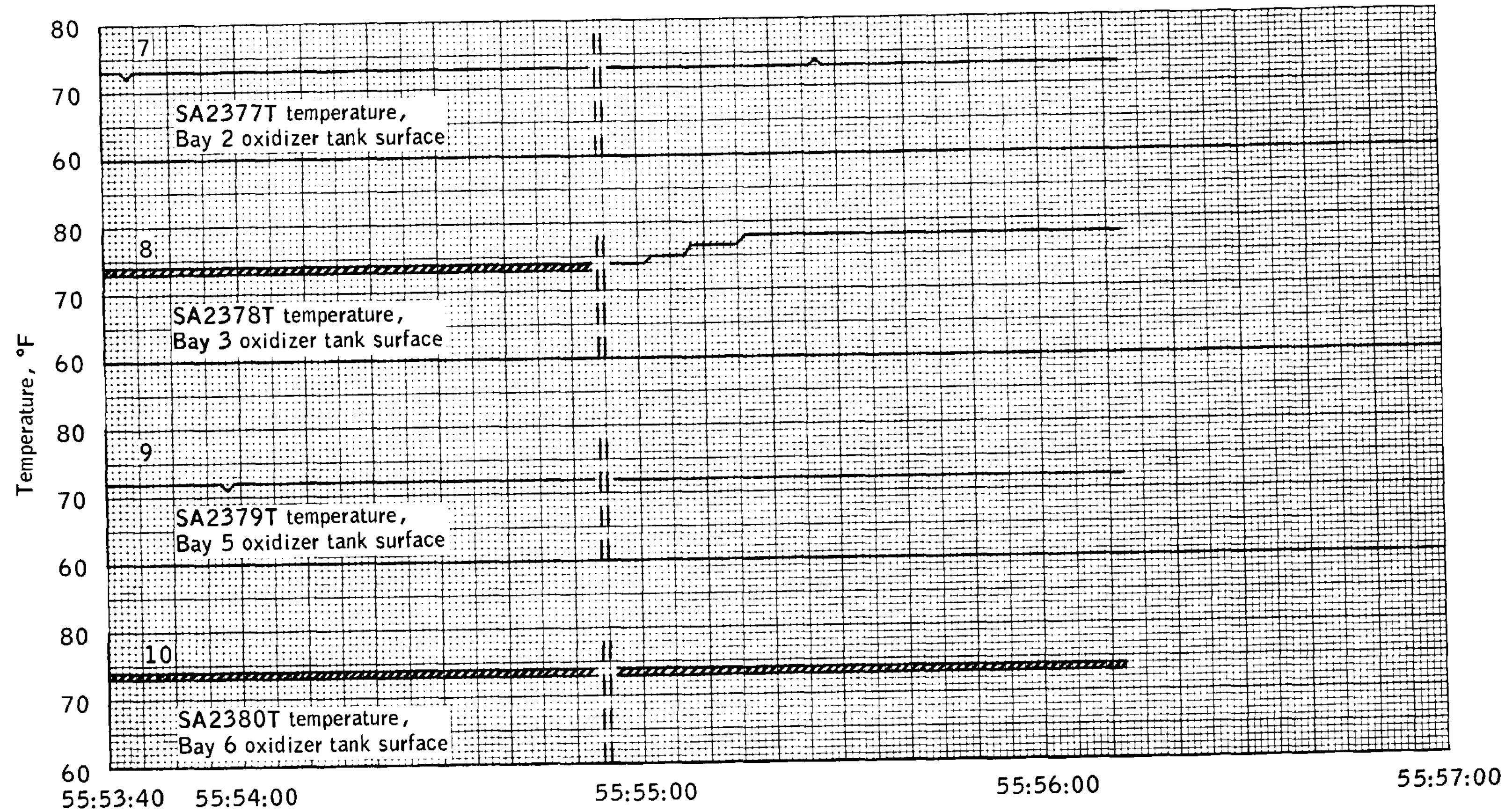
(a) Radiator inlet temperatures.

Figure B5-15.- Service module temperature history.



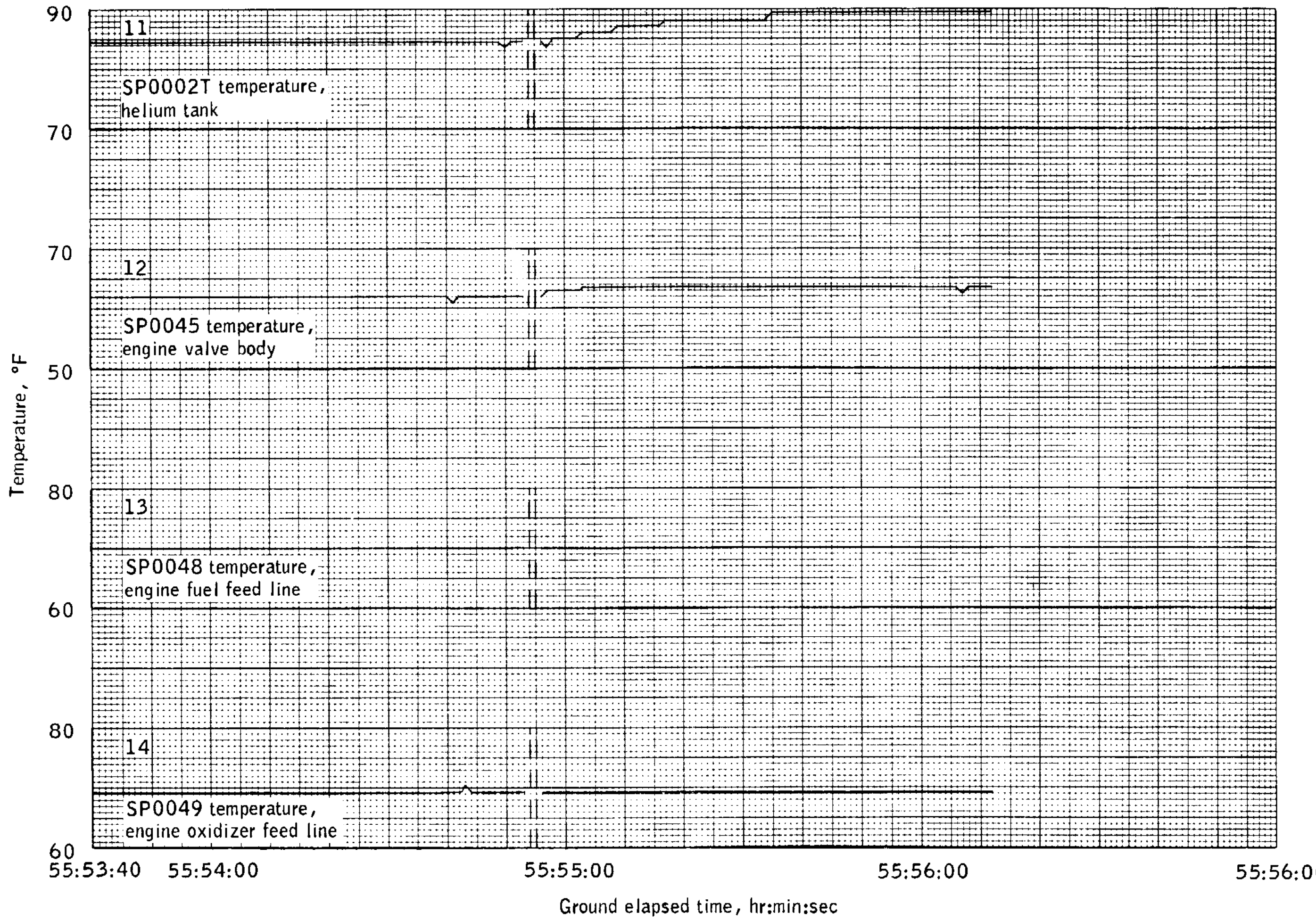
(b) Radiator outlet temperatures.

