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Introduction

Project Mercury was the United States' first program directed toward the development of a capability for manned space flight. The initial goal of this project was to place an astronaut into orbit and recover him safely. This objective was satisfied by the successful flight of Astronaut John H. Glenn, Jr., on February 20, 1962, approximately 3 years after the award of the prime spacecraft contract. The similar mission of Astronaut Carpenter some 3 months later served to confirm the results of Glenn's mission. The final two manned flights in Project Mercury were conducted to extend the knowledge of man's reactions and capabilities in space for a longer time period. Astronaut Shirra's flight in October of 1962 lengthened the period of observation from $4\frac{1}{2}$ hours to 9 hours, and the final Mercury mission, that of Astronaut L. Gordon Cooper, Jr., in May of 1963, extended the flight duration to some 34 hours. Each of these missions was successful, but, as the present paper concludes, this success was largely dependent upon the manual control capability of the pilot. A milestone chart which indicates the flight dates for the Mercury orbital missions is shown in table I.

When the Mercury spacecraft was conceived, little was known about man's capability to function in space; therefore, most of the critical systems were designed to operate in essentially an automatic mode. However, in order to make a conclusive evaluation of the pilot's ability to exercise manual control in the space environment, many of the automatic systems incorporated a manual override capability. During each of the Mercury orbital flights, malfunctions occurred in various systems which could have compromised the initial mission objectives. In the discussion of the unmanned orbital flights, an evaluation of these malfunctions is presented with regard to the mission consequences if a pilot had been able to provide manual override. This evaluation is considerate of the pilot's capabilities demonstrated during the manned flights. The critical system failures which occurred during the manned orbital flights are examined with regard to the pilot's response and effectiveness in coping with the hazardous situations. Prior to this discussion, however, a brief description of the spacecraft systems and the philosophy which governed the associated manual operating modes are presented. The discussion of the systems malfunctions is then arranged in a chronological manner according to the orbital mission analyzed. The Mercury suborbital flights are not discussed since the nature of the trajectory involved and the brief flight times tended to minimize the consequences of any inflight systems malfunction. Although the Mercury-Atlas 3 (MA-3) mission was intended to be a three-pass orbital flight, a failure of the launch vehicle resulted in an abort.

Systems Description

The Mercury spacecraft was designed to provide a safe and habitable environment while in orbit as well as protection during the critical flight phases of launch and reentry. In the later missions, particularly, the spacecraft also served as an orbiting laboratory where the pilot could conduct limited experiments to increase knowledge in the space sciences. The many systems which the spacecraft comprised may be generally grouped into those of heat protection, mechanical and pyrotechnic, attitude control, communications, electrical and sequential, life support, and instrumentation. The arrangement of these systems within the spacecraft is illustrated by the simplified schematic diagram in figure 1. The spacecraft attitude control system is described in the greatest detail since this system represented the greatest source of trouble during the orbital flight program. Malfunctions occurred, however, in the life support and electrical and sequential systems which required action by the astronaut, and these systems are also briefly described. The remaining systems functioned properly and therefore have no bearing on the present discussion, but a cursory description of these systems may be found in references 1 to 4.

Spacecraft Control System

The spacecraft control system provided for attitude control and rate stabilization of the spacecraft during the orbital and reentry portions of flight. In addition to the system electronics, the control system was composed of two independent reaction control systems (RCS), as shown in figure 2, one of which supplied fuel for the automatic stabilization and control system (ASCS) and fly-by-wire (FBW) modes and the other, until the final mission, supplied the manual proportional (MP) and the rate stabilization and control system (RSCS) modes. The RSCS was installed in the spacecraft used for the second manned suborbital mission and subsequent spacecraft as a backup to auxiliary damping, one of the secondary modes of the ASCS. The RSCS unit was removed for the final flight because of its high fuel-consumption characteristics and weight. In addition to the auxiliary damping mode, the ASCS had three other secondary modes (see table II) selectable by the pilot, those of orientation, orbit, and reentry. The auxiliary damping mode was used to maintain a fixed roll rate, while damping rates about the other two axes. The remaining three modes were employed to keep the vehicle at a fixed attitude, with the orbit and orientation modes used during the orbital phase, and the reentry mode used to position the spacecraft for reentry. The RCS employed hydrogen peroxide as the fuel and a silver catalyst to decompose the H_2O_2 and produce thrust through variously sized thrust chambers, or thrusters. The peroxide fuel was supplied to the thrusters by a nitrogen pressurization system; and the two RCS's were independent in that they comprised separate fuel, pressurization, and thrust chamber assemblies. Fuel was metered to the thrusters by small solenoid valves, or, in the case of the MP, by proportional valves controlled through a direct mechanical linkage. Both direct-current (d-c) and alternating-current (a-c) power were used by the amplifier-calibrator, or Amp-Cal, which provided the logic for the automatic control circuitry and controlled the various ASCS operating modes. For example, the Amp-Cal regulated and received signals from the attitude gyros, which drove the pilot's attitude indicators. Figure 3 indicates the slaving cycle used to maintain the accuracy of these gyros. The horizon scanners, one each for the pitch and roll axes, sensed vehicle attitude with respect to the earth horizon, and, if a comparison with the gyro output produced a disagreement, the drifted gyro was repositioned by the slaving circuit. The Amp-Cal processed this information in acting upon a given attitude command and operating the proper RCS thrusters. A thrust impulse, of course, produced an attitude change which was detected in the scanner and gyro sensing mechanisms, thereby producing the closed-loop function. Of the two manual modes available to the pilot, one was electrically connected to one RCS, and the remaining mode used a mechanical linkage to the other RCS. The control mode arrangement had the capability of providing mechanical mode control in the event of a power failure. Although the thrust units were designed to provide an impulse sufficient for all normal spacecraft maneuvers, these redundant manual control modes could be used simultaneously, if desired, in critical situations, such as retrofire and reentry where rapid response to undesirable attitude rates might become necessary. The astronaut initiated manual attitude commands through a three-axis hand controller shown in figure 4. This controller was designed such that singular or coordinated control inputs could be accomplished with the use of the right hand only and without essential movement of the arm. This feature was particularly important during reentry where either high acceleration forces retarded arm motion or other activities required one hand to be free for switching functions.

