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APOLLO EXPERIENCE REPORT - THE DOCKING SYSTEM

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16. Abstract

The decision to accomplish the lunar landing mission by use of the lunar orbit rendezvous technique required that a docking system be developed to allow (1) spacecraft modules to be structurally joined, (2) intravehicular transfer of the crew and equipment, and (3) separation of the modules. The basic design criteria of the docking system, the evolution process, and the various docking concepts considered for the Apollo Program are presented. Docking systems that were considered for the Apollo Program included both impact and nonimpact systems; a probe and drogue impact system was selected. Physical and functional descriptions of the probe and drogue, the crew transfer tunnel, and docking ring latches are presented for both the early configuration and the present configuration as influenced by the development and qualification test programs. In addition, preflight checkout activity and mission performance of the system are discussed.

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APOLLO EXPERIENCE REPORT

THE DOCKING SYSTEM

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SUMMARY

This report describes the development of the Apollo Program docking system from the time of the decision to perform a manned lunar landing by using the lunar orbit rendezvous technique to the Apollo 13 mission. The selected Apollo Program configuration required the development of a docking system that would provide for structural connection of two space vehicles, intravehicular transfer of the crew and equipment, and separation and rejoining of the two vehicles.

Based on the initial design requirements, studies and tests were conducted to evaluate seven candidate docking concepts from which the probe and drogue impact docking system was selected. After concept selection, detailed design studies resulted in a basic system configuration that was further modified as a result of extensive analyses, development, and qualification test programs. These analytical and test programs verified the adequacy of the design to meet both normal and predicted worst-case mission conditions. In addition, each spacecraft docking system is thoroughly inspected and tested prior to flight to ensure proper manufacture and assembly. The successful Apollo 9 mission provided the first opportunity for a complete flight test of the docking system under all natural and induced environments.

INTRODUCTION

In July 1962, NASA announced the decision to accomplish the Apollo lunar landing mission by use of the lunar orbit rendezvous technique. This technique used a modular spacecraft configuration and established the requirement for a docking system that would provide for connection, crew transfer, and separation and rejoining of the manned modules.

In 1962, the NASA Manned Spacecraft Center (MSC) and the command and service module (CSM) contractor initiated studies and tests to determine which docking system configuration would be best for the Apollo Program. This activity resulted in the selection of the probe and drogue concept in December 1963, at which time the CSM contractor was directed to proceed with the design.

This report documents the evolution of the Apollo docking system from concept selection through development, qualification, and flight performance. Descriptions of the hardware (appendix A), operational characteristics of the docking system, and recommended guidelines for the design of advanced docking systems are presented. A description of the Apollo 14 anomaly, which occurred after the initial preparation of this report, is included as appendix B. Appendix B was prepared by the Mission Evaluation Team.

DESIGN REQUIREMENTS

The selection of a docking concept for the Apollo Program was initiated at a time when the docking of two vehicles in space was yet to be achieved by the United States, and the definition of the Apollo spacecraft was very preliminary. As a basis for concept selection and system design, basic design ground rules were established that remained essentially unchanged throughout the Apollo Program. These initial ground rules became part of the Apollo specifications, with the significant docking and crew transfer requirements summarized as follows.

1. Docking velocity and alinement requirements for initial contact will include an axial (closing) velocity of 0.1 to 1.0 ft/sec, a radial (transverse) velocity of 0 to 0.5 ft/sec, an angular velocity of 0 to 1.0 deg/sec, a radial alinement of 0 to 1.0 foot, an angular X-axis alinement of 0° to 10°, and a rotational alinement of $-60^\circ \pm 10^\circ$.

2. The CSM will serve as the active docking vehicle for translunar docking.

3. Both the CSM and the lunar module (LM) will be designed with the capability to serve as the active spacecraft for lunar orbit docking.

4. In the docked configuration, an unaided crewman can perform all of the functions necessary to accomplish crew transfer in either direction (CSM to LM or LM to CSM).

As the Apollo Program progressed, it became obvious that the specified contact conditions were conservative because of spacecraft control system and optical alinement aid limitations. For example, control system thrusting time necessary to achieve the maximum radial and angular rates at docking contact requires command module (CM) and LM predocking approach positions that place the LM target out of the field of view of the CM optical alinement sight. Although such dockings would not be attempted, the docking system design had to accommodate the high lateral loads resulting from any combination of the contact criteria. Although attempts were made to eliminate some of the conservatism to minimize design problems, these efforts were unsuccessful, and the contact criteria remained as initially specified.

CONCEPT SELECTION

In 1962, MSC and the CSM contractor began studies and tests to develop a docking system that would best fulfill the Apollo Program requirements. This preliminary study phase included an evaluation of seven candidate docking systems that were further classified as either impact or nonimpact systems.

Impact Docking Systems

The impact docking systems include those systems that achieve initial capture of the passive vehicle by initiating a closure rate between the vehicles to effect contact. The three impact docking systems evaluated were the probe and drogue, the ring and cone, and the Gemini system.

Probe and drogue. - The probe and drogue docking system consists of a probe mounted on the CM and a drogue installed in the LM (fig. 1). The probe consists of a probe head, a single center piston for impact energy attenuation, three pitch arms with bungees for lateral loads and vehicle alinement, and an electrical reel mechanism to effect retraction after initial capture. The drogue is a funnel-shaped structure that guides the probe head to the initial capture position, where drogue-mounted latches engage the probe head. For crew transfer after hard docking, both the probe and the drogue have to be removed to provide a clear passageway.

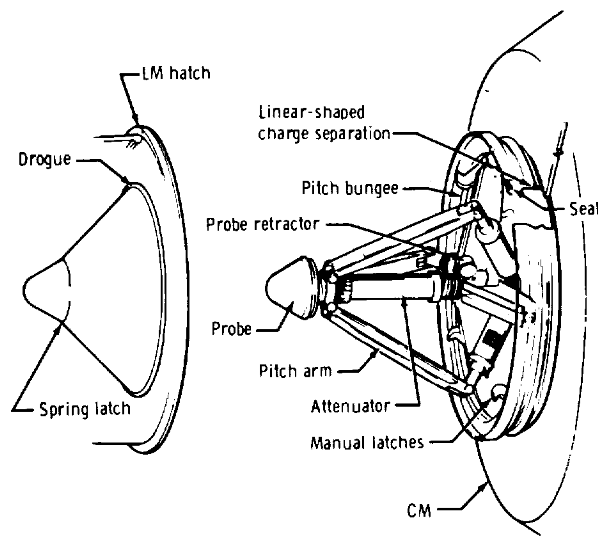


Figure 1. - Probe and drogue docking system.

Ring and cone. - The ring and cone docking system was developed by MSC and consists of a ring mounted on the CM and a cone mounted on the LM (fig. 2). The tubular ring is supported by six identical impact attenuators that attach to the CM egress tunnel. After initial capture latching, the two vehicles are pulled together to the hard-dock position by three electrical reel-in mechanisms. The cone consists of four structural elements and capture latches to engage the ring. The cone serves as the guide for the ring from contact to capture latch engagement and is removable, after hard docking, to provide for crew transfer.

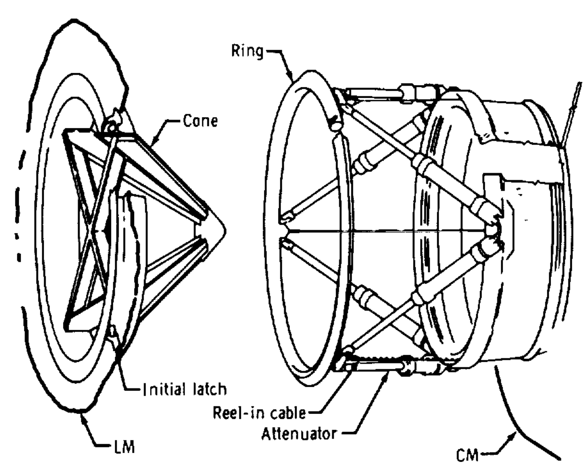


Figure 2. - Cone and ring docking system.

Gemini docking system. - The Gemini docking system consists of a structural ring on the CM and a cone on the LM (fig. 3). This system is a reversal of the ring and cone system in that the cone is reversed (similar to drogue) and is supported by the impact attenuators. This system, although used successfully in the Gemini Program, was never seriously considered for the Apollo Program because of the severe weight penalty that would be imposed on the LM.