Figure B5-15.- Continued.



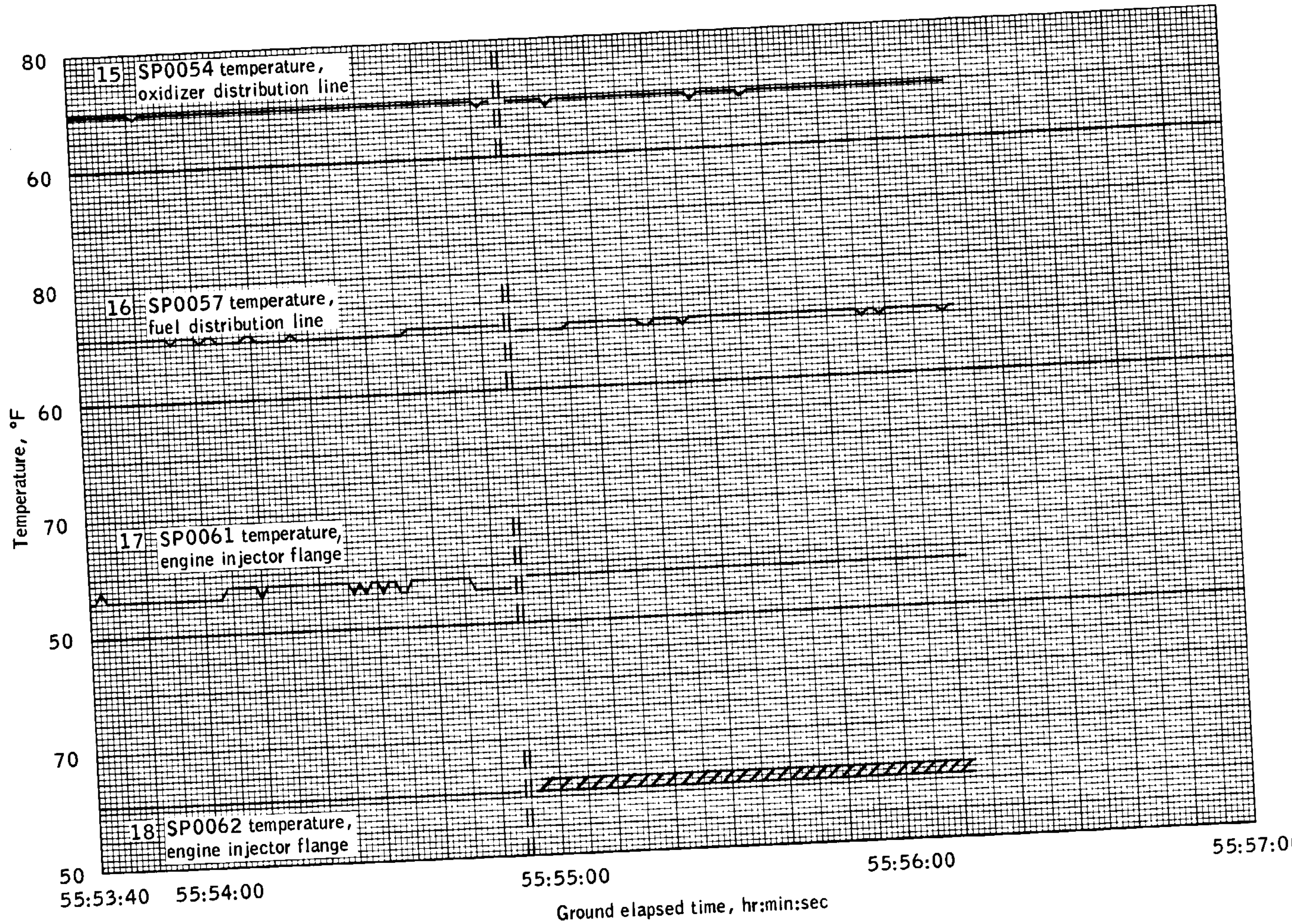
(c) Tank surface temperatures.

Figure B5-15.- Continued.



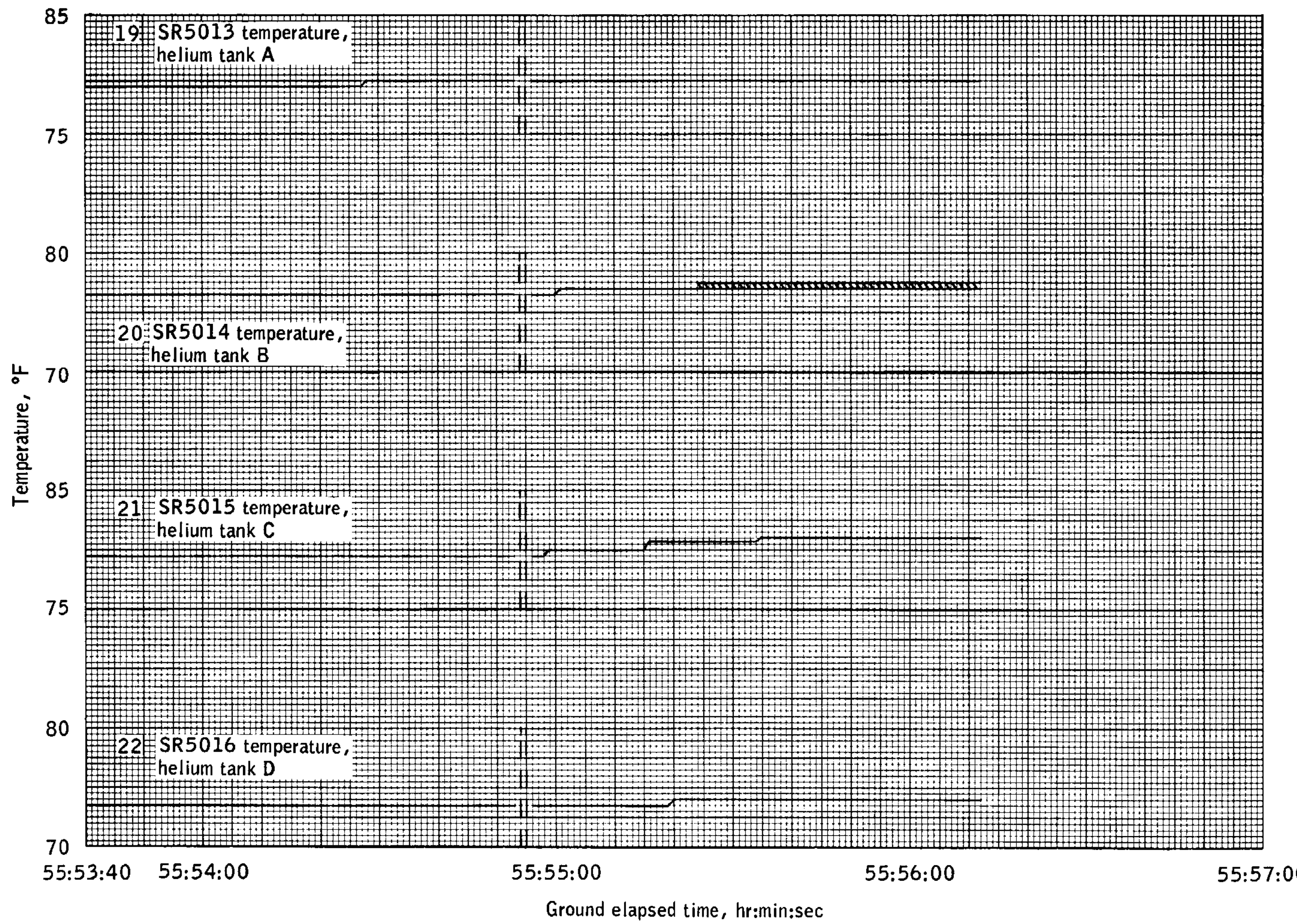
(d) Service propulsion temperatures, group 1.

