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APOLLO EXPERIENCE REPORT - COMMAND AND SERVICE MODULE INSTRUMENTATION SUBSYSTEM

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16. Abstract

A review of the Apollo command and service module instrumentation subsystem is presented. The measurements provided, design aspects considered, problems encountered, and flight results obtained are discussed.

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COMMAND AND SERVICE MODULE
INSTRUMENTATION SUBSYSTEM

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SUMMARY

The Apollo command and service module instrumentation subsystem provided data from all other subsystems for the evaluation of subsystem performance during checkout and flight. Measurements of temperature, pressure, voltage current, and other parameters were generated, conditioned, and delivered to the communications subsystem for transmission. The data were received at ground stations and transmitted to flight controllers and other personnel involved in the management of the preflight checkout and of the flight.

Because of the repetitive testing of hardware before launch, few flight failures of instrumentation occurred. The Apollo instrumentation experience emphasized the advisability of designing into future spacecraft as much instrumentation flexibility as practical because measurement requirements were changed continually throughout the program.

INTRODUCTION

The command and service module instrumentation subsystem, which was composed of the spacecraft data acquisition components, included measurement systems (transducers and signal conditioners), the central timing equipment, and the data storage equipment. Transducers were placed throughout the spacecraft near the parameter to be measured. Temperature transducers were bonded to surfaces, and pressure transducers were installed in special fittings welded into lines. In most places, the accompanying signal conditioners were mounted on nearby brackets, but some signal conditioners were mounted in a central unit in the command module. In either configuration, the function of the signal conditioner provided for each transducer was to convert the electrical signal to a standard level for interface with the communications subsystem or for data storage.

The central timing equipment provided timing signals for other subsystems and counted time from launch. The accumulated time was encoded and inserted into the telemetry stream for transmission to ground stations to provide accurate time information for each data frame required by the measurements.

The data storage equipment consisted of a multichannel magnetic tape recorder of sufficient capacity to hold all data generated by a spacecraft when the location of the spacecraft prohibited telemetry contact with a ground station. This situation occurred during lunar or earth orbital flight when the direct line between spacecraft and ground station was occluded by a portion of the earth or moon.

The components of the instrumentation subsystem, including the concepts and events of the preliminary stages, and the performance of the subsystem during Apollo missions are discussed in this report.

DEVELOPMENT HISTORY

The instrumentation subsystem (fig. 1) interfaced with all other spacecraft subsystems and therefore presented unique development problems. The development process that led to the formulation of this extremely successful subsystem is discussed in the following sections.

Requirements Determination

The process of compiling the measurement requirements included obtaining from data users the purposes intended for the data. Because various data users had different viewpoints, it was necessary to interview a representative from each group to determine the real needs. The practicality of the needs was considered from the standpoints of state-of-the-art hardware availability, implementation possibility, and the spacecraft power, weight, and size capabilities. The managers of a particular subsystem required that parameters be measured in sufficient detail to describe performance, whereas the flight controllers required analytical measurements that would yield unmistakable insight into the well-being of the entire spacecraft. (However, the flight controllers required fewer measurements for each subsystem.) These requirements were assembled, studied, and combined into a master list that could be used for satisfying each set of needs. The lists were then reviewed by instrumentation engineers from the viewpoint of implementation practicality and submitted to be reviewed by management personnel who had wider interests than either the data user or the instrumentation engineer.

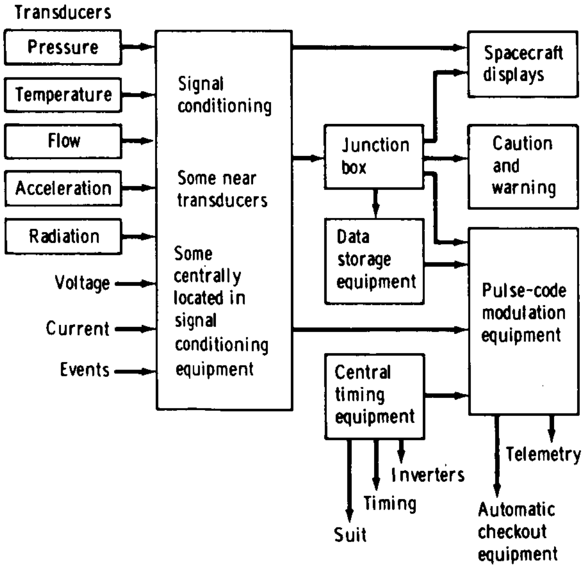


Figure 1.- Instrumentation block diagram.

Detailed schematics were necessary to facilitate decisions of whether or not to include certain measurements. The schematics showed location, function of sensors, power consumption, wiring considerations, and relationships between measurements. The schematics were also used to finalize the appropriation of measurements to each subsystem. The inclusion of a measurement into the list was under the authority of a board of managers that determined if each measurement justified the facilities necessary to include it.

Conceptual Design

Because the instrumentation had to interface with every other subsystem and also meet the telemetry interface, certain design guidelines had to be established. These guidelines were as follows.

1. The instrumentation that was integral with another subsystem and that was delivered to the prime contractor already installed in the hardware of that subsystem would not be part of the instrumentation subsystem.

2. The responsibility for all measurements not included as part of other subsystems would be centralized.

3. Every measurement would be converted to a standard electrical signal. This standardization simplified the telemetry interface and allowed interchangeability of data channels. The standard was chosen to be 0 to 5 volts direct current.

4. All measurement signals would be routed to a central junction box for distribution to telemetry, data storage, spacecraft displays, caution and warning equipment, or ground support equipment as necessary. This concept had the advantageous effect of simplifying the spacecraft wiring task.

5. Three separate classes of instruments would be determined.

    a. Operational equipment

    b. Flight qualification equipment

    c. Government-furnished equipment

6. The measurement systems selected would be subjected to definitive tests to ensure that performance met published specifications.

7. An overall system accuracy specification of ± 5 percent would be established. This figure was based on a study of realistic requirements from the data users and accuracies achievable from the available hardware and controlled by reasonable methods. The study considered the errors introduced at each stage of the system, summed the errors using probability laws, and arrived at an average acceptable from all viewpoints.

These ground rules were established early in the planning stage of the Apollo Program and were adhered to throughout the program. The ground rules proved to be beneficial with the exception of the first one, which deprived other subsystems of experienced instrumentation engineers. The instrumentation chosen to be part of other subsystems should have been reviewed by professional instrumentation personnel, because some instrumentation design deficiencies were found later in the program. However, the reason for the ground rule was to maintain an overall responsibility for proper operation of the subsystem equipment rather than fragment that responsibility. On a typical spacecraft, approximately 500 measurements were made. Of these measurements, 125 were the responsibility of the instrumentation group and the remainder were considered to be parts of other subsystems.

The most beneficial early concept was probably that requiring definitive testing before an instrument was used on the spacecraft. This testing removed conjecture and wishful thinking from the program and provided assurance of successful performance.