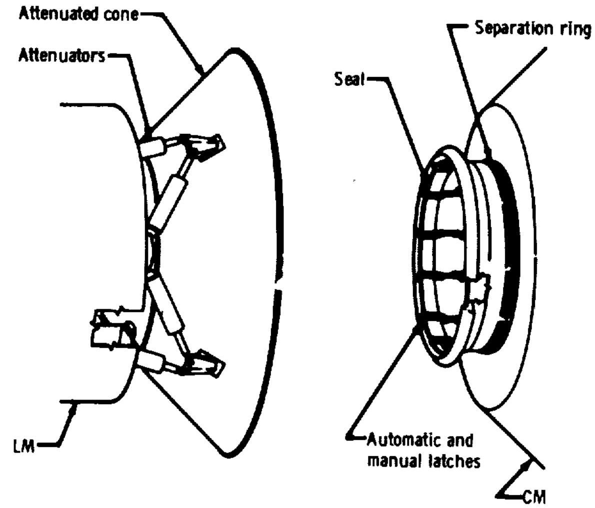


Figure 3. - Gemini docking system.

Nonimpact Docking Systems

The nonimpact docking systems include those systems that achieve initial capture of the passive vehicle by extending a member from the active, stationkeeping vehicle. The four nonimpact systems evaluated were the inflatable probe, the stem, the stem and cable, and the inflatable tunnel.

Inflatable probe. - The inflatable probe system uses an extendible inflatable tube and support structure mounted on the CM and a conical drogue mounted on the LM (fig. 4). The 4-inch-diameter tube is housed on a reel mechanism located at the base of the support structure. The tube is extended to 20 feet and made rigid by gas inflation. The capture latch mechanism is mounted on the forward end of the tube for engagement of the latches in the LM drogue. After capture, the tube is reeled in to achieve hard docking.

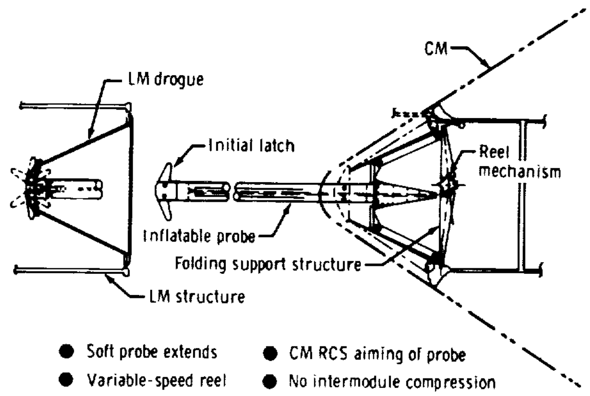


Figure 4. - Inflatable probe docking system.

Stem. - The stem docking system (fig. 5) consists of a CM-mounted stem device and a combined drogue and hatch installed in the LM. The stem device is constructed of sheet metal that is heat treated in the rolled position so that a metal tube is formed upon extension of the sheet from the spool of the reel mechanism. Once the tube is extended, the crew manually guides the stem probe head into the drogue to effect capture latch engagement. Retraction is provided by the reel mechanism.

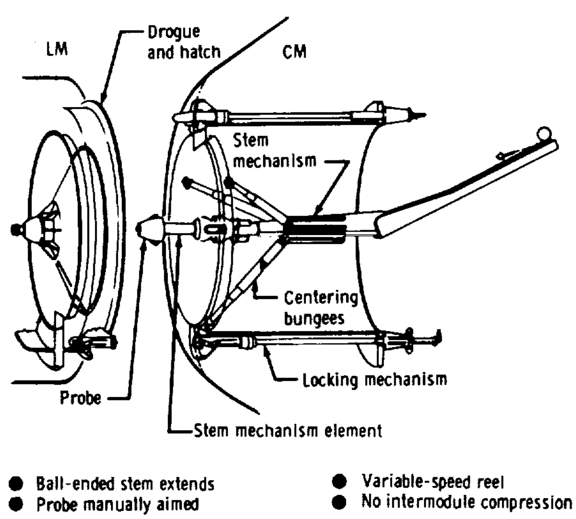


Figure 5. - Stem docking system.

Stem and cable. - The stem and cable system (fig. 6) is almost identical to the stem system, except that the stem cannot be manually directed, and the probe head is permanently attached to a cable rather than to the stem. After capture latch engagement, the stem retracts and leaves the vehicles attached by a single cable tether. A variable-speed cable-reel device then effects a closure rate to the hard-dock position.

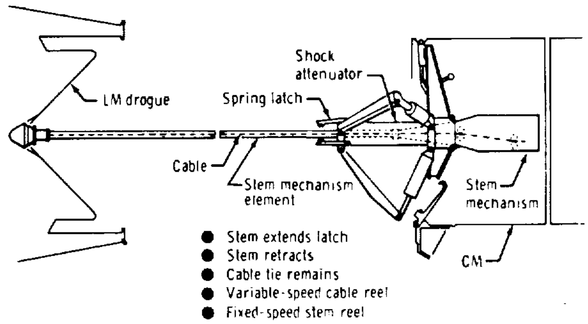


Figure 6. - Stem and cable docking system.

Inflatable tunnel. - The inflatable tunnel (fig. 7) is a flexible device that is stowed in the CM tunnel and releases and extends by gas pressure. After capture latch engagement with the LM drogue, the tunnel is retracted to achieve a hard-dock configuration.

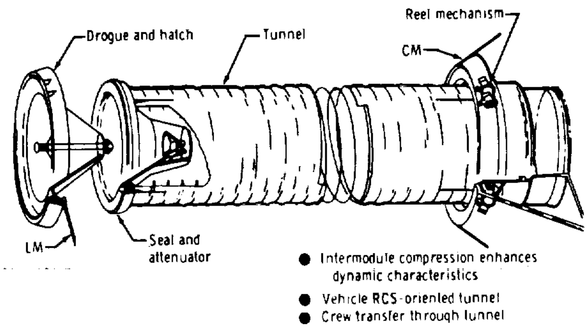


Figure 7. - Inflatable tunnel docking system.

Selection Process

The selection of a docking system for the Apollo Program was based on limited knowledge because experience with actual hardware in space or from ground-based docking simulations was almost nonexistent. Therefore, the development of a mathematical model and a testing technique that would yield rapid results for a comparative evaluation of the proposed docking concepts was necessary.

The CSM contractor developed a two-dimensional mathematical model to define the dynamic characteristics of the proposed systems. The model was a mathematical description of the docking configurations, vehicle masses and moments of inertia, and control systems. The model was simplified by limiting dynamics to planar motion and by considering the vehicles as rigid bodies.

The testing technique used by both MSC and the CSM contractor consisted of test vehicles supported by air bearings to simulate docking dynamics in a single plane. Although the test vehicles and the conceptual docking hardware were rather crude, the results were fairly good in that one docking concept could be evaluated with respect to another concept, even though the test results of a given hardware configuration were inaccurate. Full-scale hardware, cold-gas reaction control system thrust simulation, and man-in-the-loop vehicle control were used in the CSM contractor test program. The MSC test vehicles were approximately one-half scale and, where possible, the docking hardware was one-half scale. Also, a cold-gas thruster system with man-in-the-loop control was used with the MSC test vehicles. The factors used in evaluating the proposed docking systems included analyses, results of the test programs, and a considerable amount of engineering judgment.

Results of the test and dynamic analysis programs indicated that all of the proposed system concepts were feasible, although the inflatable probe was considered to be marginal. In addition, the following conclusions were reached: (1) nonimpact systems would require more fuel or more complex piloting procedures than impact systems, and (2) the Gemini docking system would result in a prohibitive weight increase on the LM.

Results of the test and analysis programs were inconclusive on the following significant items.

1. The CSM contractor analyses and tests indicated that a very stiff (high spring rate) probe was best dynamically, whereas the MSC tests showed that a relatively flexible (low spring rate) or pivotable probe was superior. These differences were probably due to the fidelity of the respective analytical and test models.

2. Estimates of system effective weights were difficult to determine accurately and could be used to promote or degrade any of the concepts.

3. The ease of crew transfer was completely unknown for all system concepts, even though attempts were made to simulate the tasks involved. Therefore, because only two of the proposed concepts could be eliminated from contention and because no single concept was clearly superior, judgment was obviously the key factor in selecting a docking concept.

Selection of the Probe and Drogue System

On November 19 and 20, 1963, the CSM contractor presented MSC with the evaluation results at an Apollo docking interface meeting. A summary of the CSM contractor evaluation is presented as table I. The primary importance of the table is that it reflects the factors used to evaluate the various concepts and the choice of the concepts that the CSM contractor believed could be produced with the best results.

During the meeting, MSC and the CSM contractor agreed that the probe and drogue concept and the ring and cone concept were the candidate systems. The probe and drogue system was considered to provide the least weight penalty; however, the ring and cone system would provide a better crew transfer operation. The docking interface panel recommended selection of the probe and drogue concept as the Apollo Program docking system; and on December 31, 1963, the CSM contractor was formally directed to proceed with design and analysis of the probe and drogue system.