Figure B5-15.- Continued.



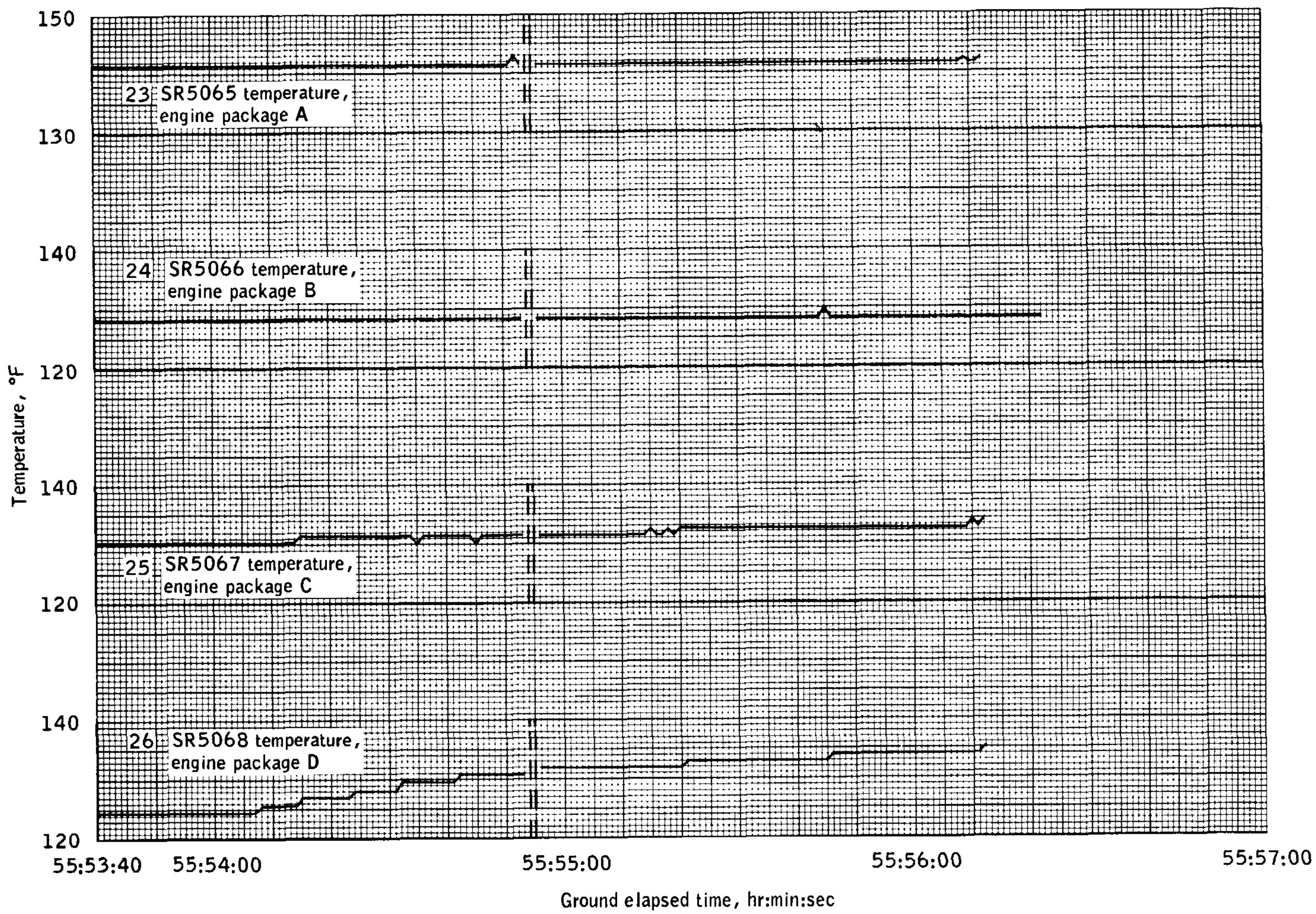
(e) Service propulsion temperatures, group 2.

Figure B5-15.- Continued.



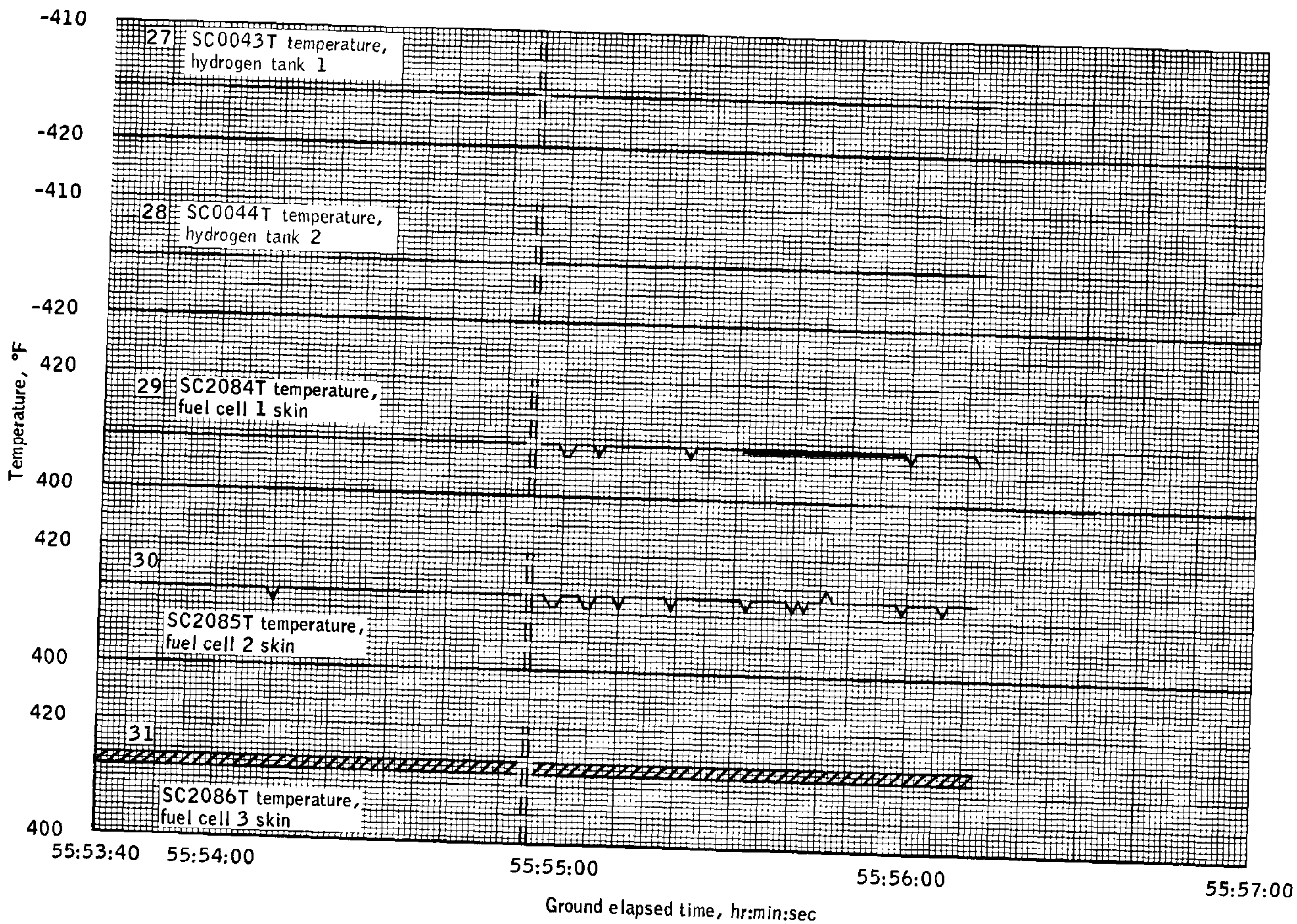
(f) Reaction control helium tank temperatures.