Development Phase

Each type of measurement system (for example, the pressure measurement device) was assigned to a team consisting of an instrumentation engineer, a reliability engineer, a quality assurance engineer, and a procurement officer. This team was responsible for the procurement and followup activities. As measurement requirements were defined, activities to obtain implementing hardware were begun. Procurement specifications were written, and requests for proposals were issued. The proposals were reviewed and vendors were selected on the basis of a rating system that included technical acceptability, price, and company capability as demonstrated by the facility, management record, and quality assurance techniques.

As the hardware was developed, it was subjected to testing to provide assurance that it could perform in the operational environments to which it would be subjected, that it could conform to the accuracy requirements of the specification, and that it was reliable. Design proof tests, qualification tests, off-limits tests to destruction, and accuracy determination were performed for each type of measurement device. Failures or unsatisfactory results from these tests required analysis and corrective action to eliminate inadequacies in design and fabrication techniques.

After procurement was complete, the instrumentation engineer, with reliability and quality assurance personnel, directed acceptance, installation, and checkout. A subsystem manager and an engineer from the program office at the NASA Lyndon B. Johnson Space Center (JSC) were assigned to oversee these efforts; to provide direction; to review plans, procedures, and test results; and to provide certification of acceptability.

Special developments, which were required for the heat shield instrumentation, nuclear particle detection, and quantity gaging, were accomplished by development contracts with experienced companies and were monitored closely by the prime contractor.

Reliability and Quality Assurance

Each type of measurement system was subjected to a series of environmental and performance verification tests aimed at type qualification. Each hardware item was further subjected to an acceptance test at the vendor's plant, an inspection by the prime contractor, a preinstallation test, recalibration every 6 months before installation, and several verifications of performance after installation. Failures at any of these stages were reported to JSC, and the subsystem manager consulted with the contractor to determine an appropriate course of action. Failure analysis was begun, and corrective action was determined.

Qualification test procedures for measuring instruments were structured on a matrix of environments derived from the exact location of each instrument. This matrix was necessary because the instrumentation components were spread throughout both the command module and the service module and a common set of conditions did not exist for all components. The matrix is shown in table I, and the environmental levels are shown in tables II to IV.

TABLE I. - MATRIX OF QUALIFICATION TEST ENVIRONMENTS

Component	Part number	Temperature	Vacuum	Humidity	Oxygen	Propellant compatibility	Vibration	Shock	Acceleration	Electromagnetic interference	Acoustics
Thermocouple, tube sheath	ME361-0013	X	X				X			X	X
Thermocouple reference junction	ME476-0012	X	X				X	X	X	X	X
Amplifier, power supply	ME473-0083	X	X		X		X			X	
Differential amplifier	ME473-0093	X	X	X	X		X				
Power supply, regulated	ME464-0090	X	X	X			X	X		X	
Temperature measurement system	ME431-0068	X	X		X	X	X	X	X	X	
Temperature sensor	ME432-0082					X	X				
Pressure measurement system	ME431-0069	X	X			X	X	X	X	X	
Differential pressure system	ME449-0101	X	X	X	X		X				
Pressure/temperature ratio system	ME449-0124	X	X	X	X	X	X	X			
Flow measurement system	ME449-0015	X	X				X	X	X	X	X
Linear accelerometer	ME449-0091	X	X	X	X		X	X	X	X	X
Signal conditioning equipment	ME901-0713	X					X	X	X	X	
Current limiter assembly	V36-7595xx	X	X	X	X		X	X			
Power control module	V36-759525	X	X	X	X		X	X			
Central timing equipment	ME456-0041	X					X	X	X	X	
Data storage equipment	ME435-0035	X	X	X	X		X	X	X	X	

TABLE II. - COMPONENT QUALIFICATION TEST AND FLIGHT LEVEL TEMPERATURES

Component	Qualification test temperature, °F	Flight level temperature, °F
Thermocouple	0 to 5000	4000
Reference junction	-65 to 600	200
Amplifier, power supply	-65 to 200	-40 to 150
Differential amplifier	-65 to 200	-40 to 150
Power supply	-65 to 200	-40 to 200
Temperature transducer	-65 to 200	-20 to 150
Pressure transducer	-65 to 200	-30 to 200
Differential pressure transducer	-65 to 200	-45 to 150
Pressure/ temperature ratio transducer	-65 to 200	20 to 150
Mass-flow transducer	-125 to 200	-30 to 150
Accelerometer	-65 to 200	40 to 125
Current limiter	-65 to 200	200 to -50
Junction box	-65 to 200	40 to 125
Signal conditioning equipment	-45 to 150	40 to 125
Central timing equipment	-45 to 150	40 to 125
Data storage equipment	-45 to 150	40 to 125

TABLE III. - VIBRATION QUALIFICATION TESTS AND FLIGHT LEVELS

Component	Qualification, g^2/cycles/sec	Flight launch phase, g^2/cycles/sec
Thermocouple	0.7	0.2 to 1.6
Reference junction	.7	.2 to 1.6
Amplifier, power supply	.7	.08
Differential amplifier	.8	.3
Power supply	.65	.1
Temperature transducer	.3 and 10	1.0
Pressure transducer	.3 and 10	1.0
Pressure transducer	.3	.06
Differential pressure transducer	.03	.03
Pressure/temperature ratio transducer	2.0	1.0
Mass-flow transducer	1.2	.13
Accelerometer	.6	.02
Current limiter	.6	.13
Junction box	.06	.06
Signal conditioning equipment	.06	.06
Central timing equipment	.06	.06
Data storage equipment	.06 survival .015 operating	.06

TABLE IV. - QUALIFICATION TESTS AND FLIGHT LEVELS FOR OXYGEN, HUMIDITY, PROPELLANT COMPATIBILITY, AND VACUUM

Component	Oxygen		Humidity		Propellant compatibility		Vacuum	
	Qualification	Flight	Qualification	Flight	Qualification	Flight	Qualification	Flight
Thermocouple			A[a]	X			A	X
Reference junction			A	X			A	X
Amplifier, power supply	X			X			X	X
Differential amplifier	X			X			X	X
Power supply			X	X			X	X
Temperature transducer	X	X			X	X	X	X
Pressure transducer	X	X			X	X	X	X
Pressure transducer	X	X					X	X
Differential pressure transducer	X	X					X	X
Pressure/temperature ratio transducer	X			X	X	X	X	X
Mass-flow transducer			A	X	A	X	X	X
Accelerometer	X	X					X	X
Current limiter	X	X					X	X
Power control module	X	X					X	X
Junction box	X	X					X	X
Signal conditioning equipment	X	X					A	X
Central timing equipment	X	X					A	X
Data storage equipment	X	X					X	X

[a] Qualified by analysis.

To establish that the instrumentation did not create hazards to the spacecraft by being the weakest link in other subsystems, destructive tests were made to determine the failure level of transducers. The results of these off-limits tests are shown in table V.