After selection of the probe and drogue docking concept, the probe configuration underwent a rather significant change as a result of preliminary design trade-off studies conducted by the CSM contractor in early 1964. The selected design, termed the basic probe (fig. 8), incorporated the following major deviations from the initial concept configuration.

1. The initial capture latches were relocated from the drogue to the probe head to reduce the LM weight.

TABLE I. - DOCKING SYSTEM CONCEPTS SUMMARY EVALUATION

Factor	Maximum score	Inflatable probe	Stem mechanism	Stem and cable	Inflatable tunnel	Center probe and drogue	Cone and ring	Gemini concept
Dynamics	35	19	24	22	28	35	28	23
Operational tasks (docking)	25	12	16	14	18	25	20	22
Crew transfer (postlatch)	25	15	18	13	22	17	21	25
Abort and recovery compatibility	20	15	15	10	6	16	7	20
CM protection	15	10	10	11	15	12	13	12
Design simplicity	10	7	6	5	4	10	4	4
Environment	10	5	10	9	4	8	6	6
Backup mode flexibility	10	7	6	8	10	10	9	9
Total score	150	90	105	92	107	133	108	121
Injected weight, lb	--	217	162	232	227	149	232	283
Effective weight, lb	--	392	335	410	426	308	587	1343

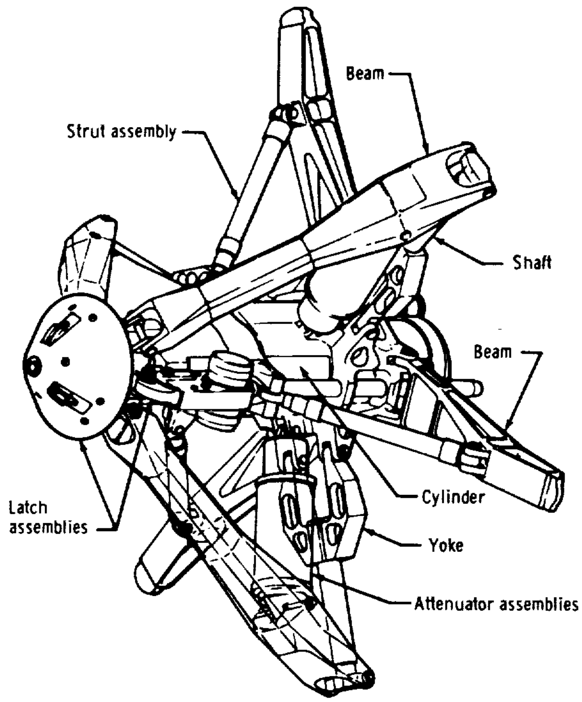


Figure 8. - Basic probe assembly docking system.

2. The central attenuator was deleted and three pitch bungees were replaced with an attenuator and a tension tie; this change provided redundant axial attenuation as well as attenuation for pitch arm contact loading.

3. The mechanical retract device was deleted and an internal pneumatic retract system was incorporated to improve reliability.

DOCKING SYSTEM FUNCTIONAL DESCRIPTION

Design of the Apollo docking system began in December 1963 and evolved through a rigorous program of development tests, performance analyses, design studies, and qualification tests to the present flight configuration. Development and qualification of the docking system are discussed in the section entitled "Docking System Development and Qualification," and a hardware description is provided in appendix A. The present configuration of the Apollo docking system (fig. 9) consists of the CM forward hatch, the CM docking ring and automatic ring latches, the probe assembly, the drogue assembly, the LM tunnel ring, and the LM hatch.

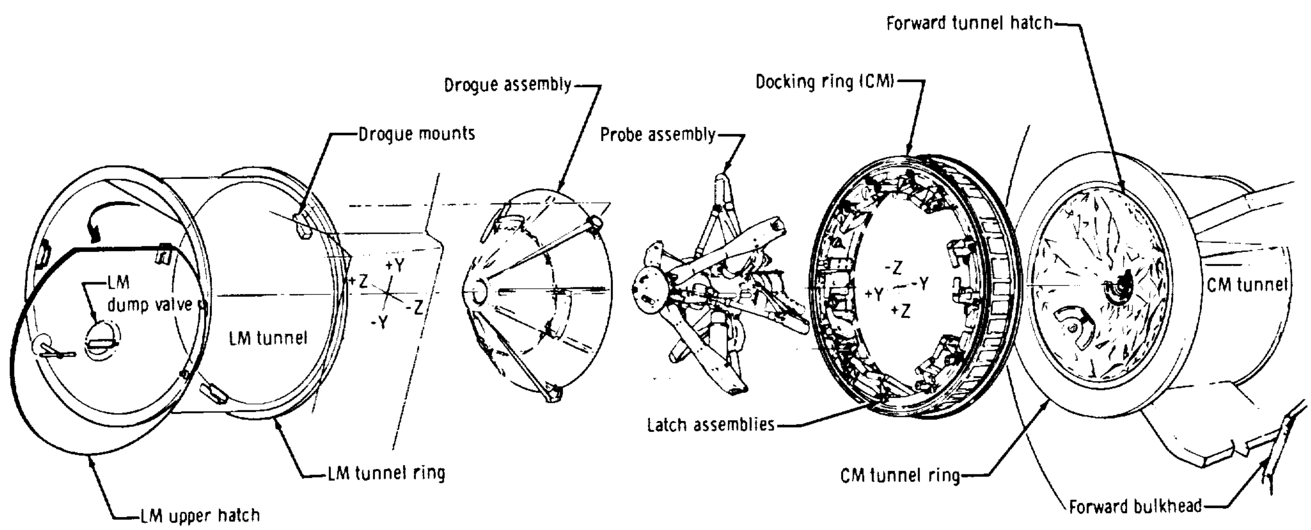


Figure 9. - Major assemblies of the docking system.

Prior to lift-off of the Apollo spacecraft, the docking probe assembly is installed in the CM docking ring in the retracted configuration and is attached to the boost protective cover by a tension-link mechanism. If, during ascent, a launch escape system (LES) abort of the CM is required (fig. 10), the docking ring is severed from the CM by a mild detonating fuse (MDF) charge, and the docking ring and probe assembly are jettisoned with the launch escape tower. For normal ascent, the docking ring is not severed; however, the tension link is separated from the probe as the tension-link-to-probe attach pins shear when the launch escape tower is jettisoned. If a service propulsion system (SPS) abort occurs, the MDF charge separates the docking ring from the CM in the same manner as in an LES abort.

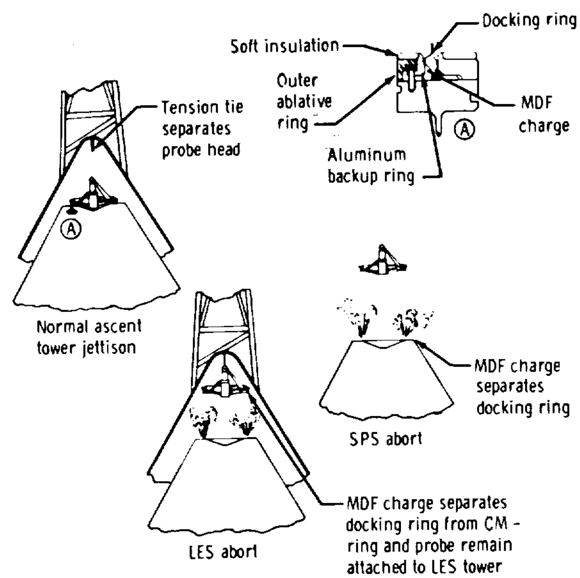


Figure 10. - Docking probe separation modes.

When the spacecraft is in earth orbit, the crew extends the docking probe in preparation for docking with the LM and Saturn booster (S-IVB) during translunar flight. This docking maneuver, termed transposition docking, occurs shortly after translunar injection and begins with separation of the CSM from the S-IVB (fig. 11). Once the CSM is free of the S-IVB, a transposition maneuver of the CSM is executed to aline the CSM and LM docking ports in preparation for docking. The crew then initiates a closing velocity with the LM so that the probe head contacts and engages with the drogue. The crew observes an indicator to confirm capture latch engagement prior to initiating the probe retract system to pull the LM toward the CSM. The 12 docking ring latches are automatically actuated when the LM tunnel ring depresses a trigger on each of the latches. Ring latch engagement provides a pressure-tight, structurally rigid connection between the CSM and the LM. To allow crew ingress, the tunnel and the LM are pressurized from the CM by opening a valve in the CM forward hatch. One crewman then removes the CM forward hatch, verifies engagement of the 12 latches, connects the CM to LM electrical umbilical, verifies engagement of the probe extend latch, vents the gas from the probe retract system, and reinstalls the CM forward hatch. The LM is then separated from the S-IVB, and the docked CSM and LM continue in translunar flight.