Figure B5-15.- Continued.



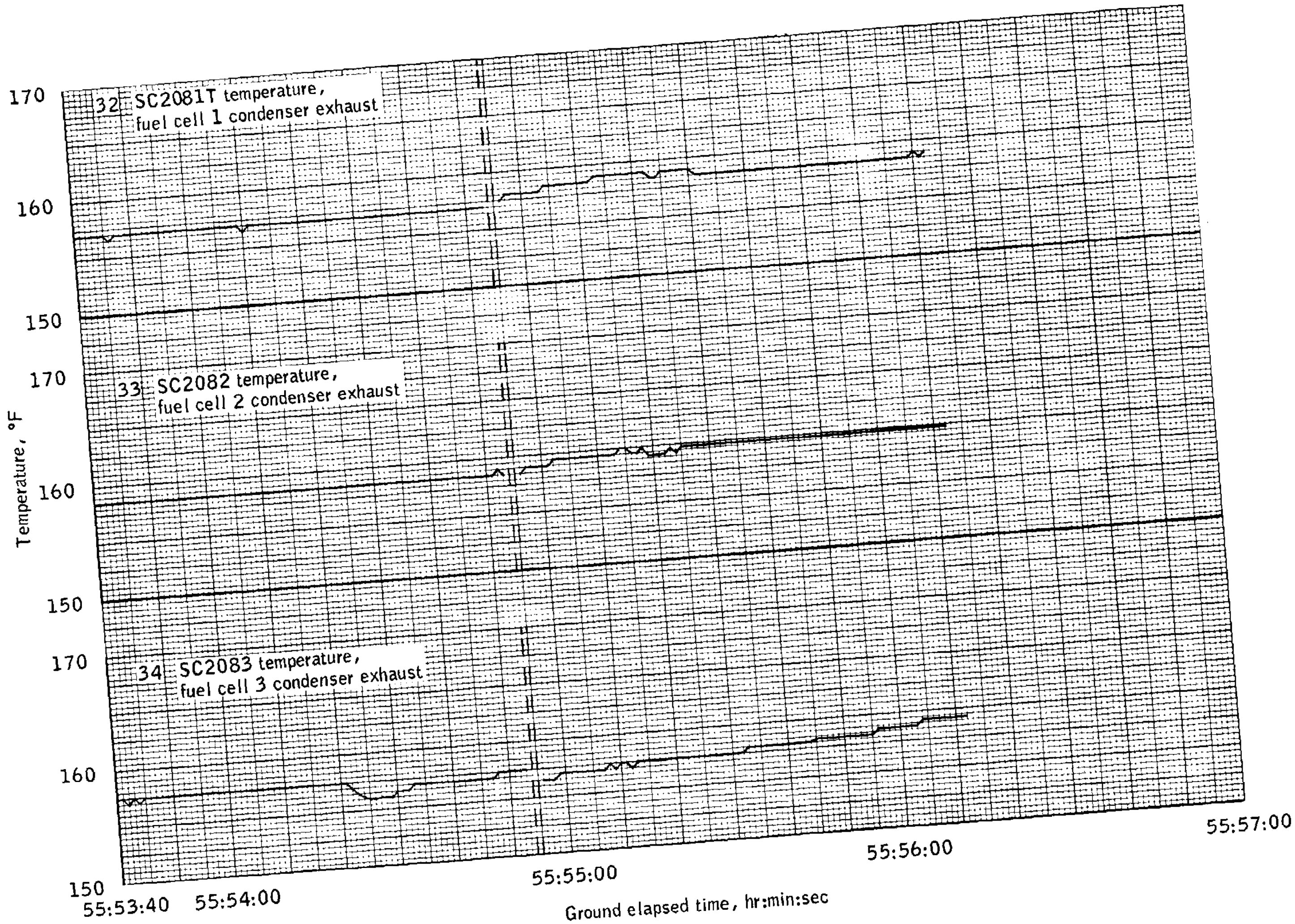
(g) Reaction control engine package temperatures.

Figure B5-15.- Continued.



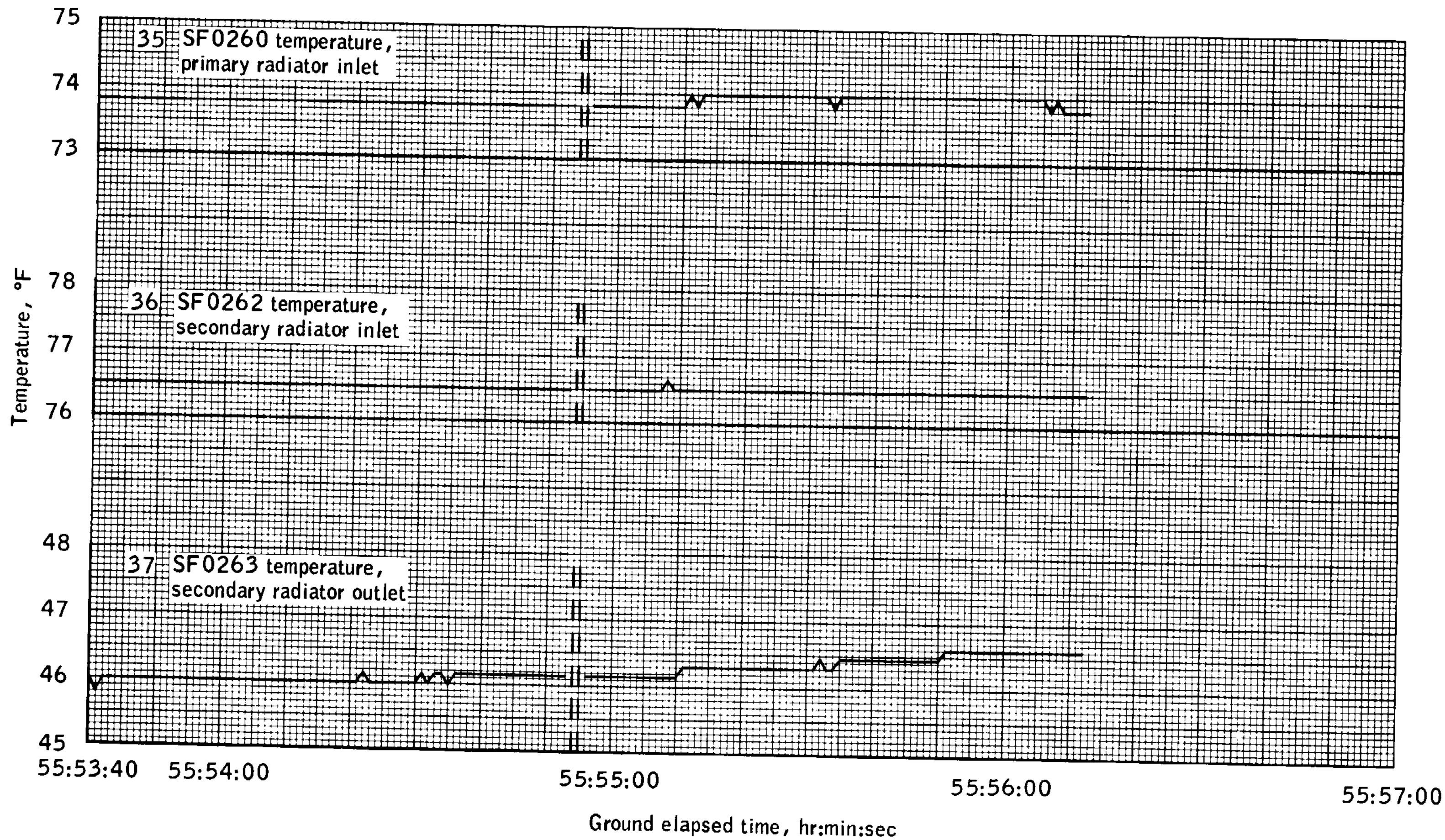
(h) Fuel cell skin temperatures.