TABLE V.- OFF-LIMITS TEST RESULTS

Range, psia	Burst pressure, psia
0 to 100	
-65° F	6 000
200° F	6 000
0 to 1000	
-65° F	7 000
200° F	6 500
0 to 15	
-65° F	3 250
200° F	2 000
0 to 30	
-65° F	6 300
200° F	4 100
0 to 8000	
-65° F	21 000
200° F	16 000

Installation

Because of the large size of the instrumentation subsystem, both in quantities of components and in occupation of the spacecraft volume, installation required careful planning to achieve successful integration with the structure, power, telemetry, and originating subsystems. A wiring diagram was generated by the cognizant instrumentation engineer, and optimum locations for the transducers and signal conditioners were determined. This information was developed into schematics and installation drawings that satisfied those responsible for the structural integrity and those responsible for the spacecraft wiring, that met the required interfaces, and that could be used by the manufacturing shops.

As manufacturing progressed, the instrumentation engineer provided support in meeting schedules and resolving difficulties and reviewed the installations and inspection documentation. The subsystem manager was informed of all difficulties and was cognizant of the status of manufacturing at each stage. Shortages, damages, deviations in configuration, and other problems were solved as they arose; work-around plans and other corrective actions were taken, coordinated, and documented for review by management personnel. The flow of measurement devices in procurement and installation is shown in figure 2.

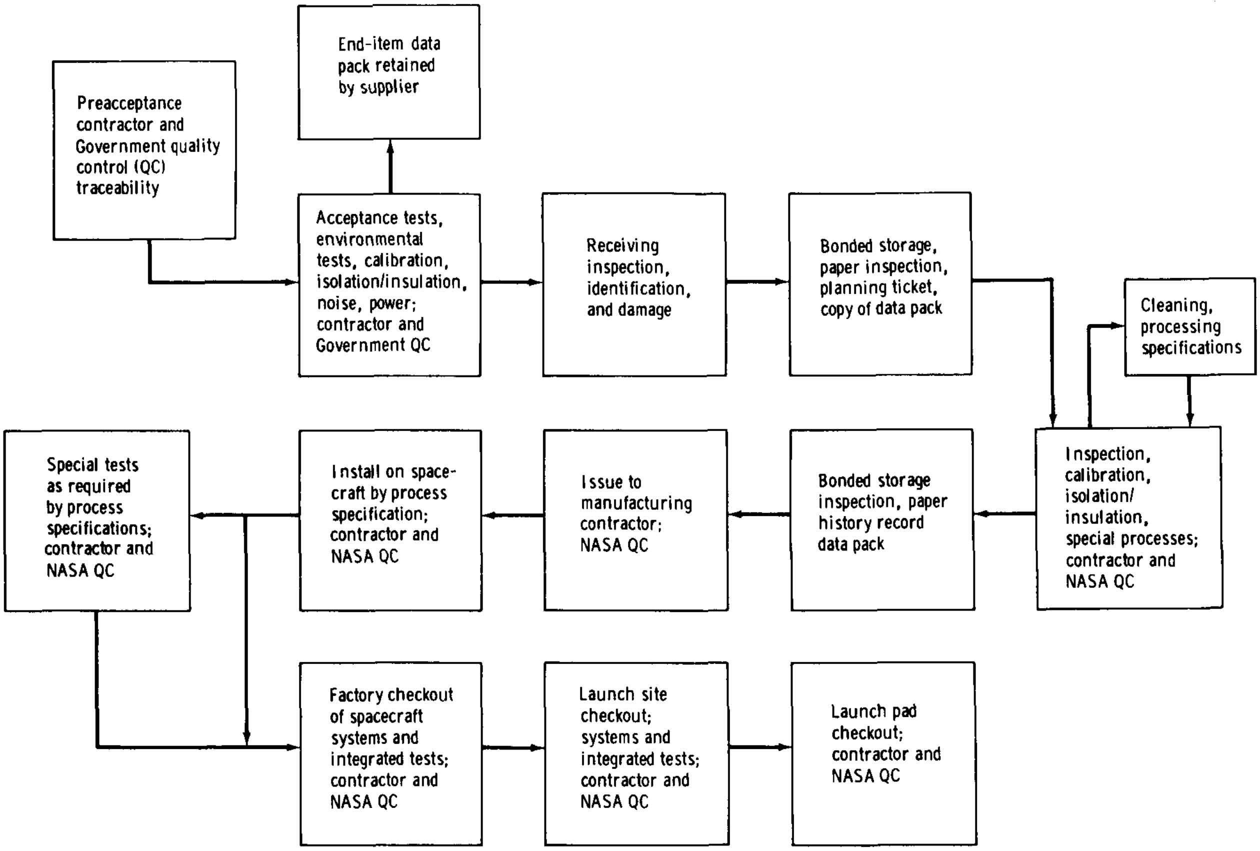


Figure 2.- Typical manufacturing and test flow.

Checkout

After installation, the first activity on the spacecraft in the checkout phase was to verify the proper operation of the instrumentation in the spacecraft so that subsequent checkout procedures could be accomplished. As other subsystems were verified, a constant flow of instrumentation verifications was obtained as a byproduct. These accumulated considerable instrumentation data and provided opportunities to evaluate not only failures but also trends. It was possible, with these data, to detect incipient failures and to schedule removals and replacements on a timely basis.

After checkout at the contractor's plant, the checkout history was reviewed and the subsystem was certified as ready for acceptance and shipment to the launch site.

At the launch facility at the NASA John F. Kennedy Space Center, further checkout before flight provided additional verification of the operation of the instrumentation. Before launch, the records were again reviewed and certification of readiness for launch was made.

Flight

During the missions, each measurement was monitored closely by the astronauts, flight operations personnel, subsystem specialists, and instrumentation engineers. This excellent coverage led to rapid identification of instrumentation anomalies. It was thereby possible to diagnose troubles with transducers and signal conditioners without delay and to provide other means of obtaining missing data in the event of a questionable measurement. Fortunately, the instrumentation was so arranged that the loss of a measurement did not result in loss of a parameter. There were always means to obtain the value of a parameter by other measurements, by calculation, or by deduction. The technique of purely redundant measurement hardware was not used, but rather a matrix of measurements existed whereby an experienced specialist could usually deduce missing data if necessary. For example, the quantity in a fuel tank might be calculated on the basis of pressure, temperature, and volume if a quantity gage was not operating.