Sequential System

As stated previously, the Mercury spacecraft was initially designed to be flown solely in an automatic mode; therefore, a sequential system had to be devised which would initiate and control critical flight events, such as separation from the launch vehicle, retrofire, and reentry. Most flight events had to occur in the proper sequence and were sometimes separated by only milliseconds of time. It is not intended here to describe the mechanics of the sequential system, but rather to present briefly the operating philosophy and its manual override implications. This system consisted of cascaded electrical elements, such as time-delay and zero-delay relays, positional limit switches, inertially actuated switches, pressure-sensing units, and timing devices. These elements controlled events which were dependent upon the elapsed time of the flight, spacecraft attitude and position, the vehicle environment, and the status of spacecraft systems. Redundant sources of power and electrical paths were provided to increase reliability. Manually initiated backup and override modes were provided for all major events. These manual controls permitted the pilot to initiate a sequence when the automatic system had failed or to pre-empt the automatic system when the consequences of the normal event might be catastrophic, such as jettisoning the retrorockets prior to their ignition. A mission abort could have been initiated automatically, as well as by ground command, during the launch phase, and by the astronaut during all flight periods. Most of the manual control of flight sequences was accomplished through a series of switch fuses on a panel of sequence lights with associated push buttons that could have initiated major flight events. If these lights did not indicate the function had been initiated at the proper time, the astronaut was able to respond immediately. Many of the events during powered flight were related to launch-vehicle functions and are not discussed herein. The sequence of events for the retrograde and reentry phases are pertinent to a later discussion and are shown in figure 5.

Life Support System

The life support system consisted primarily of the environmental control system (ECS), but also included the astronaut's drinking water and food supplies, personal survival equipment, and the support couch and restraint system. A more complete description of the life support system may be found in reference 5. The ECS comprised two separate environmental circuits, one for the astronaut's pressure suit and one for the spacecraft cabin. A schematic diagram of the ECS is presented in figure 6. The ECS controlled the pressure and temperature of the cabin and suit environments and supplied breathing oxygen for the astronaut. Temperature was controlled through an evaporative-type heat exchanger in each of the two circuits. Distilled water was used as the coolant. The evaporated water, or steam, was exhausted into space. The only item common to both circuits was the single cooling water supply, which incorporated a positive-expulsion bladder system. The warm air from the cabin and the suit circuits was forced through the heat exchangers by separate fans. Two devices were used to extract condensed water from the suit circuit gas stream. Water was removed from the suit circuit by a water separator, and, for the final flight, an inline water trap, and was stored in a condensate tank. In the suit circuit, a solids trap was used to remove particulate matter, and a lithium-hydroxide canister was employed to remove carbon dioxide. One-hundred percent oxygen was supplied from two pressurized bottles, and a means existed to permit direct flow of this oxygen into the suit circuit without passing through the heat exchanger. This capability provided immediate cooling in the event of an ECS failure, or a pure breathing atmosphere if the suit circuit air became toxic. The two environmental circuits were independent for reliability reasons, particularly in the instance of a rapid decompression of the spacecraft cabin. Manual metering valves were placed on the astronaut's instrument console to permit adjustment of the coolant flow in both ECS circuits and thereby control temperature.

Electrical System

The electrical power system in the Mercury spacecraft consisted of three main, one isolated, and two standby batteries, which provided d-c power directly and a-c power through one standby and two main inverters. These batteries and inverters were linked to a series of electrical power buses from which all systems derived their operating power. These power sources could be switched selectively by the astronaut should one or more fail in flight. The astronaut had a visual indication of power-system status from d-c and a-c voltmeters and a d-c ammeter installed on the instrument panel. Since the ammeter is necessarily connected in the line, or in series, and an open-circuit failure of this unit could interrupt available power, a bypass switch was incorporated to permit rerouting the circuit around a failed instrument. As shown in figure 7, the primary electrical power buses supplied power to the ASCS portion of the control system, the ECS fans, and the various communications systems. For a-c power, a special control circuit regulated current flow through a series of relays, which were controlled by both automatically and manually operated selector switches. Batteries and inverters were redundant to provide a high reliability within their intended operating life.

Unmanned Orbital Missions

Mercury-Atlas Mission 4 (MA-4)

The MA-4 mission was a second attempt, after the failure during powered flight of MA-3, to place an unmanned spacecraft into orbit carrying a device which simulated the metabolic conditions imposed by the pilot. Anomalies occurred in the performance of three of the spacecraft systems which could have jeopardized the success of the mission: an inverter failure during powered flight, a leak in the oxygen supply, and various malfunctions in the spacecraft control system.

The faulty inverter, which resulted from vibration, was successfully switched out of the circuit and the standby inverter was switched into the circuit by an automatic device. If a pilot had been present in the spacecraft, he could have completed this switching operation manually. If neither the manual control nor an automatic switchover system had been present to perform this task in a manned mission, the faulty inverter, which powered the cooling fans, would have prompted a mission abort.

The leak in the oxygen supply was found to have resulted from a relaxation of spring force which permitted partial opening of the emergency-rate control handle (see "Emer Flow", fig. 6). Since the mission was planned for only one orbital pass, sufficient oxygen was available at the leak rate involved to sustain a pilot had one been present. However, for a longer flight where the required oxygen quantity might have approached the design limit, the leak, if uncorrectable, could have resulted in early termination of a manned flight. It is believed that had a leak of this type been detected either on the ground or by a pilot, an analysis of the problem would have resulted in the recommendation to check the position of the emergency-rate handle. Pressure exerted by the pilot to close this handle would have satisfactorily corrected the leakage problem.