Figure B5-15.- Continued.



(i) Fuel cell condensor exhaust temperatures.

Figure B5-15.- Continued.



(j) Environmental control radiator temperatures.

Figure B5-15.- Concluded.

when it began a steady decrease which ended at 55:56:48 in an off-scale-low reading. This behavior is a possible result of a failure of the sensor. For an explanation of possible failure modes of this sensor, see Part B7 of this Appendix. The pressure of cryogenic oxygen tank no. 2, sensed remotely, read off-scale low and continued to show this reading. Off-scale low for this sensor represents a pressure of 19 psia or below.

The quantity gage read full-scale high after telemetry recovery and continued in this state until 55:56:38 when it began oscillating in an erratic manner. The oscillation continued until 55:57:47 when the gage assumed an off-scale-low reading. The quantity gage and its failure modes are described in Part B7 of this Appendix.

The pressure in cryogenic oxygen tank no. 1 had dropped from 879 psia to 782 psia during telemetry loss. This pressure continued to drop at a slow rate for about 2 hours until it was insufficient for operation of the last remaining fuel cell.

The heaters in both cryogenic oxygen tanks were off prior to telemetry loss as a result of the high pressure in tank no. 2. After telemetry recovery the total fuel cell current indicated an increase of about 5 amperes after known loads had been accounted for. The low pressure levels in both oxygen tanks should have caused both heaters to be on at this time. The total current drain by the heaters in any one tank is about 5 amperes. It therefore appears that the heaters in one tank had come on since telemetry loss and were operating at this time. It is possible that the heaters in cryogenic oxygen tank no. 2 were either physically open-circuited before or at the time of the bang.

Additional evidence that the heaters in only one tank were on can be obtained by observing that at 56:19:03 the spacecraft dc current decreased 5 amperes. This is the time at which the crew began to power down the spacecraft according to the emergency powerdown checklist. If heaters in both oxygen tanks had been on at that time, the current should have decreased approximately 11 amperes instead of the observed 5 amperes.

OPERATION OF THE ELECTRICAL POWER SYSTEM

Following the period of telemetry loss, a high-current condition existed on the fuel cell outputs for 19 seconds. In the same time period, the two dc main voltages were approximately 0.9 volt lower than their previous values. By 55:55:14 the voltages and currents had become normal. The observed currents during the 19-second period have been correlated with reaction control system jet firings and an inertial measurement unit heater cycle. The excellent correlation indicates that no unaccountable loads were added to the power system during this time period.

The crew observed a master caution and warning signal 1 or 2 seconds after the bang, along with an indication of undervoltage on dc bus B. The master caution and warning was turned off at 55:55:00.

Within 5 seconds after the resumption of telemetry data, the oxygen flow rates to fuel cells 1 and 3 had decreased to approximately 20 percent of their prior values. These flow rates remained at a sufficiently low level to cause failure of fuel cells 1 and 3 at approximately 55:58. The most probable explanation for the reduced oxygen flow rates is that at the time of the bang a sufficiently intense shock occurred to close the valves in the oxygen lines feeding fuel cells 1 and 3.

There is sufficient volume in the oxygen lines between the supply valves and the fuel cells to maintain fuel cell operation for the observed time of about 3 minutes. The intensity of the shock is indicated by the fact that the reaction control system valves on quad C were closed. Tests on these valves have shown that 80g for 10 milliseconds will cause them to close. Tests on the oxygen supply valves have shown that a shock of 86g for 11 milliseconds will cause them to close.

The crew was not alerted to the abnormally low flow rate of oxygen to fuel cells 1 and 3 because the hydrogen supply valves had not been closed. The valve closure indicator is only activated when both the oxygen and hydrogen supply valves to a fuel cell are closed. The first indication to the crew that the power system was failing came at 55:57:39 when the master caution and warning was triggered by a main bus B undervoltage, occasioned by the failure of fuel cell 3. Main bus B voltage dropped to an unusable level within 5 seconds, causing ac bus 2 to drop to zero at 55:57:45.

The crew quickly checked the ac and dc voltage levels, recognized that ac bus 2 had failed, and responded by switching ac loads from ac bus 2 to ac bus 1. This heavier load on ac bus 1 was reflected as a heavier load on dc main A, causing it to drop in voltage. At 55:58:06, a dc main A undervoltage master caution and warning was triggered as the main voltage dropped to between 25 and 26 volts. Shortly afterwards, at approximately 55:58:06, fuel cell 1 failed, placing the entire load of dc main A on fuel cell 2. Fuel cell 2 was now called upon to supply a current of 50 amperes.

Fuel cell 2 remained the major source of electrical power in the command module for the next 2 hours. During this time, telemetry continued to indicate a decreasing cryogenic oxygen pressure in tank no. 1. At 58:04 battery A was connected to main bus A and fuel cell 2 was removed from operation when oxygen flow became insufficient.

PART B6

POSTINCIDENT EVENTS

The description of postincident events is presented in two sections. The first, entitled "Immediate Recovery," describes the flightcrew and flight controller actions during the 2-1/2-hour period following the incident. This section is primarily concerned with actions of the flightcrew and flight controllers during this period in response to the immediate problems caused by the spacecraft failures. The long-term problems addressed by Mission Control are described in the second section, entitled "Plans and Actions Taken to Return the Crew to Earth."

IMMEDIATE RECOVERY

The first indication in the Mission Control Center of any problem in the spacecraft came from the Guidance Officer who reported that he had observed a "hardware restart." This term describes the action of the onboard computer when certain computer electrical problems occur, such as a reference voltage or an oscillator frequency getting out of tolerance. When this occurs, the computer stops its computations and recycles to a specified location in the program. Computations will not resume until the out-of-tolerance condition is cleared. At 55:55 this event occurred so rapidly that the flight controllers did not observe the computer halt; they only saw that it had occurred.

The report of the hardware restart was followed almost immediately by the crew's report, "I believe we've had a problem here." This was followed quickly by a statement from the crew that they had a main bus B undervolt indication from the master caution and warning (MC&W) system. Flight controllers responsible for the electrical, environmental control, and instrumentation systems immediately searched their displays, but at that time there were no indications of any electrical problems, all voltages and fuel cell currents appeared normal. Apparently, the main bus B undervolt problem was a transient that had cleared up, for the crew next reported the bus voltages were "looking good." However, the flight controllers knew that all was not well because the oxygen tank measurements indicated some major problems in this system, or its instrumentation.

The next report in Mission Control was from the flight controller responsible for the communication systems. He stated that the high-gain antenna on the spacecraft had unaccountably switched from narrow beam width to wide beam width at approximately the same time the problem had occurred.

In sorting out these pieces of information, the flight controllers initially suspected that there had been an instrumentation failure. However, with the subsequent failure of main bus B and ac bus 2 it became more obvious that a serious electrical problem existed. The flight controllers considered the possibility that a short had occurred, and that this was in some way related to the unusual behavior of the high-gain antenna. The rapid rate at which so many parameters in the electrical and cryogenic system had changed state made it impossible to tell which were causes and which were effects.

The Mission Control Center response to the situation is described in this section of the report. The time interval covered is from 55 hours 58 minutes ground elapsed time (55:58 g.e.t.) to 58:40 g.e.t., when all power was removed from the command module (CM). The major portion of the activities of both the flightcrew and the flight controllers in this time period was directed toward (1) evaluation and management of the electrical and cryogenic oxygen problems; (2) maintenance of attitude control; and (3) activation of the lunar module (LM). A chronological listing of all significant actions is presented first. This is followed by a more detailed description of the three categories of activities mentioned above.