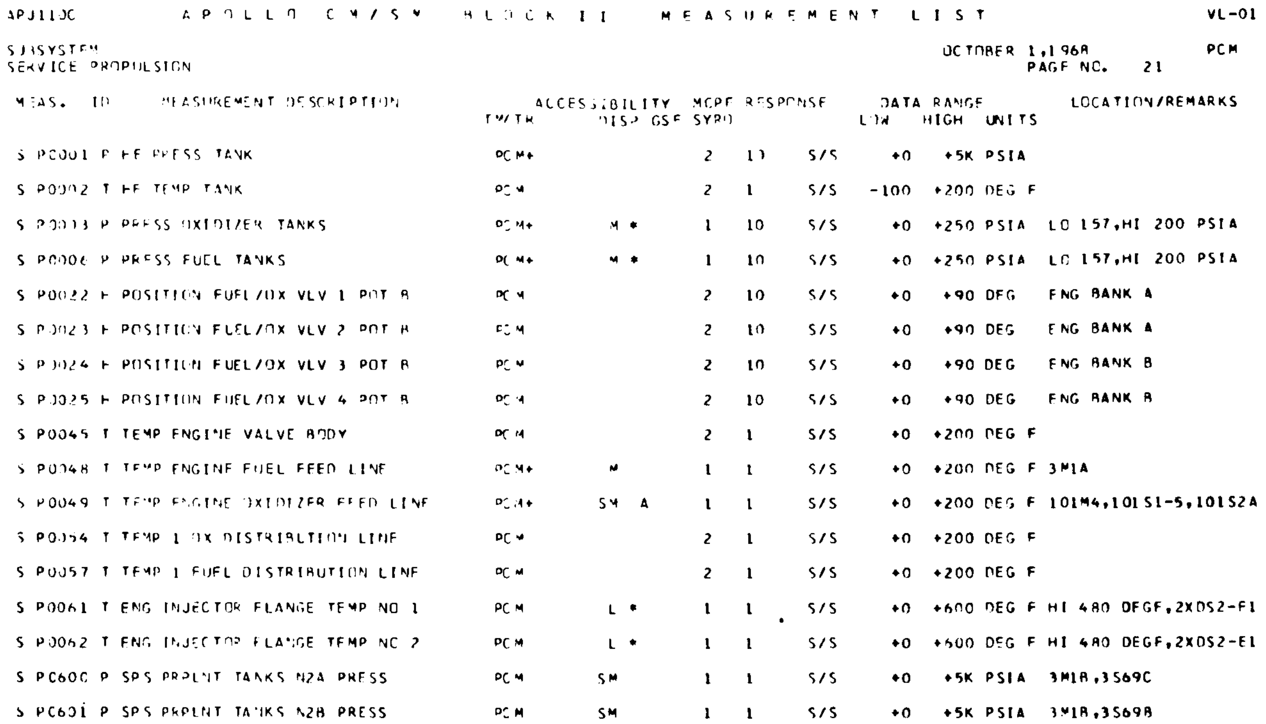
DOCUMENTARY CONFIGURATION CONTROL

To maintain precise control of the configuration of the instrumentation subsystem, what was known as a "tree" of documentation was established composed of lists, specifications, schematics, and drawings. Two of the important lists will be discussed in this section. These are the measurement requirements list and the equipment list. The procurement specifications and the specification control drawing will also be discussed.

Measurement Requirements List

Each group oriented to a particular discipline and charged with the proper management of a part of the Apollo Program (for example, the propulsion group) had its own particular requirements concerning the list of measurements needed to fulfill its responsibility. An attempt was made to provide each group with its required measurements within the necessary constraints of weight, power, and cost. Compilation of the measurements requirements list was centralized in a division of the Apollo Spacecraft Program Office and controlled by the Configuration Control Board. The list was made a contractual document and served as the authority for implementing measurements. It was a dynamic document that changed as the types of data needed changed, resulting in a different list for each spacecraft. A sample page from the final list for the Apollo 11 spacecraft is shown in figure 3.

Each measurement was assigned an alphanumeric identification that denoted the spacecraft module in which it was located, the subsystem or discipline to which it was applicable, a serial number of four digits, and the type of parameter it measured. The list formed the management basis for the instrumentation subsystem. From the list,



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APJ11DC          A P O L L O   C M / S M   B L O C K   I I     M E A S U R E M E N T   L I S T                       VL-01

SUBSYSTEM                                                                              OCTOBER 1,1968             PCM
SERVICE PROPULSION                                                                           PAGE NO.    21

MEAS.  ID      MEASUREMENT DESCRIPTION                ACCESSIBILITY  MCPF RESPONSE       DATA RANGE         LOCATION/REMARKS
                                                   TM/TR       DISP GSE SYRD             LOW   HIGH  UNITS