The malfunctions in the control system for MA-4 were those of the horizon scanner, wiring in the amplifier-calibrator (Amp-Cal), and two 1-pound thrusters. The malfunctions of the horizon scanner included random error signals, which were sent to the attitude gyros because of cold-cloud effects, and a continuous ignore signal from the roll scanner during most of the dark side of the orbit because of a short circuit in the capacitor. Ignore signals were employed to prevent improper slaving of the gyros when the scanner became saturated with incident light. The random error signals were not sufficiently serious to warrant discussion. The opening of the circuit from the pitch rate gyro to the Amp-Cal was caused by a loose wire and resulted in erratic spacecraft motion and excessive fuel usage. The thruster-assembly failures occurred in the 1-pound roll-left and yaw-right thrust units, shown in figure 8. Loss of these smaller thrusters caused the spacecraft to exceed the normal attitude limits in the automatic control mode, thereby activating the high-thrust units. Frequent actuation of these larger thrusters resulted in a relatively high fuel-usage rate. Adequate fuel was available and the control system was sufficiently accurate to complete the planned one-pass mission. However, there was not enough fuel, based on the indicated usage rate, to complete a three-pass orbital mission in the automatic control mode. Because of the random nature of the attitude control errors, it cannot be stated whether an attitude error about any axis at retrograde for a three-pass mission could have existed which would have compromised a manned but automatic mission.

It is safe to assume that, if a pilot had been present to exercise proper manual control, a three-pass mission could have been successfully completed within the attitude and fuel-usage constraints normally imposed. During the orbital phase, the pilot could have used either manual proportional or fly-by-wire control to circumvent the errors introduced by the scanners and the open gyro circuit. During the MA-4 mission, an uprange deviation in landing was partially caused by angular errors at retrofire. With the use of manual proportional control and with particular attention to accuracy in yaw attitude, the pilot could have kept angular deviations well within the required limits during the retrofire period to effect a landing within the designated landing area.

Mercury-Atlas Mission 5 (MA-5)

The MA-5 mission was unmanned, but included a chimpanzee as the spacecraft occupant, and was planned for three orbital passes about the earth. The flight was terminated after two passes because of a failure in the control system. Flight control personnel on the ground wanted assurance that there would be sufficient control fuel available for a normal retrofire maneuver so that the spacecraft could be recovered in a planned landing area.

Although there was a recurrence of the cold-cloud effects on the horizon scanners, the foremost problem was the failure of the 1-pound roll-right thruster. This failure caused the spacecraft to cycle repeatedly to high thrust actuation about the roll axis, which again resulted in a high rate of fuel consumption. The electrical inverters also approached their design upper limit in temperature, but a failure of these units was not experienced.

As stated previously for the MA-4 mission, a pilot using manual proportional or fly-by-wire control could have kept the spacecraft at the desired attitude throughout the MA-5 flight with a near-normal fuel consumption. A three-pass orbital mission with a pilot present could therefore have been completed successfully in the absence of additional malfunctions.

Manned Orbital Missions

Mercury-Atlas Mission (MA-6)

The MA-6 mission, which was planned for three orbital passes, was successfully completed as the free world's first manned orbital flight. A faulty limit switch in the circuit which normally indicated release of the heat shield during landing-bag deployment resulted in an uncertainty as to whether the heat shield could prematurely part from the spacecraft in orbit. This uncertainty prompted a decision to retain the retropackage into reentry, thereby maintaining the heat shield in place until aerodynamic pressure could safely secure it. Other inflight system anamolies included control system thruster failures and an early deployment of the drogue parachute. The thrusters which failed during the MA-6 mission were the four 1-pound pitch and yaw thrusters in the automatic RCS, shown in figure 8.

Following the control system failures, the MA-6 pilot controlled the spacecraft in the manual proportional mode and completed the mission in a satisfactory manner. Without the presence of the pilot, the flight would have been terminated at an earlier time, because, as in the MA-5 mission, sufficient fuel would not have been available for a three-pass mission in the automatic control mode. Further discussion of the MA-6 pilot's ability to control spacecraft attitudes manually is presented in reference 6.

Although the early deployment of the drogue parachute did not affect the success of the MA-6 flight, more serious conditions could have resulted. After exhaustive testing, the exact cause of the anomoly remained undetermined. With a parachute drogue deployment prior to the spacecraft's approximately 70,000 feet in altitude during reentry, the heating rate might have been sufficient to compromise the structural integrity of the parachute. Because of this possibility, the automatic sequence, as shown in figure 5, was changed for later missions to include manual deployment of this parachute, rather than deployment through the usual means of sensing pressure altitude.

With regard to the faulty heat-shield instrumentation, the spacecraft would have reentered successfully whether or not the retropackage had been retained into the atmosphere. The action taken was prompted by safety considerations in that the instrumentation could have been correct and the heat shield released prior to reentry. If the heat shield had been released from the spacecraft, and if the pilot had not been able to override the automatic sequence that jettisoned the retropackage (shown in fig. 5), the heat shield would have undoubtedly parted from the spacecraft causing it to burn catastrophically during reentry. In this case, the action of the pilot would have been necessary to preclude this occurrence.

Mercury-Atlas Mission 7 (MA-7)

The MA-7 mission was similar to the MA-6 flight in that three orbital passes were planned and completed successfully. The only failure which occurred that is pertinent to this discussion was a malfunction of the pitch horizon scanner. This malfunction, discussed in greater detail in reference 7, resulted in an excessive signal bias, which was not constant in magnitude, in the output of the scanner and caused large errors in pitch attitude of the spacecraft while in the automatic mode.

As a result of a very ambitious flight plan, the scanner malfunction did not become clearly evident to the pilot and ground personnel until late in the orbital phase of the mission. Therefore, sufficient time was not available for a complete analysis of the control problem, once it had been discovered, and the pilot was faced with the immediate task of controlling the spacecraft manually during the critical retrofire period. Because of the scanner malfunction, an additional complication arose which made the pilot's task more difficult. The attitude indicators on the astronaut's instrument panel, shown in figure 9, were driven by the output of the attitude gyros and were normally used in precise manual control of the spacecraft. The bias in the scanner, however, made the indication in pitch attitude erroneous and therefore invalid as an attitude reference. The pilot was then forced to cross-reference between his instruments and the view through the window for attitude indications. The bias in the pitch scanner effectively placed the spacecraft at a negative pitch angle which was greater than the intended attitude. During the countdown for retrofire, the astronaut once again checked to verify that the malfunction in the ASCS was still present. During this check, a large deviation in pitch attitude was recognized by the pilot, and a sizeable excursion in yaw attitude resulted when the pilot quickly attempted to restore the pitch attitude to a proper value. At the beginning of retrofire, the error in yaw attitude was approximately 27°, as determined by radar tracking. The pilot recognized this error on the yaw indicator and corrected it before the conclusion of the retrofire period. However, the mean effective error in yaw was the primary reason that the spacecraft landed about 250 nautical miles downrange from the intended landing point. The mean errors in pitch and roll attitude, which the pilot corrected from a window reference, were effectively zero. It should be stressed that yaw attitude is the most difficult to aline from a window reference, and since a good portion of the pilot's time was spent using this attitude reference, the lack of effectiveness in immediately correcting the yaw error is understandable. For additional details of the astronaut activities during the retrofire period, consult reference 8.