Chronology of Spacecraft Reconfiguration Actions

This listing was obtained from transcripts of air-to-ground voice records (ref. 2) and the "Flight Director" loop in the Mission Control Center. Additional information was obtained from interviews with members of the flight control team. Some editing has been done to eliminate the description of routine actions which obviously have no significance to this investigation: examples are omni antenna switching and the loading of weight and inertia information in the digital autopilot. The times at which specific actions are listed are only approximately correct, (±1 minute) since there was no precise time correlation available.

55:59 - Fuel cell main bus connection.- Mission Control requested the crew to connect fuel cell 1 to main bus A and fuel cell 3 to main bus B. Although there was no direct evidence the crew had changed the fuel cell and main bus configuration, the flight controller believed that this might be the case. The configuration prior to the loss of main bus B was as follows: fuel cell 1, main A; fuel cell 2, main A; and fuel cell 3, main B.

56:03 - Entry battery on line.- The crew placed entry battery A on main bus A to increase the bus voltage. Mission Control was just about to ask that this be done. The bus voltage was approximately 25 volts, which is about 1-1/4 volts below the MC&W trip limit.

56:08 - Open circuit fuel cell 1.- Mission Control requested the crew to open circuit fuel cell 1. Flight controllers did not understand the problems with the fuel cells; the data were confusing and incomplete. In an effort to get some new information, the controllers decided to take all loads off fuel cell 1 to see if it would behave any differently. It was not putting out any power so there was no reason to leave it connected to the main bus.

56:11 - Power RCS jets from main bus A.- Mission Control requested the crew to position some RCS jet select switches to main A power. All of the quad C jets and B-3 and B-4 jets had been powered from main bus B and since that bus had no power on it, they could not fire except by the "Direct" coils. By switching these jets to main bus A, there was at least one jet available for automatic control in each direction about each axis.

56:14 - Start emergency powerdown.- Mission Control advised the crew to use page 1-5 of their Emergency Powerdown Checklist, part of the Flight Data File (ref. 7) carried by the crew. Mission Control wanted to get the current on main bus A reduced by at least 10 amps, and then take the entry battery A off-line. The list down to "BMAG #2-off" was to be turned off; it included the following: all cryo tank heaters and fans, G&N optics power, potable water heater, SPS line heater, SPS gaging, suit compressor, all fuel cell pumps, SMRC heaters, ECS radiator heaters, and SPS gimbal motors.

56:23 - Power AC bus 2 with inverter (INV) 1.- The crew was requested to power both ac busses with inverter no. 1. The primary purpose was to get telemetry data from oxygen tank no. 2 which is powered by ac bus 2 only.

56:24 - Turn fuel cell no. 2 pump on.- The crew had turned the pumps off in following the emergency powerdown list. The pumps circulate glycol and hydrogen for internal cooling in the fuel cells. They could have been left off for an hour or more, but fuel cell performance would have been degraded.

56:30 - Select main bus A power to RCS jet A-3.- The spacecraft was drifting in pitch without any apparent control. Quad C, which should have been controlling pitch, did not seem to be firing at all. To try to regain control in pitch, the quad A-3 jet was switched to main bus A power.

56:33 - Open circuit fuel cell no. 3.- Same reason as for open circuit fuel cell no. 1.

56:33 - Reconfigure quad B and D thrusters.- Flight control felt that a quad B thruster might be causing the spacecraft attitude deviations, and asked the crew to take off all power to the quad B jets. To compensate for quad B being off, all jets in quad D were selected to be powered from main bus A.

56:34 - Battery A taken off line.- The bus loads had been reduced sufficiently to allow fuel cell 2 alone to keep the bus voltage up. It was highly desirable to use the battery as little as possible, because there was no guarantee it could be recharged.

56:35 - Isolate the surge tank.- The crew was directed to isolate the CM oxygen surge tank. The purpose was to preserve an oxygen supply for reentry.

56:38 - Oxygen tank no. 1 heaters and fans.- Mission Control requested the crew to turn on the heaters in cryogenic oxygen tank no. 1 in an effort to build up the tank pressure. The current was observed to increase about 5 amperes, indicating they did come on. About 2 minutes later, since there was no increase in pressure, the crew was asked to turn on the fans in this tank.

56:45 - BMAG 2 off.- In an effort to further conserve power, the second BMAG was powered down.

56:51 - Turn off thruster C-1.- Thruster C-1 seemed to be firing very frequently without any apparent reason. The crew was requested to turn off all power to this thruster. The attitude disturbances were noted to have been virtually ended at about 56:40.

56:57 - Fuel cell no. 3 shutdown.- Fuel cells 1 and 3 had been open circuited earlier because they were not putting out any power. With the cryogenic oxygen leaking at its present rate, there would be no reactants for the fuel cells within a short time. Because there was a possibility that the oxygen was leaking down stream of one of the fuel cell reactant valves, it was decided to shut off these valves in an effort to save the oxygen remaining in tank no. 1. Fuel cell 3 was selected because it had been the first of the two to fail.

57:03 - Main bus A power to thruster A-4.- The crew was told to put power to thruster A-4 by connecting to main bus A. The spacecraft had a positive pitch rate and the crew was unable to stop it with quad C thrusters. With A-4 activated, pitch control was regained.

57:18 - Fuel cell no. 1 shutdown.- Shutting down fuel cell 3 did not effect the oxygen leak rate, so the reactant valves to fuel cell 1 were closed in an effort to try to stop the leak.

57:22 - Charge battery A.- The crew was directed to charge battery A. The fuel cell 2 was maintaining main bus A voltage at an adequate level to support the battery charger. Mission Control decided to charge battery A for as long as possible. Since the oxygen was still leaking, it was obvious that all fuel cell operation would be lost within about an hour.

57:29 - Disable power to quad C.- It appeared that quad C was not thrusting, although it was receiving firing signals. The explanation of this was that the propellant isolation valves had been closed by the "bang" at 55:55 and no propellant was being fed to the thrusters. Since these valves are powered by the main bus B, they could not be opened without getting power to this bus. The firing signals to quad C therefore were a useless drain of power on bus A, and the crew was directed to disconnect the thrusters from it.

57:39 - Fans on in oxygen tank no. 2.- In a final effort to try to increase the pressure in oxygen tank no. 2, the crew was directed to turn on the fans in that tank.

57:40 - LM power on.- The crew reported, "I've got LM power on."

57:49 - Stopped charging battery A.- In order to be ready to bring battery A on-line when fuel cell 2 failed, it was decided to terminate the charge. A total of about 0.75 amp-hours had been restored.

57:53 - CSM glycol pump off.- To reduce the main bus A loads, the crew was directed to turn off the glycol pump and to bypass the environmental control system radiators.

57:55 - Turn off oxygen tank no. 2 fans.- To further reduce the load on main bus A, the pumps in fuel cell 2 and the fans in oxygen tank no. 2 were turned off.

57:57 - LM data received.- Low-bit-rate telemetry data were received in the Mission Control Center at this time.

58:04 - Battery A on.- The crew powered main bus A with battery A in anticipation of the loss of fuel cell 2. The pressure in oxygen tank no. 1 was approximately 65 psi at this time.

58:07 - CSM communication reconfiguration.- The Command Module Pilot (CMP) was directed to turn off the CSM S-band primary power amplifier and to select low bit rate and down-voice backup. This was to reduce the load on battery A and maintain adequate circuit margins on the communication downlink.

58:18 - CSM guidance and navigation powerdown.- The CSM inertial platform (IMU) alignment had been transferred to the LM and verified by Mission Control. The crew was directed to turn off the CSM computer, the IMU, and the IMU heaters.