Prior to spacecraft injection into lunar orbit, the crew must enter the LM. To achieve a clear passageway, the CM forward hatch, the probe, and the drogue must be removed, and the LM hatch must be opened. After the LM checkout activity is completed, the two crewmen reenter the CM, and the removed hardware is reinstalled in the tunnel, but is not electrically connected.

In preparation for lunar descent from lunar orbit, the LM crew enters the LM after the tunnel hardware has been removed. The probe and the drogue are then reinstalled, the LM hatch is closed, the probe is preloaded, the 12 ring latches are manually released, and the CM forward hatch is installed in preparation for the undocking.

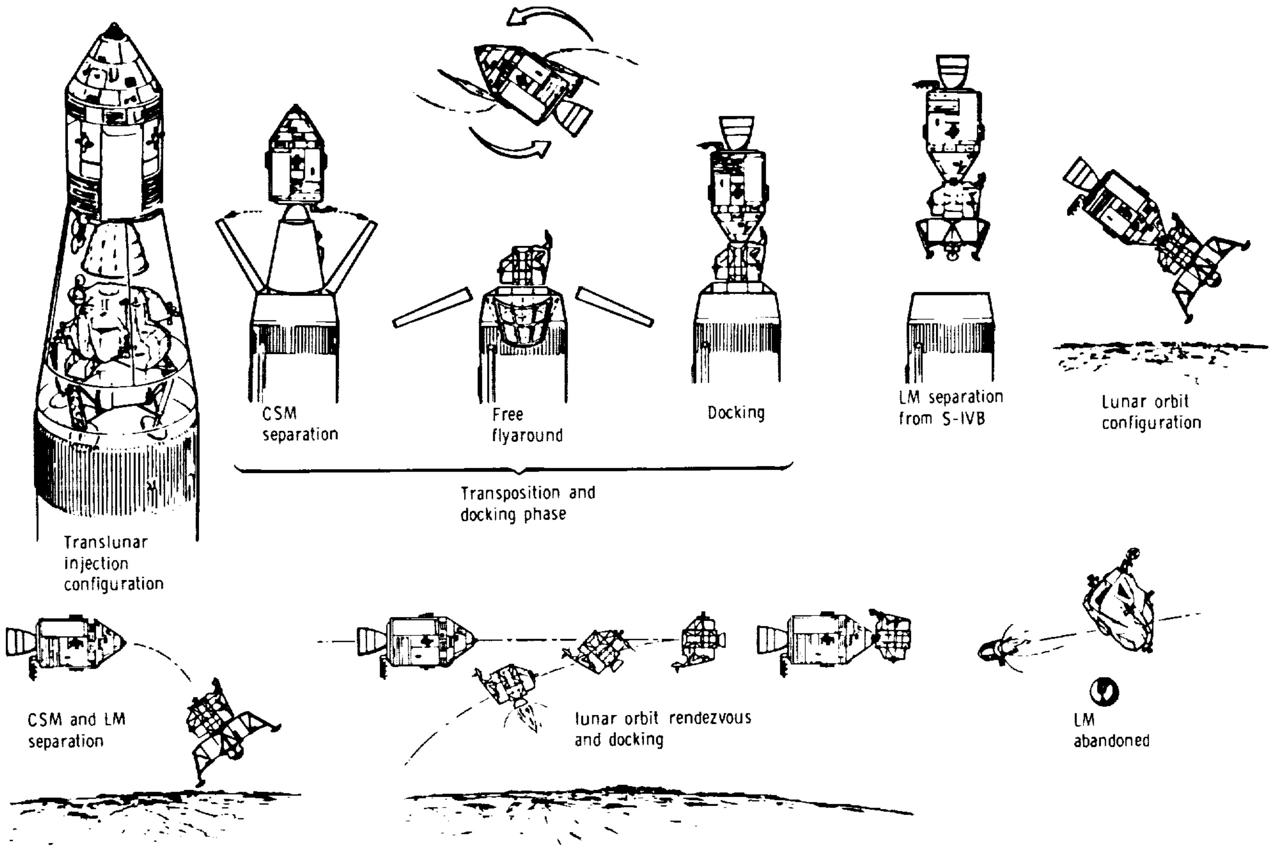


Figure 11. - The CSM and LM docking operational phases.

Thus, the docking system is configured so that the CM and the LM are held together by the probe and drogue. The undocking is initiated from the CM by remotely unlatching the probe to allow extension of the probe and separation of the LM. This sequence also leaves the docking system prepared for the subsequent docking event.

The next docking event, termed lunar orbit docking, occurs between the CSM and the LM ascent stage and, relative to the docking system, is almost identical to the transposition docking. Once the vehicles are docked, the tunnel hardware is removed, the crew and various items are transferred to the CM, and the modules are prepared for final separation. All items of no further use, including the probe and drogue, are stowed in the LM, and the LM and CM hatches are secured. The tunnel area between the hatches is vented, and the LM is jettisoned by explosively severing the CM docking ring.

DOCKING SYSTEM DEVELOPMENT AND QUALIFICATION

Test Programs

Development of the docking system consisted of a series of test programs and dynamic loads analyses that began in 1964. The initial group of component and system testing is summarized in table II. These early development tests were planned to

TABLE II. - DEVELOPMENT TESTS

Test identification	Test environments	Results
Probe assembly	Structural loading for lateral load versus deflection, axial compression and tension, probe head torque, single solenoid release load, and preload versus torque	Determined load deflection data and adequacy of piston plating for high loads
Passive tension tie	Functional operation and shear load of pin	Verified configuration for a clean shear at proper load
Probe and drogue - low-temperature removal	Manual removal of hardware from simulated tunnel for -150° F case	Demonstrated that low-temperature icing was not detrimental to hardware removal
Extend latch	Thermal vacuum	Demonstrated single solenoid operation
Dynamic docking test - phase IB	Full-scale system, three-degree-of-freedom dynamic test for lunar orbit docking case	Verified mathematical model and evaluated physical and functional operation of system
Drogue impact test	High- and low-temperature dynamic loading of various honeycomb sandwich configurations	Evolved optimum core density for minimum weight drogue construction
Mass energy concept testing	Same as phase IB program, except energy absorption simulated the transposition docking case	Demonstrated energy attenuation and need for "high squeeze" piston seals to prevent leakage for -80° F retract case
Automatic docking latch	Structural loads and multi-cycle actuation	Resulted in material change of selected parts to eliminate failure caused by impact loading
Shock attenuator	Load versus stroke test at ambient and low temperatures	Resulted in change to orifice configuration

support the design release of the basic hardware configuration by revealing potential problem areas. After the development tests, there were two major periods of test activity to qualify the docking system for use in Apollo missions. The first qualification test phase used the basic docking system configuration; the second test phase was necessitated by redesign to the simplified docking system configuration. These formal qualification test programs are summarized in tables III and IV with other significant supporting test programs. In addition to the environmental testing, the crew and hardware interface acceptability was verified by system installation and removal tests that used (1) a hardware counterbalance device to simulate zero-g operations, (2) a water immersion facility test program to develop handle loads, and (3) KC-135 aircraft zero-g flights.

TABLE III. - FIRST PHASE QUALIFICATION TESTS

Test identification	Test environments	Remarks
Nitrogen pressure system	Proof pressure, leak rate, salt fog-oxygen-humidity, vibration, thermal vacuum, pressure cycling, and bottle burst pressure	Minor changes were made to seals and procedures; flow restrictors were added
Extend latch assembly	Vibration, salt fog-oxygen-humidity, and thermal vacuum	Successful
Capture latch and actuator	Thermal vacuum and life cycles	Successful
Drogue assembly	Salt fog-oxygen-humidity, vibration, and high-low temperature impact loads	Successful
Attenuator assembly	Vibration, thermal vacuum, and load stroke	Successful
Tension tie assembly	Salt-humidity, vibroacoustic, shear test, and tension load	Successful
Probe assembly	Functional, salt fog-oxygen-humidity, vibration, high-low temperature with load, and vacuum-low temperature	Resulted in revision to piston chromium plating process
Probe and drogue static structural	Static loads for predicted worst-case ultimate load conditions	Successful

TABLE IV. - SECOND PHASE QUALIFICATION TESTS

Test identification	Test environments	Remarks
Dynamic docking	High and low temperature, six-degree-of-freedom simulations of predicted worst-case docking conditions	Successfully completed except for maximum tip load case, which was limited by the test device
Probe assembly mission simulation	Humidity, vibration, thermal vacuum, salt fog-oxygen-humidity, probe preload, high- and low-temperature installation and removal, vacuum-low temperature piston function, and life cycles for ratchet assembly	Resulted in changes to (1) low-temperature requirement, (2) allowable handle loads, (3) capture latch hooks, and (4) extend latch and preload thrust washer corrosion protection
Probe and drogue static structural	Static loads for predicted worst-case ultimate load conditions	Drogue failed prior to ultimate load; however, the change in low-temperature requirement reduced the load requirement to an acceptable level
Pendulum docking	Dynamic motion simulation of full-scale system for transposition docking maximum load cases	Successful
Docking ring latch assembly	Humidity, vibration, thermal vacuum, salt fog-oxygen-humidity, life cycles, and ultimate axial load	Resulted in minor design changes
Docking latch assembly static structural	Static loads for predicted worst-case ultimate load conditions	Successful

Analysis

The original design requirements for the docking system included selected design loads in addition to the performance requirements. The design loads were used to define the strength of components and the energy attenuation requirements. Because the loads and the capture boundaries of the docking system are a function of many variables, a mathematical technique was developed to evaluate the system as the influencing variables changed. Thus, mathematical models that described the dynamic docking events were prepared by the CSM contractor and MSC.