In the spacecraft sequential system, circuitry existed which determined whether or not the spacecraft attitudes were within certain prescribed limits before the system would ignite the retrorockets automatically. This circuitry is presented in figure 10. The functions of the attitude permission relay driven by the ASCS, the attitude permission bypass switch, and the manual retrofire button should be noted. Because of the horizon scanner malfunction, the spacecraft attitudes, as indicated to this automatic circuitry, did not fall within the so-called "attitude gates." In addition to controlling spacecraft attitudes manually, the astronaut was forced to bypass attitude permission and ignite the retrorockets manually.

If the spacecraft had been unmanned but with the sequential system still able to initiate retrorocket ignition, the attitudes at retrofire would have been normal about all axes with the exception of pitch. The scanner bias would have resulted in the spacecraft's pitching down to approximately a negative 54° angle. In this condition, but in the absence of other complications, the spacecraft would have landed some 50 nautical miles downrange. The initial conclusion from this statement might be that the unmanned vehicle would have completed the mission more effectively than the manned configuration. However, because of the deviations in scanner bias, it cannot be ascertained whether the attitude constraints at retrofire would ever have been satisfied. Therefore, the pilot was needed in the spacecraft to initiate retrofire manually, a procedure which, under these conditions, even the ground personnel were unable to accomplish. That is, a command from the ground was subject to the same attitude constraints at retrofire as the automatic system, whereas only the pilot could override these constraints. He could also bypass the normal 30-second delay in the retrosequence circuitry, a feature which would be important in a time-critical situation. Conceivably, the attitudes resulting from the bias could have permanently remained outside the attitude gates and the spacecraft would have stayed in orbit until atmospheric drag would eventually cause it to reenter in a matter of days. The life support supplies and electrical power would have been expended prior to this point, the heating conditions during reentry would have been excessive, and the spacecraft would not have landed in a planned landing area.

Mercury-Atlas Mission 8 (MA-8)

In the MA-8 mission, six orbital passes about the earth were completed as planned. There were no failures which could have seriously affected mission success with the spacecraft configured as it was. One malfunction, a partial blockage of the coolant control valve for the pressure-suit environmental circuit, resulted in high suit temperatures. This malfunction, analyzed more explicitly in reference 9, was effectively corrected by the pilot by precise adjustment of the faulty control valve. The time history of the temperature rise and the pilot's manipulation of the valve to correct the problem are shown in figure 11. The location of this valve in the ECS is shown schematically in figure 6. It is believed, however, that if no means had existed for controlling temperature, the mission would have been terminated early because of the uncomfortable temperature levels to which the pilot would have been subjected. If the valve were controllable only from the ground or automatically in the spacecraft, the temperature level would undoubtedly have returned to normal. Nevertheless, the presence of the pilot made possible the elimination of these features, which represent considerable weight and complexity. A detailed account of the pilot's activities in controlling the ECS and other spacecraft systems during the MA-8 flight is given in reference 10.

Mercury-Atlas Mission 9 (MA-9)

The MA-9 mission, sometimes referred to as the Mercury manned 1-day mission, was planned for up to twenty-two orbital passes. The basic Mercury spacecraft was reconfigured and procedures were changed to accommodate the increased mission duration. Many of these new procedures took advantage of the pilot's demonstrated ability to conserve spacecraft consumables through manual control of various systems. The first eighteen passes were conducted essentially as planned; the pilot had followed his flight plan closely and all planned major events and attitude maneuvers were accomplished on schedule. The mission appeared at this point to be concluding successfully.

However, on the nineteenth orbital pass, the pilot noted an indication that the 0.05g event, which normally signals the beginning of reentry, had occurred prematurely in orbit. If the indication were correct, the automatic control system had latched into its reentry mode of operation and would not be available for the retrofire maneuver. Subsequent to this anomaly, a sudden loss of a-c power from both the main inverter and, after the automatic switchover, from the standby inverter disabled even the reentry control mode. The astronaut was therefore left with the task of controlling both the retrofire and reentry maneuvers by using manual control modes. To complicate the problem still further, the loss of a-c power also caused the gyro-driven attitude indicators to become nonfunctional. The pilot conducted the manual control task with remarkable precision, landing about 4 miles from the primary recovery ship. The performance of the pilot as a result of the inflight failure is analyzed in greater detail in reference 11. A postflight examination, discussed in reference 4, revealed that moisture in the logic circuitry of the ASCS had caused electrical short circuits, which in turn had prematurely closed a relay in the 0.05g circuit. This closed relay permitted the erroneous 0.05g indication and shifted the ASCS to its reentry logic. Soon thereafter, the a-c power supply became overloaded because of the short circuits and was automatically shut down. The relationship of the electrical power system to the automatic control circuit is shown in figure 12, with points labelled as "s" indicating the locations of electrical short circuits.

Had the spacecraft not been designed to allow exercising the required manual override commands, the vehicle would never have assumed the proper attitude for retrofire, and the sequential system would therefore have failed to initiate this event for reasons stated in the previous discussion of MA-7 mission. Without retrofire, the same situation also previously mentioned would have existed. That is, the spacecraft would have remained in orbit until atmospheric drag initiated reentry about 2 or 3 days later and after life support consumables had been expended.

Summary of Mercury Pilot's Role

For the two unmanned missions, MA-4 and MA-5, control system difficulties made impossible the successful completion of a three-pass orbital flight, which was the design mission for the Mercury spacecraft. But in both cases, the presence of a pilot and the capability to control the spacecraft attitudes manually would have made the three-pass mission possible. This fact was demonstrated in the MA-6 mission in which a similar malfunction occurred but in which the astronaut completed the flight by using his manual control modes. A summary of the pilot's role in circumventing Mercury systems failures is presented in table III. Although not previously discussed, the MA-7 and MA-8 flights also demonstrated the feasibility of operating in an attitude-free drifting flight mode, which was an effective means of conserving control fuel and electrical power. This experience made it possible to plan long periods of drifting flight for the MA-9 mission and thereby accomplish the extended mission without prohibitive systems design changes.