58:21 - Powerdown CM attitude control.- In an effort to reduce electrical power requirements in the CM, the CMP was directed to turn off "SCS Electronics Power," and "all Rotational Control Power Off." This completely removed all attitude control capability from the CM.

58:22 - LM RCS activation.- The LM crew was advised to pressurize the RCS, turn on the thruster heaters, and power up the attitude reference system.

58:27 - Activate "Direct" attitude control.- It was discovered that neither module was configured to provide attitude control. The quickest way to regain it was to have the CMP power up the rotational hand controller and the Direct coils.

58:36 - Fuel cell 2 shutdown.- The pressure of the oxygen being fed to this fuel cell had dropped below the operating level at 58:15 and it had stopped supplying current. As part of the CSM "safing," the fuel cell was disconnected from the bus and the reactant valves were closed.

58:40 - CSM powered down.- Battery A was disconnected from main bus A at this time, removing all power from the CSM.

Evaluation of Electrical and Cryogenic Oxygen Problems

The failure of fuel cell 3 resulted in the interruption of electrical power to several components in the spacecraft, including part of the telemetry signal conditioning. Main dc bus B was being powered only by fuel cell 3, so when its output dropped from about 25 amperes to less than 5 amperes, the bus voltage dropped from the normal 28 volts to less than 5 volts (fig. B5-2). Inverter no. 2, supplying power to ac bus 2, was being driven by main bus B and dropped off the line when the bus B voltage fell below about 16 volts. The bus failures, coupled with the cryogenic oxygen tank indications and some questionable instrumentation readings in fuel cells 1 and 3 (nitrogen and oxygen pressures), caused some initial uncertainty in the Mission Control Center.

The initial reaction was that there possibly had been a problem with major related instrumentation discrepancies. It was not clear that the telemetry quantities of cryogenic oxygen tank measurements or the fuel cell parameters were valid indications of conditions. For instance, the indication of no reactant flow and no fuel cell currents was compatible with fuel cells 1 and 3 having become disconnected from the main busses. Therefore, there was no reason to believe that they could not be reconnected. The lack of power output from the fuel cells could not be explained by the available information, i.e., the rapidity with which the fuel cells had failed. An additional factor that had to be considered was that the high-gain antenna had unaccountably switched from narrow to wide beam width at about this same time. Some trouble had been experienced earlier in getting this antenna to "lock on" in narrow beam width, and the possibility of a short in the antenna electronics could not be ruled out.

The first direction given to the crew was at 56:00 to return the bus power configuration to the normal operating mode; that is, fuel cell 1 powering bus A and fuel cell 3 powering bus B. The primary purpose of this direction was to get the spacecraft in a known configuration and determine if the fuel cells could be reconnected to the main busses. There are no telemetry parameters which show which fuel cells are supplying power to which busses, but the flight controllers were of the opinion that some reconfiguration might have been done by the crew.

In operating with split busses, that is, with two fuel cells powering main bus A and one fuel cell powering main bus B, the amount of equipment tied to bus A represents approximately twice the load as that to bus B. When fuel cell 1 failed, fuel cell 2 had to take up the additional load on bus A. In doing so, the voltage dropped to about 25 volts, which is low enough to cause a caution and warning indication. There was no particular harm in the bus voltage being this low, but if it dropped any lower the performance of some of the telemetry equipment would be affected and the flight controllers and crew were concerned. Normal bus voltage is above 27 volts, and the master caution and warning indication is triggered at 26-1/4 volts or less. Had fuel cell 2 been tied to both main busses as on previous missions, the total spacecraft current of 73 amperes would have driven both busses as low as 21 volts. The crew put entry battery A on bus A at 56:03 to bring the bus voltage up. Mission Control concurred in this action.

In an effort to obtain more data for troubleshooting the situation, the crew was asked to read out the onboard indications of oxygen pressure and nitrogen pressure in fuel cells 3 and 1, respectively. At 56:08 the crew was requested to disconnect fuel cell 1. This fuel cell was not supplying any power, so to disconnect it should have no effect on the bus voltage, but there was a possibility that it might give some different indications in the fuel cell telemetry parameters. There was no change in the fuel cell parameters when it was disconnected and the onboard readouts of nitrogen and oxygen pressure were the same as those on the ground, which did not add to the understanding of the situation.

Efforts to sort out the various telemetry indications and crew reports continued for the next several minutes. The next direction given to the crew was to proceed with the emergency powerdown of the electrical system, using page EMER 1-5 of the CSM Emergency Checklist which is part of the Flight Data File carried in the CSM (ref. 7). It was important to reduce the electrical loads to a low enough value for the single operating fuel cell to be able to supply all the necessary power. Mission Control was anxious to get entry battery A back off line to preserve as many amp-hours as possible.

The next step in the attempt to determine what was happening was to get power back to ac bus 2. Flight controllers considered powering ac bus 2 with inverter 3 driven from main bus A. Further consideration, however, led to the decision to simply tie ac bus 2 to inverter no. 1 which was already powering ac bus 1. Mission Control was interested in getting power to ac bus 2, since this is the only bus that powered the cryogenic oxygen tank no. 2 quantity and temperature telemetry. A temperature measurement was needed to confirm the zero pressure indication. The indications from oxygen tank no. 1 were that pressure and quantity were decreasing at a relatively high rate and it was imperative to immediately establish the condition of tank no. 2. It was not until after ac bus 2 had been powered up and oxygen tank no. 2 indicated empty, that the extreme seriousness of the situation was clear.

In proceeding through the emergency powerdown, the crew had placed the fuel cell pump switch to the "off" position in the one remaining good fuel cell; however, the pumps actually went off with loss of main bus B/ac bus 2 power. At 56:24, the Lunar Module Pilot (LMP) pointed this out to Mission Control, who in turn directed him to turn the pump back on. The only problem associated with leaving it off as much as an hour is that the fuel cell power output would start to degrade and no harm was done. But in the situation that existed, it is not inconceivable that had the crew not advised Mission Control of the fuel cell pump being off it would have been overlooked until a rise in the fuel cell 2 loop temperatures gave this indication.

Further direction in the management of the electrical system was not given until about 56:33. At this time the crew was directed to open circuit fuel cell 3 for the same reason as fuel cell 1 was open circuited earlier. At 56:35 the crew was requested to isolate the surge tank and at approximately this same time Mission Control also directed the crew to remove battery A from main bus A. The emergency powerdown had resulted in a load reduction such that the fuel cell alone could maintain bus voltage above 27 volts.

It had become apparent that the operation of fuel cells 1 and 3 probably could not be regained under any condition, and that with oxygen tank 1 quantity decreasing at its then present rate, the service module would soon become incapable of providing any life support or electrical power. The heaters and fans in this tank were turned on at 56:38 in an effort to increase the pressure, but to no avail. Because there was a possibility that a rupture had occurred in one of the inoperative fuel cells and the oxygen was leaking through it, Mission Control decided to shut down the cryogenic inputs to fuel cell 3 to see if this would stop the leak, and the reactant valves to it were closed at 57:00. It should be pointed out that this is an irreversible step; once a fuel cell is shut down, it cannot be restarted in flight. Fuel cell 3 was shut down first since its internal oxygen pressure indication was zero; there was no change in the oxygen tank pressure decay rate, however, and the reactant valves to fuel cell 1 were closed at 57:18, with equally negative results. Mission Control made one last attempt to increase oxygen pressure by directing the crew to turn on the fans in tank no. 2. At about 57:22, the crew was directed to initiate charging of battery A. By this time it became clear, with the leaking oxygen tank no. 1, that fuel cell 2 could continue to operate only for a short period of time. Since the fuel cell was maintaining an adequate bus voltage and could provide the additional power to operate the battery charger, it was decided to charge battery A as long as possible. The charging of battery A was stopped after 22 minutes. At this time the oxygen tank no. 1 pressure had decayed to a point where continued operation of fuel cell 2 was questionable. Battery A was to be connected to main bus A at the first indication that the output of the fuel cell was decaying. Since the battery cannot be connected to power a bus while it is being charged, it was necessary to terminate the charging in anticipation of the fuel cell failure.