The CSM contractor model was a two-dimensional rigid-body representation that was correlated with the CSM contractor test data. The CSM contractor model has been improved considerably since its inception; however, MSC played the leading role for load and capture boundary definition. The MSC model was superior to the CSM contractor model because it was a three-dimensional description of the docking event and also included the dynamics of ring latch engagement. The mathematical technique provided a rapid means for exploring the many combinations of the docking criteria to determine the critical design cases. Based on these critical design cases, the docking hardware subsequently was qualification tested to demonstrate capture performance and strength margins.

Significant Problems

Although numerous problems were encountered during the development of the docking system, most of the problems can be classified as relatively minor and were caused by (1) poor communication of design specifications to manufacturing or (2) laxity of inspection and quality control requirements. The more significant problem areas are summarized as follows.

Preload release shock. - On March 12, 1969, the CSM-108 docking probe indicated erroneous talkback display during ground checkout with the LM simulator tool. Subsequent troubleshooting verified that the actuator assembly had separated from the nitrogen bottles and rotated so that the switches no longer operated at the proper indexing position. The separation and rotation anomaly was caused by the high shock loading associated with releasing the extend latch with the probe preload at 5900 pounds. The solution (fig. 12) consisted of bonding the nitrogen bottles into a machined guide and attaching the guide to the actuator assembly to provide a wobble joint.

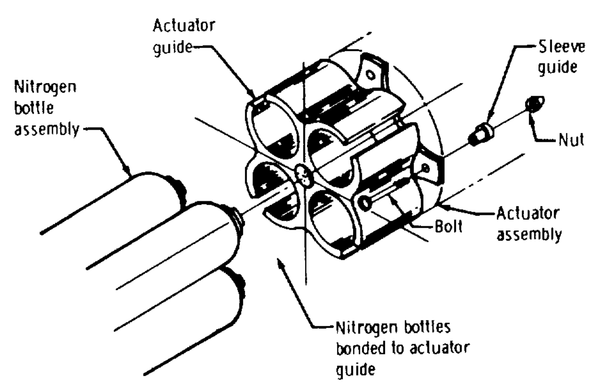


Figure 12. - Actuator guide installation.

Docking ring latches. - The original docking requirements resulted in the design of a manual docking latch configuration with four of the required 12 latches equipped with a trigger mechanism. All 12 latches would be placed in a retracted or cocked position prior to launch, and the LM interface tunnel would actuate the four semiautomatic latches by depressing the latch triggers during the docking retraction cycle. The four latches were semiautomatic; that is, depression of the latch trigger did nothing more than release the latch hook, allowing the hook to rotate to a position over the LM tunnel lip. This setup would allow pressurization of the tunnel area with a high allowable leak rate so that the crewmen could remove the CM forward hatch, enter the tunnel, and manually engage all 12 latches. This manual function resulted in a hard-dock configuration because depressing the latch handle would displace the latch hook by a preset stroke and establish a "hard seal" interface. Thus, a high hook preload (4000 pounds) could be achieved by a minimal force applied to the handle, if the CM and LM tunnel-sealing surfaces were manufactured so that the combined ring distortion (flatness) did not exceed 0.006 inch.

In late 1966, the 0.006-inch interface criterion was discovered to be far exceeded on existing CM and LM docking tunnels. Because the docking latches were fixed-stroke devices with all energy supplied by the crewmen, the handle operating forces became excessive and the total latch reach was inadequate. Although the respective docking rings could be machined in place to achieve the required flatness, accounting for distortion caused by spacecraft pressurization was not practicable. Therefore, the decision was made to design a new docking ring latch to (1) accommodate a combined CM and LM interface gap of 0.065 inch, (2) provide a total latch reach of 0.150 inch, (3) provide a minimum preload of 2700 pounds, (4) maintain a CM tunnel 28-inch-minimum clear passage, (5) minimize crew tasks and operating loads, and (6) provide automatic engagement to establish initial pressure seal.

Crew task modifications. - Tool interface points were incorporated in the basic docking probe to accomplish the manual operations of installation, removal, preload, and capture latch release. At the time, the design philosophy was to use the crew as much as possible and provide a universal inflight tool set. The objective was to simplify the design and reduce the overall weight of the systems. This simplification is a significant point because the change to the simplified probe was, in part, the result of a reversal in the design philosophy. The term "simplified" is a misnomer because the term does not relate to design simplicity, but rather to the crew and hardware interface. The design complexity of the probe was thus increased to provide the crew with integral, low-force actuation devices to simplify crew effort and reduce the number of manual tasks. The design changes consisted of the addition of a ratchet assembly for probe installation and removal, a preload handle with a torque limiter, a manual capture release handle, and an installation strut. These changes were implemented in 1967 after the development test program and after some of the qualification tests of the basic probe assembly were performed. Additionally, from 1967 to 1969, many detail design, procedural, and quality assurance changes were implemented.

Probe barrel friction. - During the docking sequence, the magnitude of the loads is influenced by the coefficient of friction between the probe piston and the cylinder for those contact conditions that result in lateral probe tip loading. The basic probe configuration consisted of metal-to-metal nonlubricated surfaces; however, as tests and analyses progressed, the necessity for reduction of piston-to-cylinder friction became obvious, especially for the low-temperature docking requirement. The solution (fig. 13) consisted of adding a Garlock bushing in the cylinder, a Teflon slipper seal (bushing) on the piston, and increased piston clearance at the second land of the cylinder.

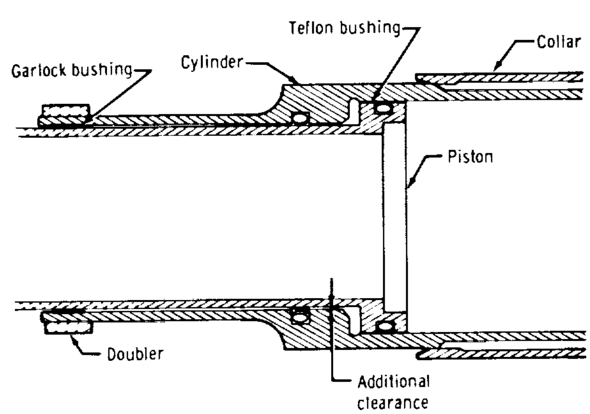


Figure 13. - Piston and cylinder modification.

Probe capture latch assembly. - The design of the docking probe capture latch assembly is such that friction and dimensions of the various parts are extremely critical. Problems with the capture latch assembly began to evolve in the spring of 1968 as flight-configured hardware became available. An inspection of existing hardware verified that failure modes existed, or could be produced, because of tolerance accumulations and poor quality of many parts of the assembly. This activity resulted in design changes, improved manufacturing and inspection techniques, and additional acceptance test requirements.

After implementation of the foregoing changes, the dynamic qualification probe (qualification probe 1) continued to experience failures of the capture latch assembly. Although documentation indicated that qualification probe 1 was flight configured, this particular probe was determined (October 1968) to have been treated as a separate entity and, hence, was not properly configured. After rework of the unit, the complete Apollo dynamic qualification test program was conducted without capture latch anomalies.

When the Apollo dynamic test program was completed, qualification probe 1 was refurbished to support the Skylab Program. This refurbishment included replacing the capture latch assembly with a spare unit. However, when the tests were initiated in March 1970, the capture latch response time was found to be exceptionally slow. Subsequent teardown of the capture latch assembly revealed that some parts (cam and head) were not within the specified tolerance. As a result of this discrepancy, the acceptance test procedure was modified to include a measurement of the capture latch response time.

Another capture latch anomaly occurred in January 1969 during dynamic testing at St. Louis, Missouri. As the test program progressed, the force required to depress the capture latch hooks was noticed to be excessive; and the force eventually cut the face sheet of the drogue during a docking attempt. An investigation of the capture latch assembly revealed that, although the components were in accordance with design specifications, tolerance accumulations relative to the toggle links caused the problem. Therefore, changes were implemented to reduce design tolerances, to round the edges of the hooks and the slots in the cap, and to modify the acceptance test procedure to include measurement of the hook depression force and cap-hook to cap-slot clearances.