For the MA-6 mission, it was pointed out that, without the pilot, the flight would undoubtedly have been terminated before the planned time because of an excessive rate of fuel consumption in the automatic control mode. In the successful MA-7 flight, manual initiation of the retrorocket-ignition sequence prevented the horizon scanner malfunction from significantly delaying this critical event. Although an error in yaw angle caused the spacecraft to land somewhat beyond the planned landing area, this error would have undoubtedly been much greater had the pilot not been present. The six-pass MA-8 mission was successful, although a problem of an abnormal increase in suit temperature could have terminated the flight early had no means been available for reducing this temperature. The pilot, however, was able to correct this situation by manual adjustment of his coolant flow valve. Short circuits in the automatic control circuitry during the MA-9 flight made it essential for the pilot to control the spacecraft manually during retrofire and reentry.

Since the comprehensive preflight preparation for each of the Mercury astronauts was a major factor in their ability to analyze and correct inflight problems, the reader is directed to reference 12 for a summary of the Mercury pilot training program.

Concluding Remarks

Although the Mercury spacecraft was designed for completely automatic or remote control of all normal mission events, a careful analysis of the types of failures which have occurred in the Mercury orbital flights clearly indicates the importance of the pilot's role. This role involves his decision capability, his ability to actuate system controls and initiate flight sequences manually, and his irreplaceable capacity to recognize, accept, analyze, and act upon the unpredictable events which nearly always occur. As in Mercury, the effectiveness of preflight training is a key factor in the proficiency with which the space pilot assumes this role.

Man's versatility and judgment will always be an inherent factor when considering the human pilot as an integral part of the operating systems for space vehicles. One of the first-order objectives of the MA-9 mission was "... to verify that man can function as a primary operating system of the spacecraft." This objective was, of course, achieved by Astronaut Cooper when he successfully completed the planned mission and safely returned the spacecraft despite a disabled control system. As a result of Mercury experience, many of the systems in the Gemini and Apollo manned spacecraft have been designed with manual control as the primary or sole mode of operation. If it were possible to design an automatic system which would duplicate man's role as a spacecraft commander, the added burden in weight and complexity under our present state of technology would clearly preclude the practicality, if not the possibility, of complete automation in exploratory research spacecraft.

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TABLE I. - ORBITAL FLIGHT PROGRAM SCHEDULE

Unmanned	1961	1962	1963
MA-4 (Sept. 15)	▲		
MA-5 (Nov. 29)	▲		
Manned			
MA-6 (Feb. 20)		▲	
MA-7 (May 24)		▲	
MA-8 (Oct. 3)		▲	
MA-9 (May 15)			▲

TABLE II. - OPERATING MODES OF ATTITUDE CONTROL SYSTEM

Primary modes	Secondary modes of primary mode	Reaction control system (RCS) used	Type of Linkage[a]
Automatic stabilization and control system (ASCS)	Orbit Orientation Reentry Auxiliary damping	Automatic[b] RCS	Automatic, electrical
Fly-by-wire (FBW)	High and low thrust Low thrust only[c]	Automatic RCS	Manual, electrical
Rate stabilization and control system (RSCS)		Manual[d] RCS	Automatic and manual[e] electrical
Manual proportional (MP)		Manual RCS	Manual, mechanical

[a]Includes mode of initiating control and physical means of achieving control.

[b]So named because supplied fuel for automatic control mode.

[c]For MA-8 and MA-9 only.

[d]So named because supplied fuel for manual proportional mode.

[e]Rates could be initiated about any axis through hand controller and maintained at the desired rate automatically by this primary control mode.

TABLE III.- SUMMARY OF MERCURY PILOT'S ROLE

Mission	Number of orbital passes planned	Number of passes completed	Mission critical malfunctions	Pilot action necessary
MA-4[a]	1	1	Inverter	Manual switchover to redundant unit if auto switch failed
			Control thruster	Manual attitude control to prevent early fuel depletion[b]
MA-5[a]	3	2	Control system	Manual attitude control to prevent early fuel depletion and maintain accuracy in pitch
MA-6	3	3	Control thrusters	Manual attitude control used to prevent early fuel depletion
			Retropack instrumentation	Manual override of normal retropack jettison needed to delay heat shield separation if instrumentation had been correct
MA-7	3	3	Horizon scanner	Bypass of attitude permission during retrofire and manual rocket ignition to permit timely reentry
MA-8	6	6	Excessive suit temperature	Manual control of suit temperature necessary to continue manned flight
MA-9	22	22	Electrical short circuit	Manual ignition of rockets and manual attitude control during retrofire and reentry

[a]These two unmanned missions are discussed from the standpoint of the expected response of a pilot had one been present.

[b]Spacecraft could not have completed design mission of three orbital passes at indicated fuel usage rate.