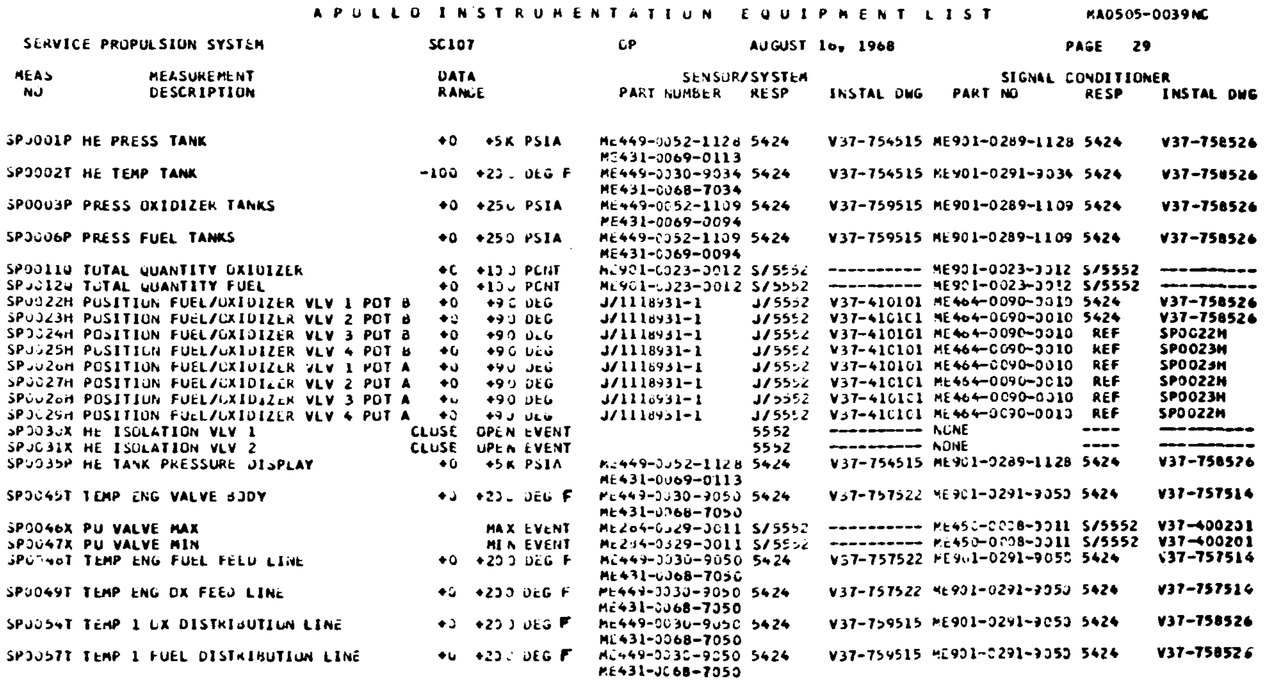
S P0001 P HE PRESS TANK                            PCM+                 2   10    S/S     +0    +5K PSIA
S P0002 T HE TEMP TANK                             PCM                  2   1     S/S   -100  +200 DEG F
S P0003 P PRESS OXIDIZER TANKS                     PCM+        M  *     1   10    S/S     +0  +250 PSIA  LO 157,HI 200 PSIA
S P0006 P PRESS FUEL TANKS                         PCM+        M  *     1   10    S/S     +0  +250 PSIA  LO 157,HI 200 PSIA
S P0022 H POSITION FUEL/OX VLV 1 POT B             PCM                  2   10    S/S     +0   +90 DEG   ENG BANK A
S P0023 H POSITION FUEL/OX VLV 2 POT B             PCM                  2   10    S/S     +0   +90 DEG   ENG BANK A
S P0024 H POSITION FUEL/OX VLV 3 POT B             PCM                  2   10    S/S     +0   +90 DEG   ENG BANK B
S P0025 H POSITION FUEL/OX VLV 4 POT B             PCM                  2   10    S/S     +0   +90 DEG   ENG BANK B
S P0045 T TEMP ENGINE VALVE BODY                   PCM                  2   1     S/S     +0  +200 DEG F
S P0048 T TEMP ENGINE FUEL FEED LINE               PCM+        M        1   1     S/S     +0  +200 DEG F 3M1A
S P0049 T TEMP ENGINE OXIDIZER FEED LINE           PCM+        SM   A   1   1     S/S     +0  +200 DEG F 101M4,101S1-5,101S2A
S P0054 T TEMP 1 OX DISTRIBUTION LINE              PCM                  2   1     S/S     +0  +200 DEG F
S P0057 T TEMP 1 FUEL DISTRIBUTION LINE            PCM                  2   1     S/S     +0  +200 DEG F
S P0061 T ENG INJECTOR FLANGE TEMP NO 1            PCM          L  *    1   1     S/S     +0  +600 DEG F HI 480 DEGF,2XDS2-E1
S P0062 T ENG INJECTOR FLANGE TEMP NO 2            PCM          L  *    1   1     S/S     +0  +600 DEG F HI 480 DEGF,2XDS2-E1
S P0600 P SPS PRPLNT TANKS N2A PRESS               PCM         SM       1   1     S/S     +0    +5K PSIA  3M1B,3S69C
S P0601 P SPS PRPLNT TANKS N2B PRESS               PCM         SM       1   1     S/S     +0    +5K PSIA  3M1B,3S69B
```

Figure 3.- Sample page from Apollo 11 measurement requirements list.

authorizations for design, procurement, installation, and checkout were generated. The list also formed the basis for decisions concerning hardware to be used, measurement ranges, accuracy to be maintained, quality assurance activities, checkout procedures, and evaluation techniques. For those who used the data, the measurement number served as instant identification of the parameter measured and was used for recordkeeping, plotting, and analysis of performance.

Equipment List

After the measurement requirements for each spacecraft were established, activities were initiated to implement those requirements. These activities included preparation of procurement specifications; issuance of requests for proposals; evaluation of proposals; selection of vendors; and preparation of testing procedures, installation drawings and procedures, process specifications, checkout procedures, and qualification plans. These activities resulted in the equipment list of instrumentation hardware for each spacecraft. A sample page from the equipment list for the Apollo 11 spacecraft is included as figure 4. Each measurement was implemented by a device that was identified by the number of its specification control drawing, and the installation drawing number was listed. These two numbers identified the hardware and its location on the spacecraft in sufficient detail to describe the measurement by reference to the two drawings. The equipment list also included a section that identified the sequence of measurements within the data bit stream assembled and transmitted by telemetry.



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                          A P O L L O   I N S T R U M E N T A T I O N   E Q U I P M E N T   L I S T          MA0505-0039NC

SERVICE PROPULSION SYSTEM                      SC107          CP           AUGUST 16, 1968                    PAGE   29

MEAS      MEASUREMENT                          DATA                  SENSOR/SYSTEM                           SIGNAL CONDITIONER
 NO       DESCRIPTION                          RANGE            PART NUMBER    RESP   INSTAL DWG   PART NO         RESP     INSTAL DWG


SP0001P HE PRESS TANK                          +0   +5K PSIA    ME449-0052-1128 5424  V37-754515 ME901-0289-1128 5424     V37-758526
                                                                ME431-0069-0113
SP0002T HE TEMP TANK                         -100  +200 DEG F   ME449-0030-9034 5424  V37-754515 ME901-0291-9034 5424     V37-758526
                                                                ME431-0068-7034
SP0003P PRESS OXIDIZER TANKS                   +0  +250 PSIA    ME449-0052-1109 5424  V37-759515 ME901-0289-1109 5424     V37-758526
                                                                ME431-0069-0094
SP0006P PRESS FUEL TANKS                       +0  +250 PSIA    ME449-0052-1109 5424  V37-759515 ME901-0289-1109 5424     V37-758526
                                                                ME431-0069-0094
SP0011Q TOTAL QUANTITY OXIDIZER                +0  +100 PCNT    ME901-0023-0012 S/5552 ---------- ME901-0023-0012 S/5552  ----------
SP0012Q TOTAL QUANTITY FUEL                    +0  +100 PCNT    ME901-0023-0012 S/5552 ---------- ME901-0023-0012 S/5552  ----------
SP0022H POSITION FUEL/OXIDIZER VLV 1 POT B     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010 5424    V37-758526
SP0023H POSITION FUEL/OXIDIZER VLV 2 POT B     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010 5424    V37-758526
SP0024H POSITION FUEL/OXIDIZER VLV 3 POT B     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010  REF    SP0022H
SP0025H POSITION FUEL/OXIDIZER VLV 4 POT B     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010  REF    SP0023H
SP0026H POSITION FUEL/OXIDIZER VLV 1 POT A     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010  REF    SP0023H