PREFLIGHT GROUND TESTING

Each docking system is checked thoroughly, prior to mission use, by a progression of ground test programs. After manufacture and assembly, the hardware is acceptance tested at the manufacturer's facility. Then, by using ground support equipment, the hardware is tested as installed in the vehicle, and final verification is achieved in the CM and LM docking mate test at the NASA Kennedy Space Center (KSC), Florida.

Acceptance Tests

Probe. - The initial acceptance test requirements consisted primarily of rigging verification, limited functional operations, and detailed electrical system checks. However, as the simplified probe began to evolve and anomalies began to appear in the various tests, it became necessary to improve inspection requirements, modify hardware to minimize failure potential, and increase significantly the acceptance test requirements. For a short period of time, these additional requirements had the effect of increasing the number of problems.

The current docking probe acceptance program starts with electrical continuity and diode tests that include overall continuity checks, structural ground and insulation resistance checks, diode forward voltage and reverse current checks, a transient suppression diode test, and a pyrotechnic cable electrical test. Testing is then performed on the probe rigging and is followed by attenuator checks of the load as a function of stroke and by vibration tests. After the vibration tests, a complete electrical functional test is performed. Mechanical tests are conducted after the electrical tests; these include lateral load friction, probe load as a function of stroke, extension and capture latch preload, pressure retract and leakage, probe installation and removal, capture latch actuation, and final verification. Finally, the extension latch is adjusted and the docking probe is prepared for shipment.

Docking latches. - The acceptance tests of the docking latches consist primarily of functional cycling, operating handle load measurement, and preload verification.

Drogue. - Because the drogue has no moving parts, acceptance consists of dimensional checks and visual examination.

System Ground Tests

Command module. - After the initial acceptance testing, the docking probe and latches are installed in the CM, and the docking system is further checked by using ground support equipment that simulates the LM. The docking latches are first checked with a small firing block tool that verifies proper installation rigging. The docking system is then functionally checked by using an LM simulator tool that represents the LM interface worst-tolerance condition and that has counterbalance provisions to simulate zero-g hardware removal and installation. During this test, the CM main display panel talkbacks and all mechanical functions are verified.

These ground tests are normally performed at the CSM contractor facility prior to shipment of the CM to KSC; however, command modules 104, 106, 107, and 108 were tested at KSC because the command modules were shipped prior to availability of their docking probes.

Lunar module. - The LM drogue testing is very minimal and consists of functional installation and removal, and verification of adequate clearance for the drogue mounting lugs.

The Command Module and Lunar Module Docking Test

Prior to each Apollo mission, the CM and LM docking interface is verified by a simulated docking of the modules as part of the KSC preflight checkout activity. This verification is accomplished by lowering the inverted LM ascent stage to the hard-dock position on the CM. In this fashion, the docking system can be verified for all mission-required functions, including sealing and pressurization of the tunnel and hardware installation and removal. In addition, the test affords the flight crew an opportunity to gain additional confidence and familiarity with the docking system.

MISSION PERFORMANCE

To date, the docking system has been used in five Apollo missions (Apollo 9 to 13). Performance of the system has been excellent, and in all cases, the contact conditions have been well within the design criteria; the crews have commented on the ease of operation in zero-g; and the probe thermal environment has been nominal (approximately 90° to 110° F). The relative CM and LM alinements and velocities at initial contact are tabulated in table V for both the transposition translunar docking (TLD) and the LM active lunar orbit rendezvous (LOR) docking events and are based on crew estimates. All other parameters are approximately zero.

TABLE V. - RELATIVE CM AND LM ALINEMENTS AND VELOCITIES AT INITIAL CONTACT

Parameter	Apollo mission								
	9		10		11		12		13
	TLD	LOR	TLD	LOR	TLD	LOR	TLD	LOR	TLD
Axial velocity, ft/sec	0.3	0.1	0.2	0.2 to 0.3	0.1 to 0.2	0.1	0.1 to 0.2	0.2	0.2
Miss distances, in.	3.0	--	--	--	4.0	--	2.0	--	--

The only flight anomaly of the docking system occurred during the Apollo 9 mission. To initiate the undocking sequence, the command module pilot placed the docking probe EXT/REL-RETRACT switch in the EXT/REL position to allow probe extension and subsequent LM release; however, the switch was released prior to full extension of the probe. This early release of the switch caused the capture latches to return to the locked position and prevented release of the LM. A second attempt to release was not successful because reaction control system thrust duration was not sufficient to provide a separation force. Subsequently, the LM was released when the switch actuation coincided with a relative separation velocity. In preparation for the LM active docking, the command module pilot placed the EXT/REL-RETRACT switch to the RETRACT position and received an improper talkback system display (barber pole) that indicated the probe capture latches were in the locked position. By cycling the switch to the EXT/REL position and then to the RETRACT position, the system indication was proper and a successful docking was achieved. Postflight ground testing demonstrated that both anomalies were related and were inherent normal features of the docking probe. To preclude these difficulties from occurring in later flights, the undocking procedure was modified.

After the initial preparation of this report, a docking anomaly was experienced during the Apollo 14 mission. Six docking attempts were required to successfully achieve capture latch engagement for the TLD phase of the flight. Although the docking system performed successfully for the remainder of the mission, the docking probe was stowed in the CM following LOR and returned with the CM so that a thorough investigation could be conducted. The results of the investigation disclosed two possible causes for the docking problem — one related to the design and one attributed to foreign material. Although a minor design modification was incorporated to preclude such a failure mode for future docking probes, most evidence indicates foreign material as being the cause of the Apollo 14 anomaly. A complete description of the anomaly, including related postflight activity, is included as appendix B.

CONCLUDING REMARKS

Prior to the Apollo 9 flight, the problems encountered in inspection and checkout testing of the docking system had caused some concern about system reliability. Much of the apparent low confidence in the system could be attributed to a lack of understanding the design. As the Apollo missions progressed and the respective flight crews demonstrated the ease of docking and conducting the manual tasks, confidence in the system increased significantly.

To preclude difficulties that were experienced during the development of the Apollo docking system, the selection, design, and testing for future docking systems could benefit from the following.

1. Establish realistic design criteria so that simplicity of design can be achieved; remain flexible on arbitrarily established requirements.

2. Integrate the docking system with the initial design of the spacecraft, rather than allocate an envelope for "scabbing on" the system at a later date.

3. Design a "forgiving" system by minimizing critical dimensions and sensitive components.

4. Identify all critical design parameters and specify 100 percent inspection of critical parts.

5. Use the Apollo-generated mathematical modeling technique and the dynamic docking test facility at the Manned Spacecraft Center to define and demonstrate the dynamic performance characteristics of the system.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, March 2, 1972
914-50-20-20-72

APPENDIX A

HARDWARE DESCRIPTION

COMMAND MODULE FORWARD HATCH

The CM forward hatch (fig. A-1) is frequently called the combined forward hatch because it serves the dual role of CM heat protection and CM pressure sealing. The hatch is located at the forward end of the CM ingress and egress tunnel, just aft of the CM docking ring. The hatch is held in place by six equally spaced latches that are located around the periphery of the hatch structure. Each latch is connected by linkage to a central drive ring. The latch position is controlled either by a gearbox assembly from within the CM or by a tool interface drive shaft from outside the CM. In addition, the latches may be moved from the unlatched to the latched position by disconnecting the gearbox and by using a special tool to drive a pinion gear that meshes with the drive ring. The gearbox is equipped with a single activating handle that is designed so that a single push stroke is required to latch or unlatch the hatch. Because the diameter of the hatch is greater than the CM tunnel seal retainer, the hatch can only be removed toward the interior of the CM. The hatch also contains a pressure equalization valve that can be manually opened or closed from either side of the hatch.

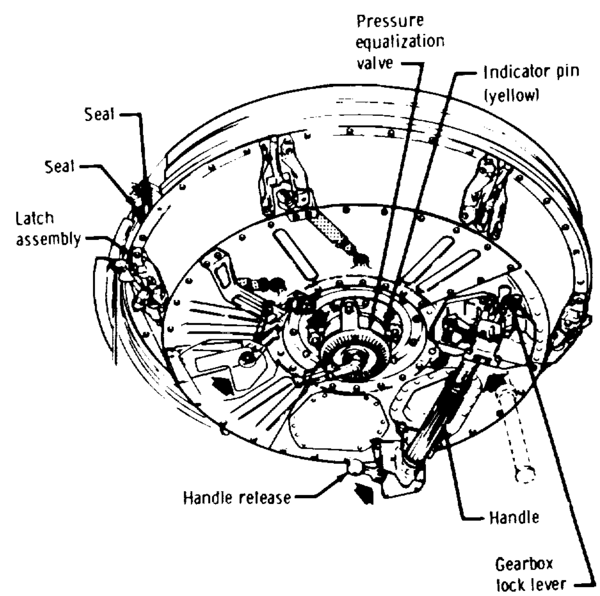


Figure A-1. - Tunnel hatch.