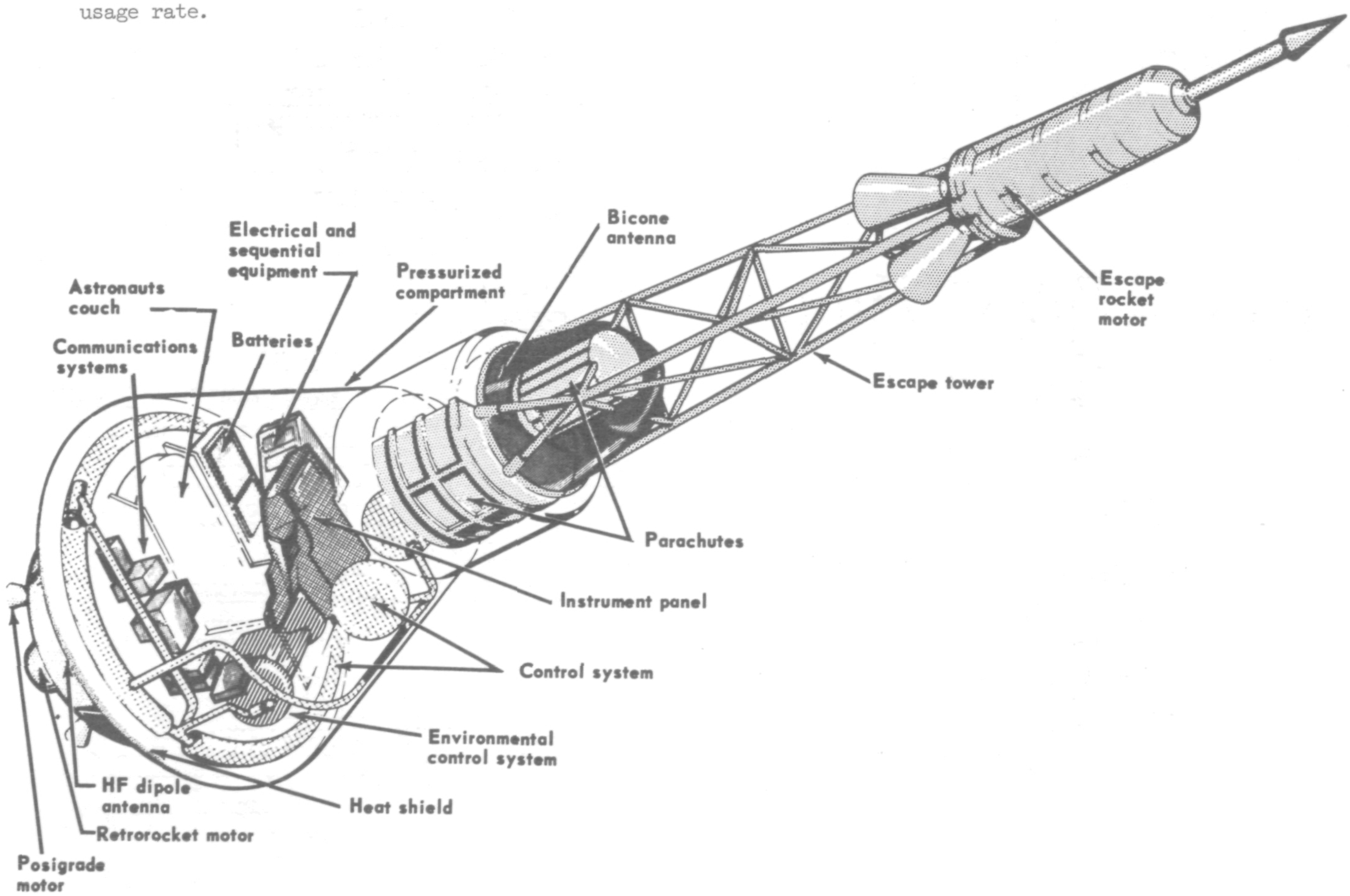

Figure 1.- Mercury spacecraft systems.

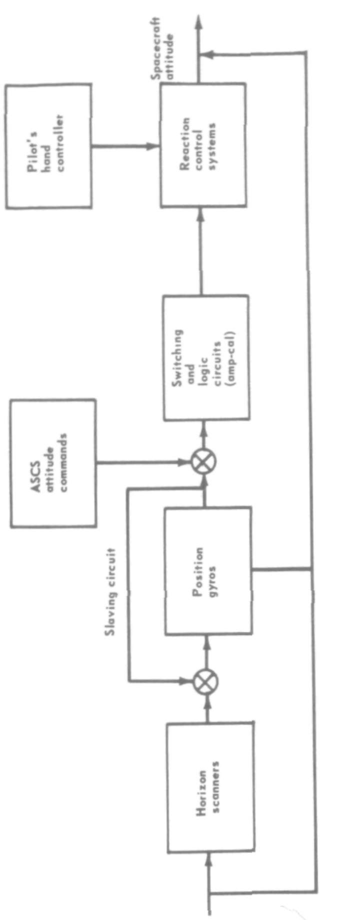

Figure 3.- Control system schematic.

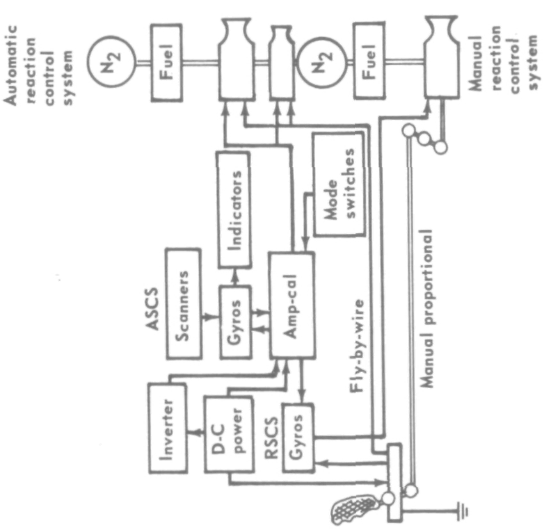

Figure 2.- Spacecraft control system modes.

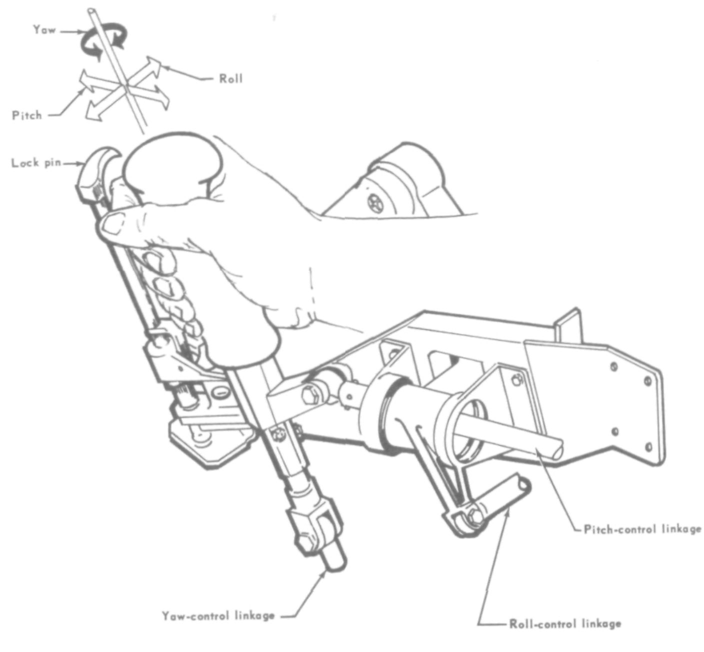

Figure 4.- Three-axis hand controller.