SP0027H POSITION FUEL/OXIDIZER VLV 2 POT A     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010  REF    SP0022H
SP0028H POSITION FUEL/OXIDIZER VLV 3 POT A     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010  REF    SP0023H
SP0029H POSITION FUEL/OXIDIZER VLV 4 POT A     +0   +90 DEG     J/1118931-1     J/5552 V37-410101 ME464-0090-0010  REF    SP0022H
SP0030X HE ISOLATION VLV 1                  CLOSE  OPEN EVENT                   5552   ---------- NONE            ----    ----------
SP0031X HE ISOLATION VLV 2                  CLOSE  OPEN EVENT                   5552   ---------- NONE            ----    ----------
SP0035P HE TANK PRESSURE DISPLAY               +0   +5K PSIA    ME449-0052-1128 5424  V37-754515 ME901-0289-1128 5424     V37-758526
                                                                ME431-0069-0113
SP0045T TEMP ENG VALVE BODY                    +0  +200 DEG F   ME449-0030-9050 5424  V37-757522 ME901-0291-9050 5424     V37-757514
                                                                ME431-0068-7050
SP0046X PU VALVE MAX                                MAX EVENT   ME264-0329-0011 S/5552 ---------- ME450-0008-0011 S/5552  V37-400201
SP0047X PU VALVE MIN                                MIN EVENT   ME264-0329-0011 S/5552 ---------- ME450-0008-0011 S/5552  V37-400201
SP0048T TEMP ENG FUEL FEED LINE                +0  +200 DEG F   ME449-0030-9050 5424  V37-757522 ME901-0291-9050 5424     V37-757514
                                                                ME431-0068-7050
SP0049T TEMP ENG OX FEED LINE                  +0  +200 DEG F   ME449-0030-9050 5424  V37-757522 ME901-0291-9050 5424     V37-757514
                                                                ME431-0068-7050
SP0054T TEMP 1 OX DISTRIBUTION LINE            +0  +200 DEG F   ME449-0030-9050 5424  V37-759515 ME901-0291-9050 5424     V37-758526
                                                                ME431-0068-7050
SP0057T TEMP 1 FUEL DISTRIBUTION LINE          +0  +200 DEG F   ME449-0030-9050 5424  V37-759515 ME901-0291-9050 5424     V37-758526
                                                                ME431-0068-7050
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Figure 4.- Sample page from Apollo 11 instrumentation equipment list.

Procurement Specifications and Specification Control Drawings

The hardware needed for implementation of each type of measurement requirement was described in a procurement specification and the associated specification control drawing. The documents described the measurement device, its size, weight, power consumption, performance, the environments under which it must perform, and the testing to which it must be subjected for qualification and acceptance. Quality assurance and reliability requirements, packaging, marking, and protection were covered.

Measurement hardware specifications are not included as a part of this report, but the different hardware types are listed. Each of these types had its own set of control documentation.

HARDWARE

The documentation and other control techniques were management tools used to obtain hardware to be assembled into a system with assurance that the mission objectives could be fulfilled. The instrumentation hardware selected for the Apollo command and service modules is described in this section.

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Transducers

Although between 200 and 1500 measurements are included in the equipment lists for each spacecraft, depending on the particular mission objectives, the transducers may be categorized as follows.

1. Pressure, absolute and differential
2. Temperature
3. Quantity of fluids such as fuel and oxidizer
4. Flow rates of fluids such as coolant and fuel
5. Attitude of the spacecraft in yaw, pitch, and roll
6. Attitude change rate in yaw, pitch, and roll
7. Voltages on buses and batteries
8. Electrical current
9. Frequency of alternating current from inverters
10. Radio-frequency power levels, received and transmitted
11. Vibration amplitude and rate of displacement
12. Strain in the structural parts
13. Acoustic level within the command module
14. Acceleration in three axes
15. Heat shield char, ablation, and heat flux
16. Nuclear particle detection
17. Biomedical measurements of the astronauts
18. Gas analysis of the spacecraft atmosphere

Signal Conditioners

Signal conditioners used to convert the detected parameters to a standard range of voltage to meet the telemetry interface are as follows.

1. Direct-current amplifiers, with various gains as required
2. Alternating-current-to-direct-current converters

3. Frequency demodulators

4. Direct-current active attenuators

5. Attenuator-inverter for negative direct-current voltages

6. Phase-sensitive demodulators

7. Differential amplifiers

8. Reference junction for thermocouples

A typical wiring diagram by which a measurement signal may be traced from the point of data acquisition at the transducer through the terminal boards, signal conditioner, spacecraft connectors, and through the junction box to the telemetry units, display meters, and other data utilization areas is shown in figure 5. A typical signal conditioner installation is shown in figure 6, and a typical installation of a transducer is shown in figure 7. Each of the cylindrical units is a signal conditioner implementing an individual measurement.

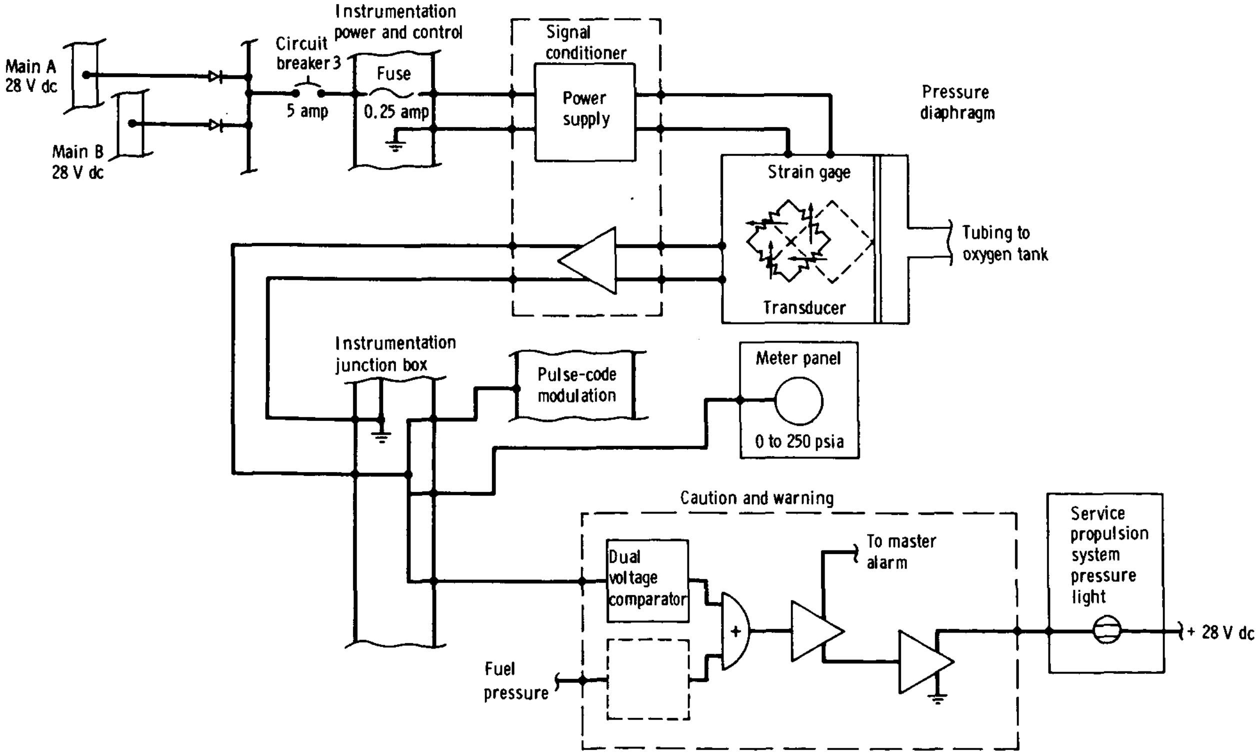

Figure 5.- Typical measurement wiring diagram.

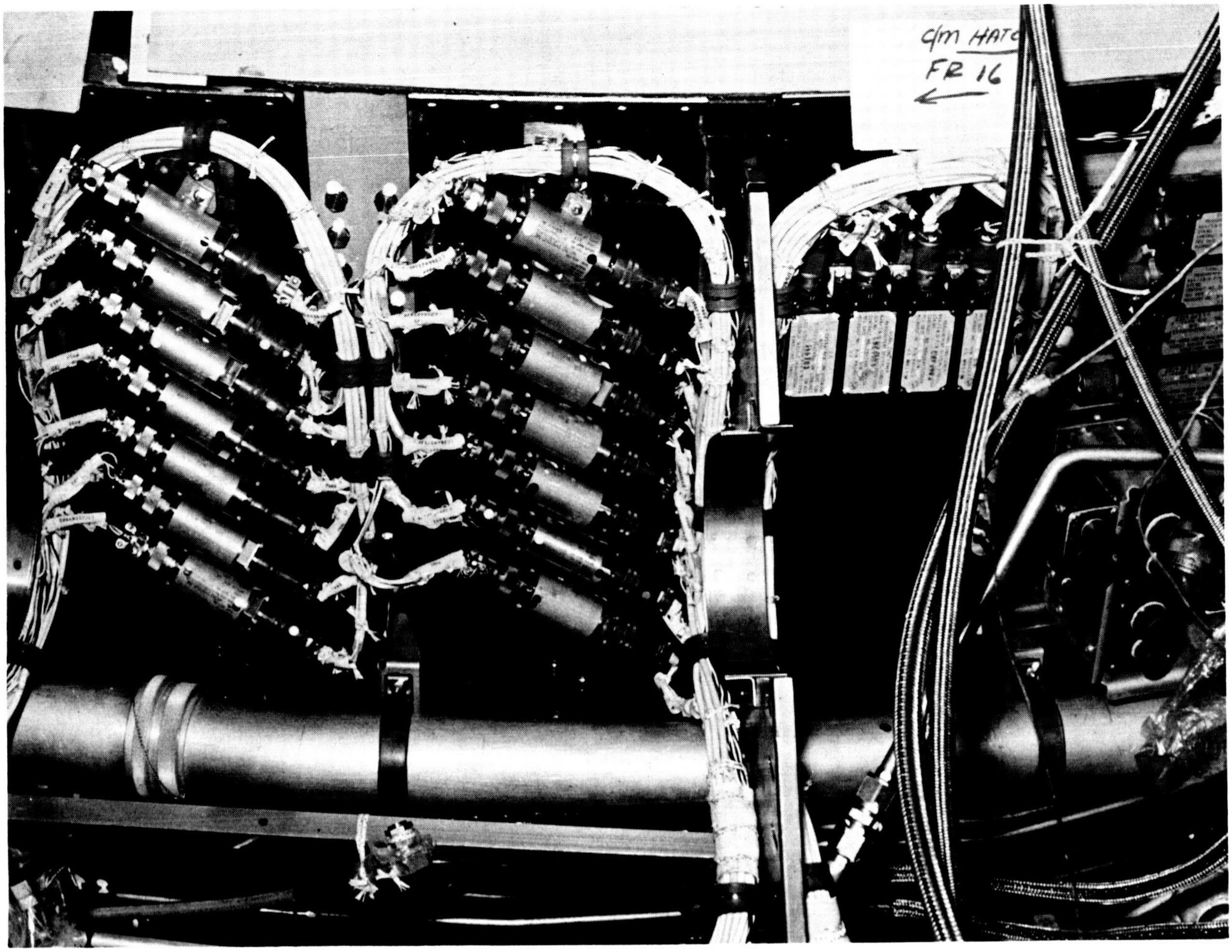

Figure 6. - Typical signal conditioner installation.

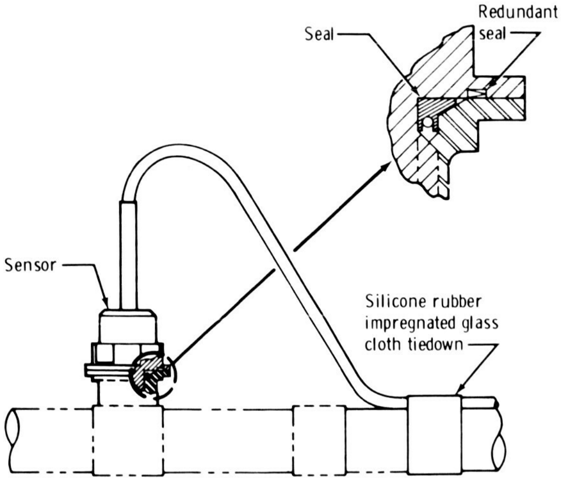

Figure 7. - Pressure transducer installation.

Data Storage Equipment