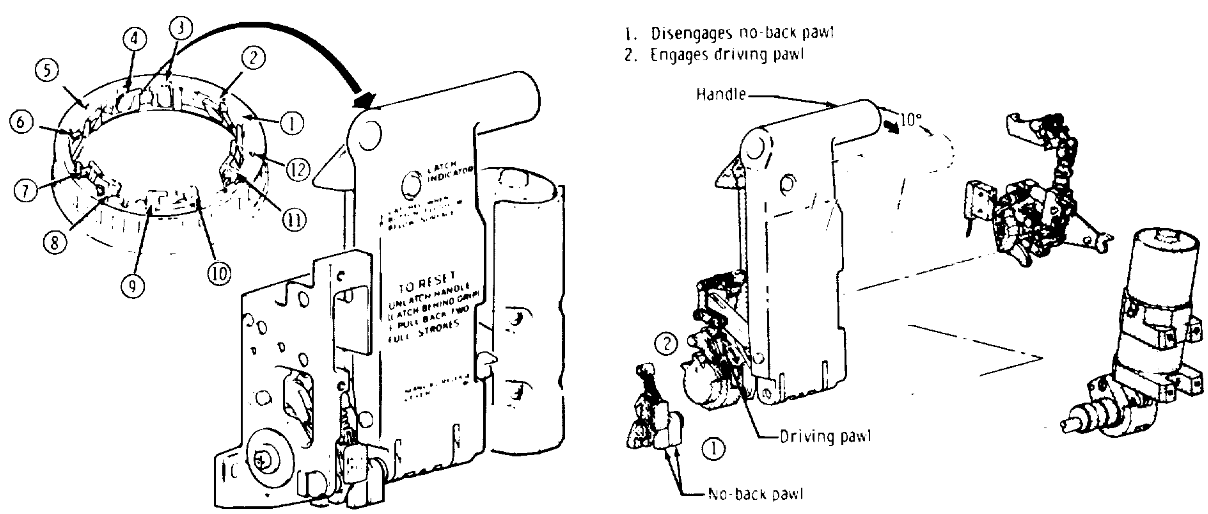
COMMAND MODULE DOCKING RING

The CM docking ring (fig. 9 of the main text of this report) is a uniquely configured aluminum structure that forms an extension of the CM tunnel. The docking ring is bolted to the CM tunnel and serves as the mounting structure for the docking latches, the probe, the electrical connectors, and the two seals that allow pressurization of the docked CM and LM intermodular tunnel area. The inner lip of the ring extends beyond the CM and LM seal interface to provide a guide surface for the LM tunnel during the retraction sequence to ensure radial alinement of the CM and the LM. Final separation of the docking ring is accomplished by pyrotechnic initiation of an MDF that explosively severs the ring structure.

DOCKING RING LATCHES

The present configuration of the automatic docking latch (fig. A-2) appears to be a very complex mechanism; however, the basic components of the latch consist of a central rotating shaft (similar to a crank shaft) to which the spring power source and latch hook are eccentrically attached. This configuration permits amplification of the low spring force to the high hook tension loads as shown in figure A-3. The load step increase shown at 0.065 inch is achieved by using an unstable link (gear shift) at the power bungee attach point to the shaft. As the central shaft rotates from the cocked position to the latched position, the unstable link shifts to a new position that increases the moment arm by a factor of approximately 1.9.

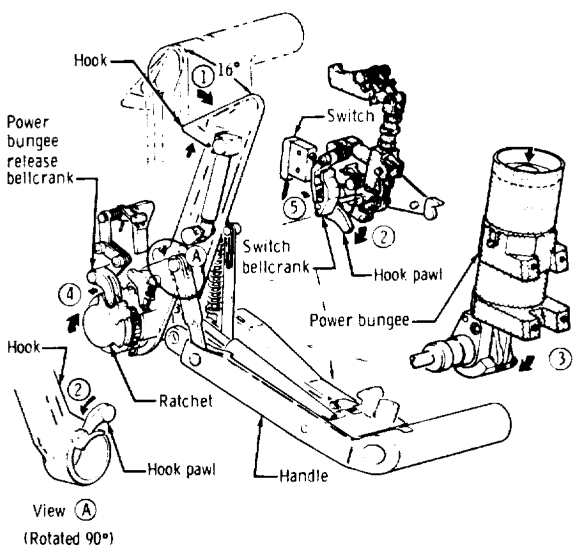
The primary latch elements are the handle, the trigger and escapement assembly, and the various linkages and pawls. Prior to flight, the ground crew places each of the 12 latches in the cocked position by two pull strokes of the latch handle. This operation rotates the central shaft, compresses the power bungee springs, and sets the trigger. The latch is automatically actuated in flight by the closing motion of the CM and the LM The LM docking ring depresses the latch trigger, which releases the hook and handle and allows them to rotate to a position where the hook is over the LM docking ring lip. At this point, the hook depresses a linkage that lifts the driving pawl and the release bellcrank from the central shaft detents, which allows the power bungee force to rotate the shaft and pull the hook down against the LM ring lip. Also, to prevent counterrotation of the shaft, two no-back pawls engage the shaft. The escapement assembly allows the latch to be cocked and manually triggered with the CM and the LM in the docked configuration and also provides for automatic reset of the trigger when the CM and the LM undock. For normal mission operations, the only manual effort required of the crewmen is to cock each of the 12 latches for the single lunar orbit undocking event.



(a) Mechanical positions. (b) First stroke (first 10° of stroke).

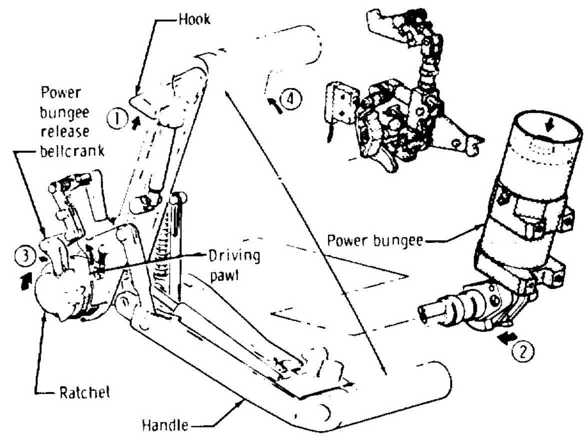
Figure A-2. - Automatic docking latch.

1. Hook lifts about halfway and retracts (16°)
2. Hook pawl engages
3. Power bungee spring compressed to approximately half stroke
4. Power bungee release bellcrank engages ratchet (first detent)
5. Switch bellcrank disengages switch



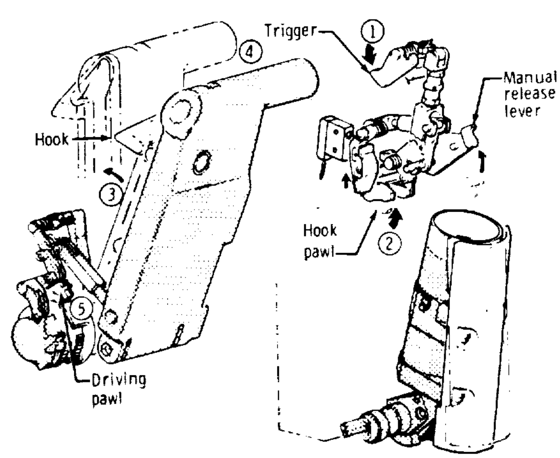
(c) First stroke (from 10° to full stroke).

1. Hook lifts to full travel
2. Power bungee spring compressed to full stroke
3. Power bungee release bellcrank engages ratchet (second detent)
4. Handle freewheels up against retracted hook



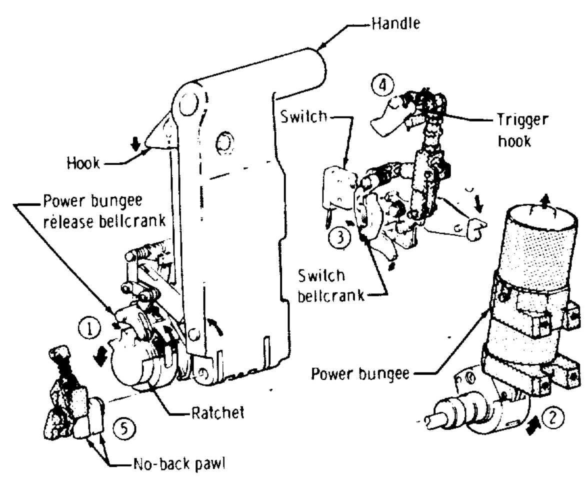
(d) Second stroke.