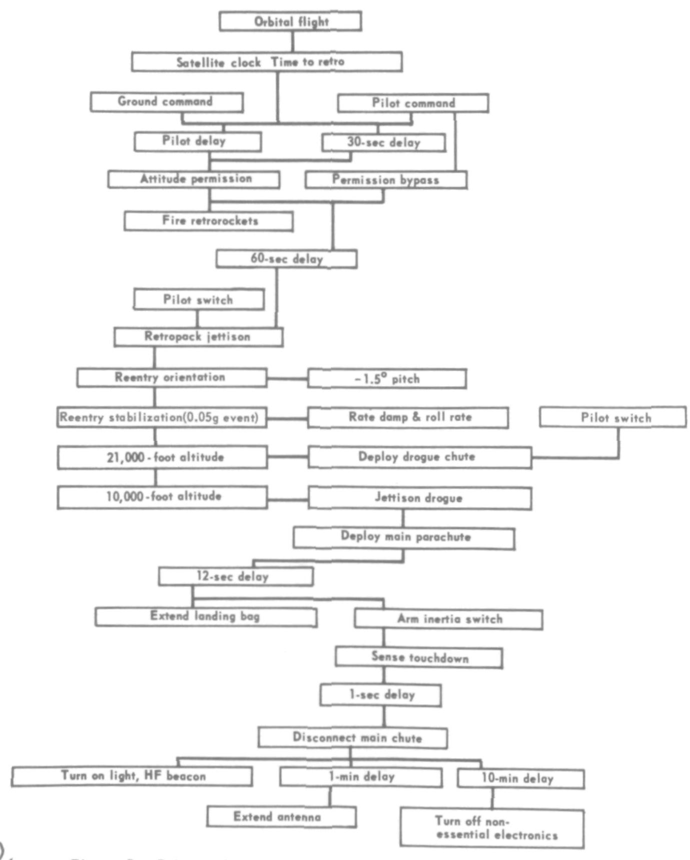

Figure 5.- Retrograde, reentry, and landing automatic sequence.

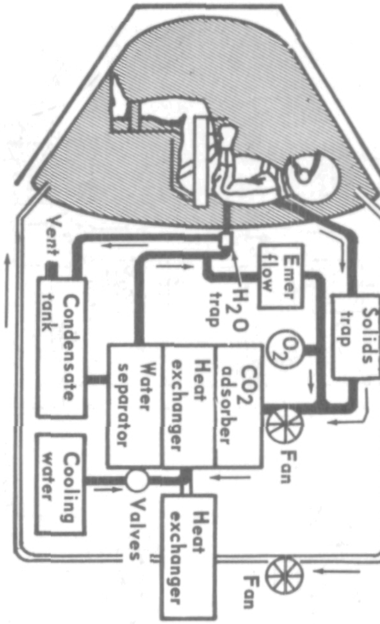

Figure 6.- Environmental control system.

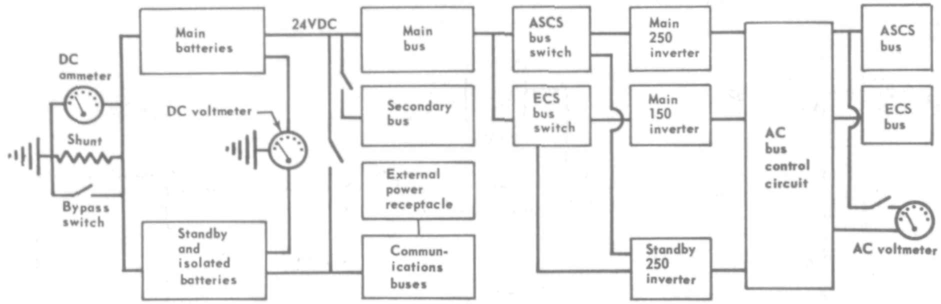

Figure 7.- Electrical power system schematic.

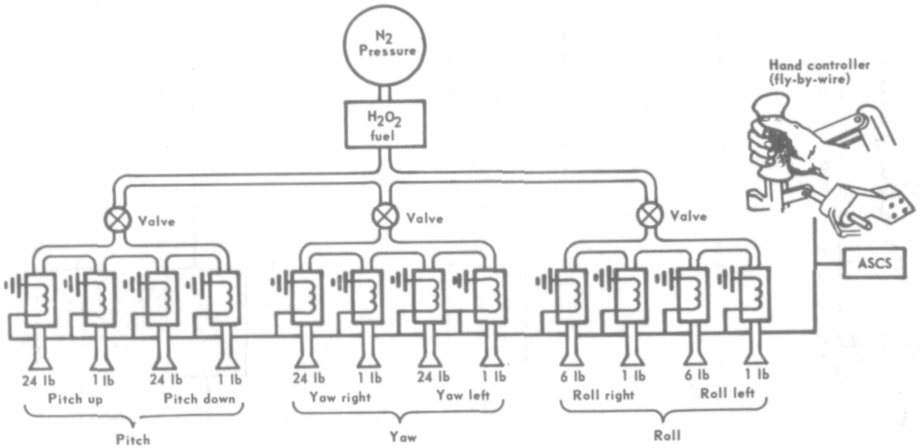

Figure 8.- Automatic reaction control system schematic.