For data storage, magnetic tape recorders were used. For the early test vehicles and unmanned flights, data were stored on 1-inch magnetic tape by use of frequency modulators on a unit called the flight qualification recorder. During the manned flights, the operational data were stored in pulse code modulation form on another 1-inch tape recorder. This operational tape recorder was called the data storage equipment.

The pulse code modulation data generated by the communications subsystem at 51 200 bps (high bit rate) or 1600 bps (low bit rate) were divided into four channels for storage. For high-bit-rate storage, the tape was run at 15 in/sec and played back at 120 in/sec. The latter mode was useful for earth orbit or lunar orbit operations.

The data storage requirements for the Apollo 15 to 17 missions were greater than the capacity of the tape recorder used on earlier missions. Thus, the recorder had to be upgraded, which was done by halving the tape speeds and increasing the data density. This upgraded recorder was called the data recorder-reproducer.

The increased data density resulted in a problem with data jitter because the minor tape speed variations were proportionally more significant than they had been at the lower density. It was necessary to condition the played-back tape recorder data with a "dejitter" device before the data were delivered to the communications subsystem for transmission.

Central Timing Equipment

The central timing equipment received a timing signal of 1.024 kilohertz from the guidance and navigation equipment and provided signals to other subsystems. In the event of loss of the input signal, an internal oscillator within the central timing equipment became active and the outputs continued. The following signals were provided.

1. A 512-kilohertz signal to the communications subsystem for synchronization
2. A 6.4-kilohertz signal to the electrical power subsystem for inverters
3. A 10-hertz signal to event timers
4. A 1-hertz signal to the communications subsystem for frame division
5. One pulse per 10 minutes to the crew suit water accumulation subsystem
6. Day, hour, minute, and second to the telemetry subsystems

The division and accumulator circuits were quadruply redundant.

DEVELOPMENT DIFFICULTIES

The instrumentation hardware was subjected to extensive testing before launch. As a result, nearly all design and manufacturing defects were discovered before any instrumentation was used in manned flight. The following difficulties, therefore, occurred in the factory during one of the many inspections, tests, or checkout procedures (except as noted).

The first item to cause concern was a rather high rate of rejections during the incoming inspection after the units had successfully passed the acceptance tests at the vendor's plant. Linearity, repeatability, and end-point specification limits were exceeded in many cases. Also, certain bridge-type transducers occasionally had calibration shifts. Two corrective actions resulted in a lower failure rate. The first corrective action was to modify the acceptance test procedure limits to be the same as the incoming inspection limits. The second corrective action was to change the transducer bridge material from silicon to platinum, which is more stable over a long period of time.

Another difficulty encountered was the phenomenon of a measurement changing abruptly in output without a change in the measured parameter. This phenomenon was referred to for convenience as a "calibration shift" and was the subject of much discussion and activity. The source was finally determined to be oscillations within the signal conditioners. Two modes of oscillation occurred. In some cases, the amplifier that establishes scale range was oscillating; and, in other cases, the regulator in the signal conditioner was oscillating. Corrective action was easily accomplished by installing small shunt capacitors across the amplifier or regulator terminals. Because of the large number of signal conditioners involved, however, the question became whether to retrofit all signal conditioners with shunt capacitors even if they were already on the spacecraft. Retrofitting all the signal conditioners would have caused prohibitive schedule and cost problems, so the decision was to retrofit only those units not yet installed. As the units on spacecraft failed in checkout, they were replaced with modified signal conditioners.

Other failures that did not cause undue trouble, because of only a few occurrences, were open bridge circuits, failed diodes, and a few transistor and connector failures. Failure trends are shown in figure 8.

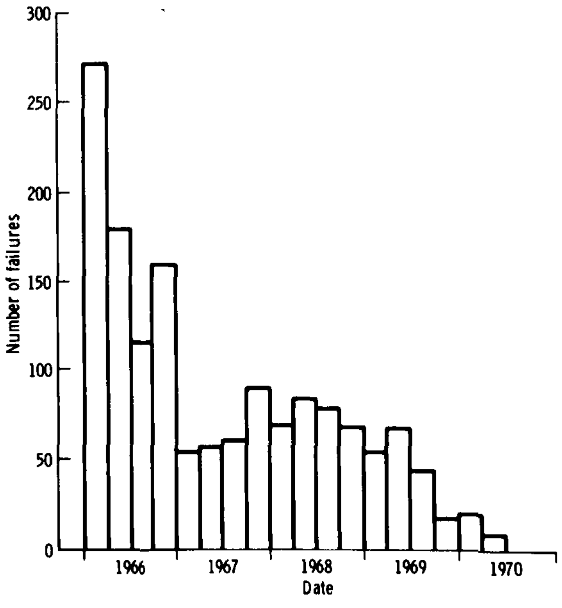

Figure 8. - Occurrences of instrumentation failures.

Some measurements were found to be susceptible to very-high-frequency interference. This interference occurred to only a few measurements located near antennas and only during the times the spacecraft very-high-frequency transmitter was in use, which was infrequent. The interference was not a source of appreciable data loss.

During the launch of Apollo 12, a few instruments were disabled by lightning. This loss was the result of an internal electrical connection between the power leads and the housings within certain signal conditioners. The practice of connecting circuits to housings should be avoided in the future. An alternating-current connection between the signal conditioner case and the signal path allowed heavy currents to flow at the instant of lightning discharge, which overstressed transistors and caused failure.

Experience also showed that some damage to the instrumentation hardware was caused by installation and checkout personnel working in the spacecraft. Recurrence of such problems was reduced by modifying installation and checkout procedures and requesting the personnel to be more careful.