In preparation for using the entry battery to power main bus A, a further reduction of the loads on this bus was performed. The following equipment was turned off: glycol pump, oxygen tank no. 2 fans, and fuel cell no. 2 pumps.

The pressure in oxygen tank no. 1 was approximately 65 psi at 58:04 when the crew connected battery A to main bus A. This is below the minimum operating pressure for the fuel cell. This battery continued to power main bus A until about 58:40. By this time, the LM had been activated and the inertial platform alignment transferred from the command module.

The attempts to determine the cause of the problem in the electrical power system were confused by the misleading symptoms that resulted from the cryogenic tank failure. The failure in the electrical power system and cryogenic oxygen was so massive that by itself it would have created some initial confusion and made the flight controllers skeptical of the data, but in addition to fuel cell output dropping to zero and bus voltages dropping to zero, there were other indications that had to be considered. The attitude excursions (now presumed to have been caused by escaping oxygen) and the peculiar RCS thruster firings added to the confused situation. The RCS problems are discussed in more detail in the following section, but regardless of how quickly the problem in the electrical power system was resolved, there was nothing that could have been done to correct it. The only thing the crew and Mission Control could do under the circumstances was to preserve as much capability as possible for reentry and to power down in an orderly manner to allow time for LM activation.

Maintenance of Attitude Control

Within 3 minutes after reporting the large bang, the Commander (CDR) reported some of the "talkback" indicators for the service module reaction control system (SMRCS) were showing "barberpole." His report indicated that the helium isolation valves to quads B and D were closed, and the secondary propellant fuel pressurization valves to quads A and C were closed (fig. B6-1). These valves have a history of inadvertant closure when the spacecraft is subjected to a large "jolt" in flight, such as the spacecraft separation from the S-IVB. This phenomenon was first encountered on Apollo 9. To reopen a valve that has closed in this manner, it is necessary to cycle the position selector switch to "close" and then back to the "open" position. All of the switches in this system have momentary "open" and "close" positions, and are springloaded to a center neutral position.

The valve position indicators in the spacecraft are the flag type which show gray when the valve is open and gray-and-white stripe ("barberpole") when closed; there is no telemetry indication of the valve position. Each valve and its respective indicator are powered from the same main dc bus and cannot be selected to the other bus. The valves in the propellant system for quads B and D are powered from main bus A and quads A and C are powered from main bus B. Therefore, there was no way to determine the status of the RCS propellant and pressurization systems of quads A and C, and there was no way to reposition the valves without powering up main bus B. The ability to open the isolation valves in quads B and D was not affected by the loss of main bus B.

Jet-firing signals, received at each individual thruster, open fuel and oxidizer valves by energizing a coil. There are two coils at each thruster. One, called "Auto," receives its signal from either the computer or the two rotational hand controllers (RHC's) and can be powered from either main dc bus, selected by the "Auto RCS Select" switches. There are 16 switches; one for each individual thruster that can be positioned to "off," "main A," or "main B." The other coil at the thruster is called "Direct" and receives its signal from the rotational hand controllers when they are rotated sufficiently far from the null detent. There are several ways of configuring the RHC's to power the Direct coils. Each RHC is limited as to which main bus and thruster combination it can be tied. Typically, the RHC's are powered so that half the jets are fired by main bus B and the other half by main bus A. As per normal procedure, the auto RCS select switches were configured so that single-jet authority in roll, pitch, and yaw attitude control would be available without reconfiguring if either main bus were lost. This protection can only be obtained if all four quads are functional. The loss of capability resulting from the failure of a main bus would be compounded by the concurrent closing of propellant isolation valves. Control about one or more axes would be lost

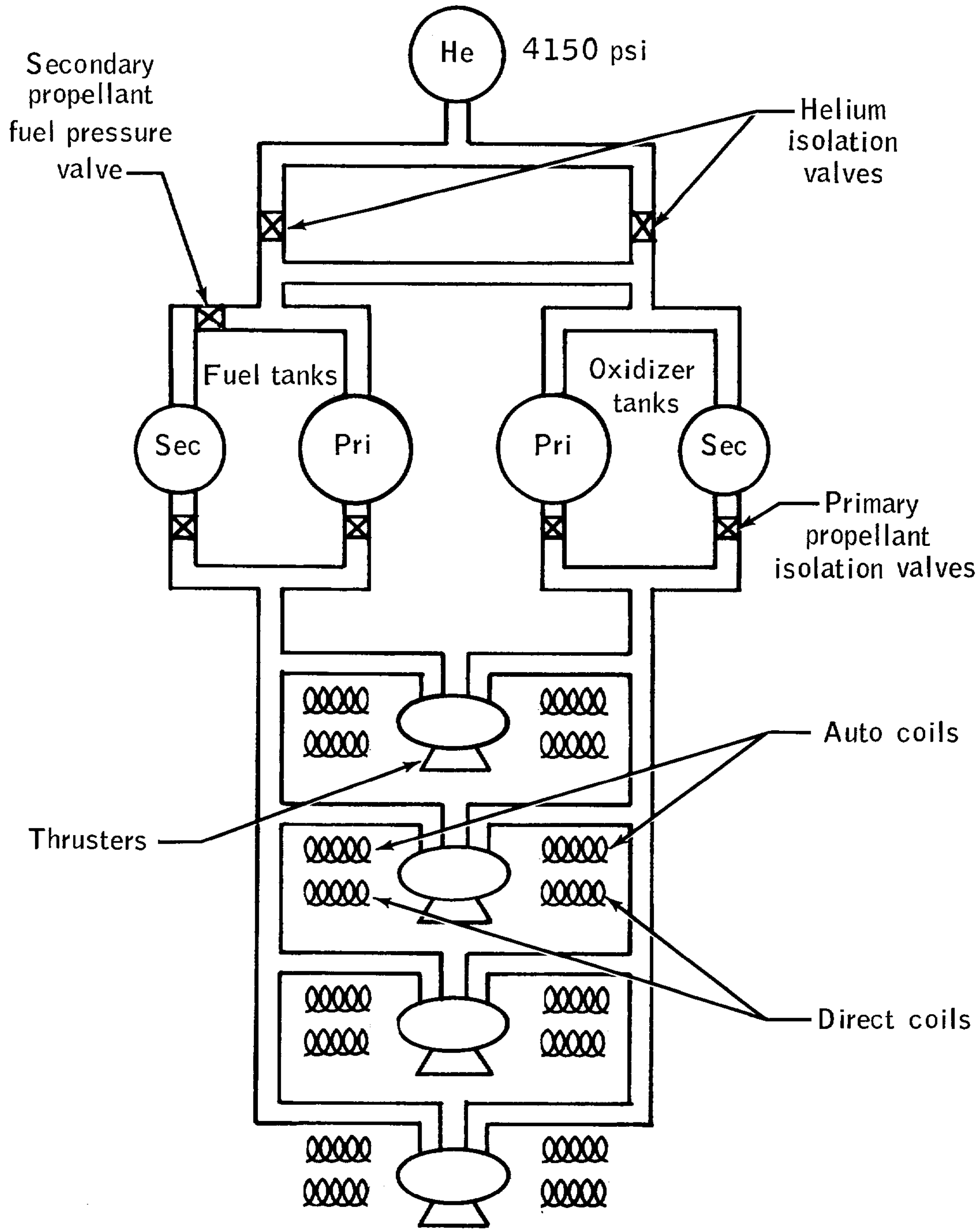


Figure B6-1.- Service module reaction control system one quad (typical of all four).