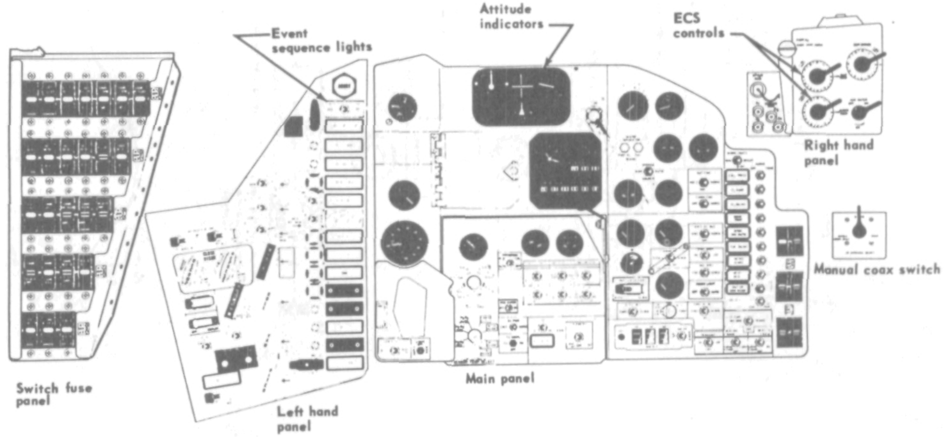

Figure 9.- Spacecraft instrument and control panels.

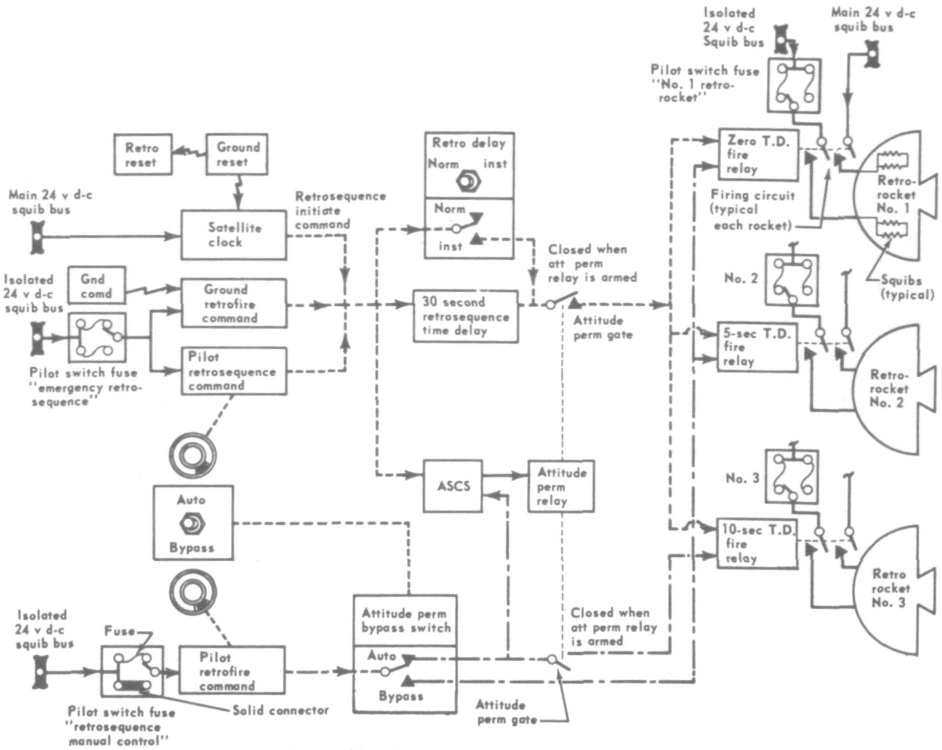

Figure 10.- Retrosequence schematic diagram.

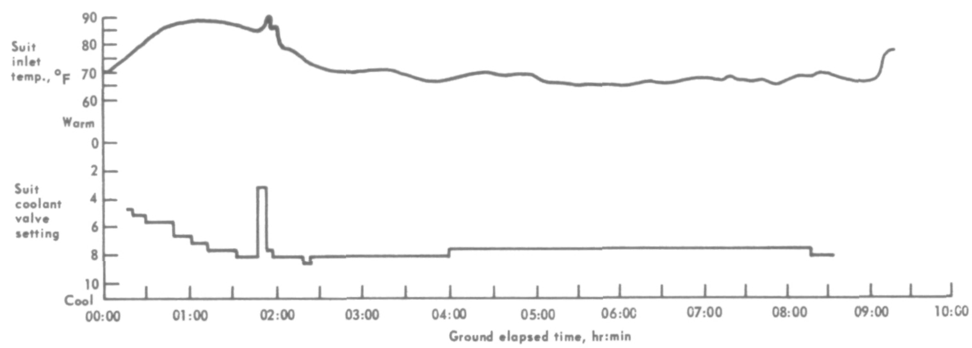

Figure 11.- Suit inlet temperature and coolant control valve setting.

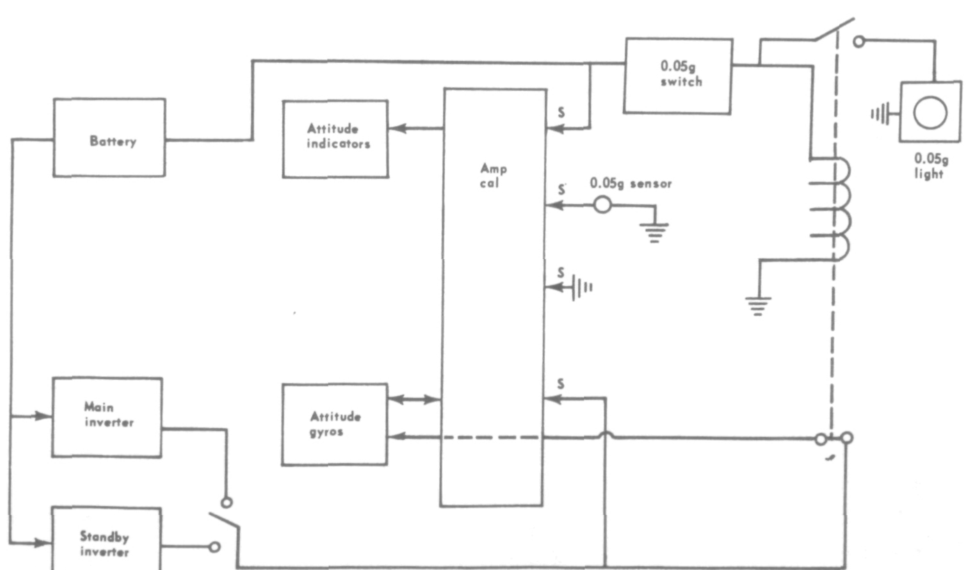

Figure 12.- Control system power circuit.