During checkout of the first manned spacecraft, it was discovered that the data storage equipment would not reproduce data. This failure was traced to excessive electrical noise on the data circuits resulting from improper connection between the signal ground and the chassis. The problem was solved by installing a large capacitor to connect the signal ground to the data storage equipment chassis. This connection met the Apollo Program rules and still reduced the noise susceptibility to a reasonable level.

The data storage equipment problem resulted from the lack of electromagnetic interference considerations in the initial specifications. The Apollo spacecraft when powered up was found to have approximately 3 volts (or 10 percent) noise on the direct-current buses; some electronics units would not tolerate this percentage of noise. It was then necessary to take corrective action through shielding, filtering, and rerouting of grounds.

The central timing equipment also had to be reworked for noise susceptibility. Capacitors were added to the powerlines and at various points within the signal circuit to eliminate resets and extraneous updates resulting from noise on the spacecraft buses.

FLIGHT EXPERIENCE

During the flights of Apollo 7 through Apollo 11, there were only six failures of hardware included in the instrumentation subsystem. Measurement devices included as a part of other subsystem hardware experienced failures that are not included in this report.

All the flight failures that occurred are listed in table VI. Two of the six failures resulted in measurements barely out of the 5-percent overall accuracy requirement. If the measurements had been 5 percent instead of 6 percent, they would not have been considered failures. These failures were probably caused by the changing of value of some resistor or other component in the electronic circuit.

The complete failures were probably caused by open connections. The tape motion slowdown on the Apollo 10 mission was caused by deformation of the tape recorder case during the pressure increase of entry. Before subsequent flights, corrective action (strengthening the case) was taken.

TABLE VI. - INSTRUMENTATION SUBSYSTEM FLIGHT FAILURES

Apollo mission	Spacecraft	Device	Failure indication
7	101	Thermocouple	Read zero
8	103	Temperature	Drifted upward 6 percent
8	103	Accelerometer	Failed at maximum dynamic pressure
9	104	Flowmeter	6 percent higher than expected for 6 hours
9	104	Pressure	Failed at lift-off
10	106	Tape recorder	Tape motion slow during entry

CONCLUDING REMARKS

The ratio of flight failures to instrumentation hardware items flown is approximately 0.01. This low failure rate can be attributed to two techniques.

1. Careful selection of hardware and insistence that the hardware adhere to published specifications

2. Repeated testing of the instrumentation hardware before installation and continual exercise of the hardware from installation to spacecraft launch

These two techniques resulted in a multitiered cross-check of instrumentation hardware at all stages of preflight preparations. Thus, failures or incipient failures could be detected immediately and any hardware of questionable capability could be removed and replaced.

A reasonable conclusion from the Apollo Program with respect to instrumentation, which parallels the experience of instrumentation managers on previous programs, is that a measurement list cannot be expected to remain fixed. Data requirements change continually as a program progresses. It is advisable, therefore, to design an instrumentation subsystem with as much flexibility as can be afforded. Means should be provided for easy changeout, addition, and removal of hardware. Standardization of the mechanical configuration of transducers and signal conditioners is a good policy, and standardization of mechanical fittings would complement this policy. Providing an excess of mechanical transducer connections beyond the number initially envisioned would be beneficial, allowing measurements to be added as desired. Electrical connectors should be standardized, and a central junction box or even a patchboard could increase flexibility. Ranges should be easily changeable.

Grounding philosophy must be carefully considered at the beginning of a program to prevent excessive noise susceptibility, and the rules decided on must be strictly enforced. Nearly all noise problems on Apollo instrumentation can be blamed on violation of good grounding practices. In particular, the cases of transducers and signal conditioners must have no electrical connection to the signal or power grounds. Electrical connections between signals and cases create undesirable circuit loops that result in noise susceptibility as currents are induced in the spacecraft frame and the cases. If the cases are isolated from the signal circuits, the noise problem is avoided.

In the Apollo Program, extreme accuracy of parameter measurement was found not to be worth extra money and time. A realistic approach to accuracy can avoid much delay and expense. The ± 5-percent system accuracy specified for the Apollo Program was found to be adequate for operational purposes.

The Apollo instrumentation experience emphasized the value of type qualification. The environments must be carefully defined, and qualification tests must be structured to verify that the hardware will operate in those environments. Most important, the results of the qualification tests must be believed and corrective action taken promptly to offset failures as they occur. It is not wise to "rationalize" failures during the qualification phase.

A final recommendation is that all instrumentation be reviewed and approved by competent, experienced instrumentation engineers. Instrumentation that is selected by specialists in other disciplines is not always reliable.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, March 21, 1973
914-11-00-00-72

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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