1. Trigger depressed
2. Hook pawl disengages
3. Hook rotates to vertical position
4. Handle freewheels to vertical position
5. Driving pawl disengages



(e) Latch actuation.

1. Power bungee release bellcrank disengages ratchet
2. Power bungee spring released to pull hook down
3. Switch bellcrank engages switch
4. Handle engages with trigger hook
5. No-back pawl engaged



(f) Latch actuation and locking.

Figure A-2. - Concluded.

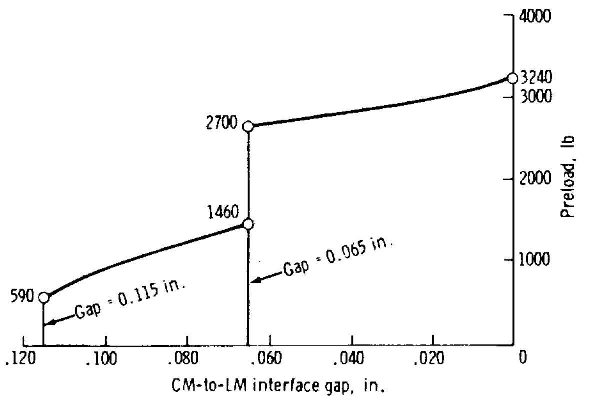


Figure A-3. - Latch load as a function of stroke.

PROBE ASSEMBLY

The docking probe is a tripod-mounted device that is installed in the CM docking ring and serves as the active portion of the docking system. The probe can be manually removed from the CM tunnel; and the probe incorporates provisions for initial capture with the LM, energy attenuation, CM and LM retraction, relative vehicle alinement, and undocking. The three probe support arms are made of titanium; most of the remaining structure is aluminum with chromium and nickel plate exterior finishes to provide passive thermal control. The structural items consist of the central cylinder, a piston that telescopes within the cylinder, a collar, three pitch arms, three struts, and three support arms.

The primary subassemblies (fig. A-4) of the probe consist of the capture latch assembly, the actuator assembly, the capture latch release handle, the nitrogen pressure system, the ratchet handle assembly, the extension latch and preload assembly, the shock struts, and the attenuators.

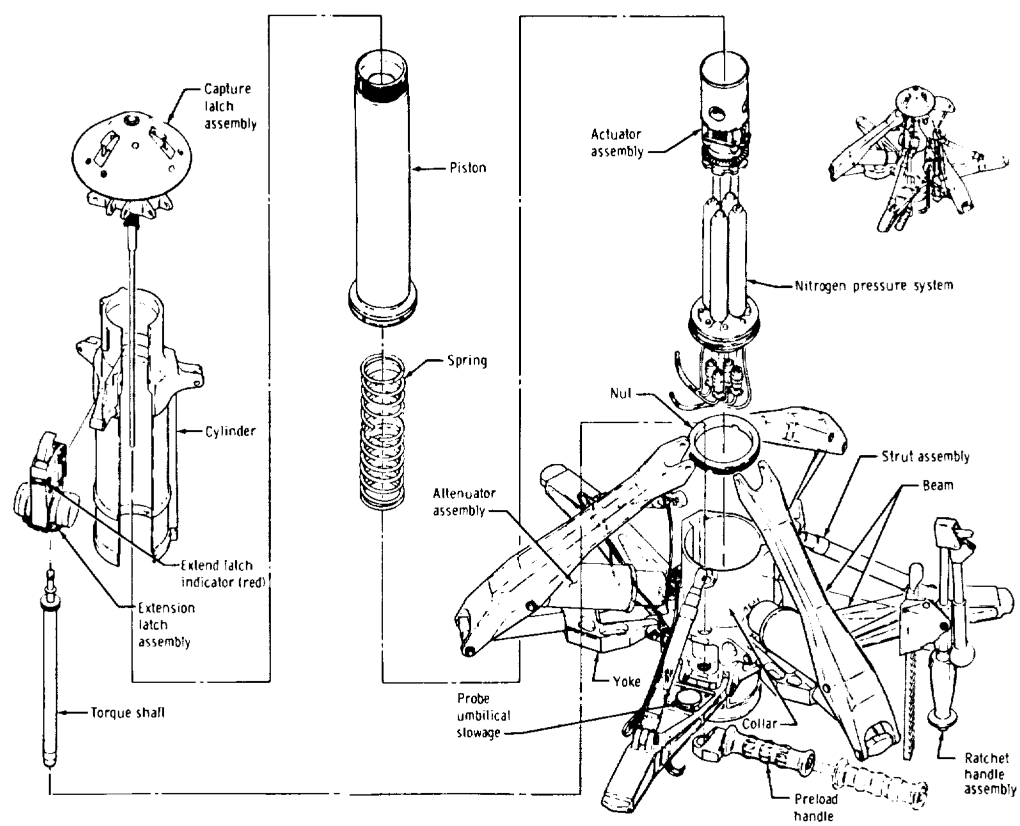


Figure A-4. - Exploded view of the probe assembly.

Capture Latch Assembly

The probe capture latch assembly (fig. A-5) is contained within the self-centering gimbal-mounted probe head and serves as the mechanism for achieving initial coupling between the CM and the LM. The assembly consists of three hooks that are pin mounted to the probe head and spring loaded so that the hook protrudes beyond the surface of the probe head. Opposite each of the hook pivot points is a two-piece toggle link that connects the hook to a fixed point on the probe head. When the hook is extended, as shown in figure A-5, the toggle link pins are almost in line and, thus, provide a means of locking the hook.

Latch locking and release are determined by the axial position of a single symmetrical spool that is spring loaded to the full-forward, locked position. In this position, a roller on the spool rests beneath each of the hook toggle links so that the hooks cannot be depressed. To unlock the latches, the spool must be moved aft and retained until subsequent latch lock is required.

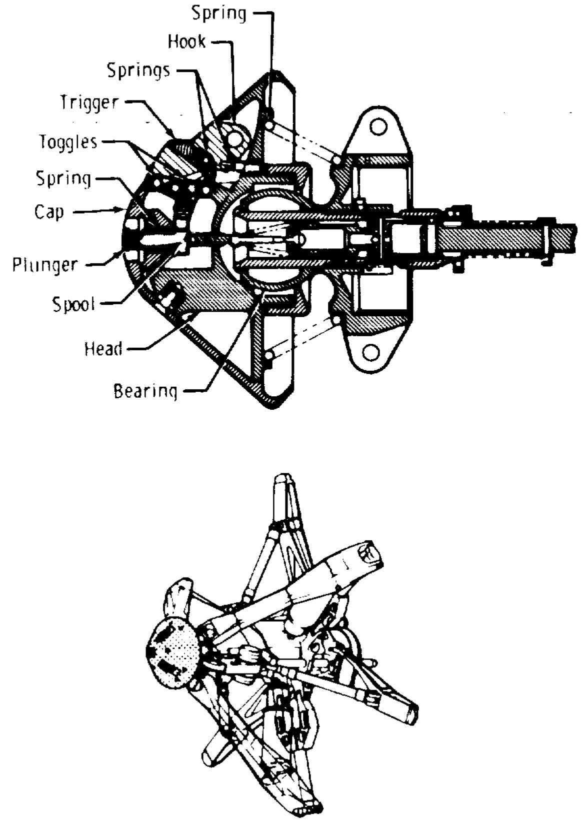


Figure A-5. - Probe capture latch assembly.

Spool retention and release are achieved by triggers located within each of the latch hooks. When the spool is moved aft of the triggers and released, pins located on the outer tip of the spool bear against the back face of the trigger and, thereby, prevent forward travel of the spool. To release the spool, all three triggers must be depressed because one or more triggers will retain the spool in the aft (unlocked) position. The spool can be moved from the forward (locked) to the aft (unlocked) position by manually depressing the plunger in the probe head or by rotation of the torque shaft. Linear displacement of the spool by rotation of the torque shaft is achieved by a helix cam. Rotation of the torque shaft can be performed remotely by the actuator assembly or manually with the capture latch release handle when the probe is in the retracted position.

Actuator Assembly

The actuator assembly consists of two tandem-mounted direct-current torque motors, switches, and electrical circuitry located within the probe cylinder. Power output of the motors is such that single motor operation will provide sufficient torque to unlock the capture latches. The actuator assembly also contains 16 microswitches and associated actuation linkage, diodes, and necessary wiring. Four switches transfer power from the extension latch solenoids to the actuator motors when the probe piston extends approximately 0.75 inch, four switches open when the probe extends 9.25 inches, and eight switches close when the torque shaft rotates to the capture latch lock position (figs. A-6 and A-7). This particular arrangement minimizes the number of wires required and provides necessary redundancy, power to probe, and a probe status indication to the crew at the CM main display panel.

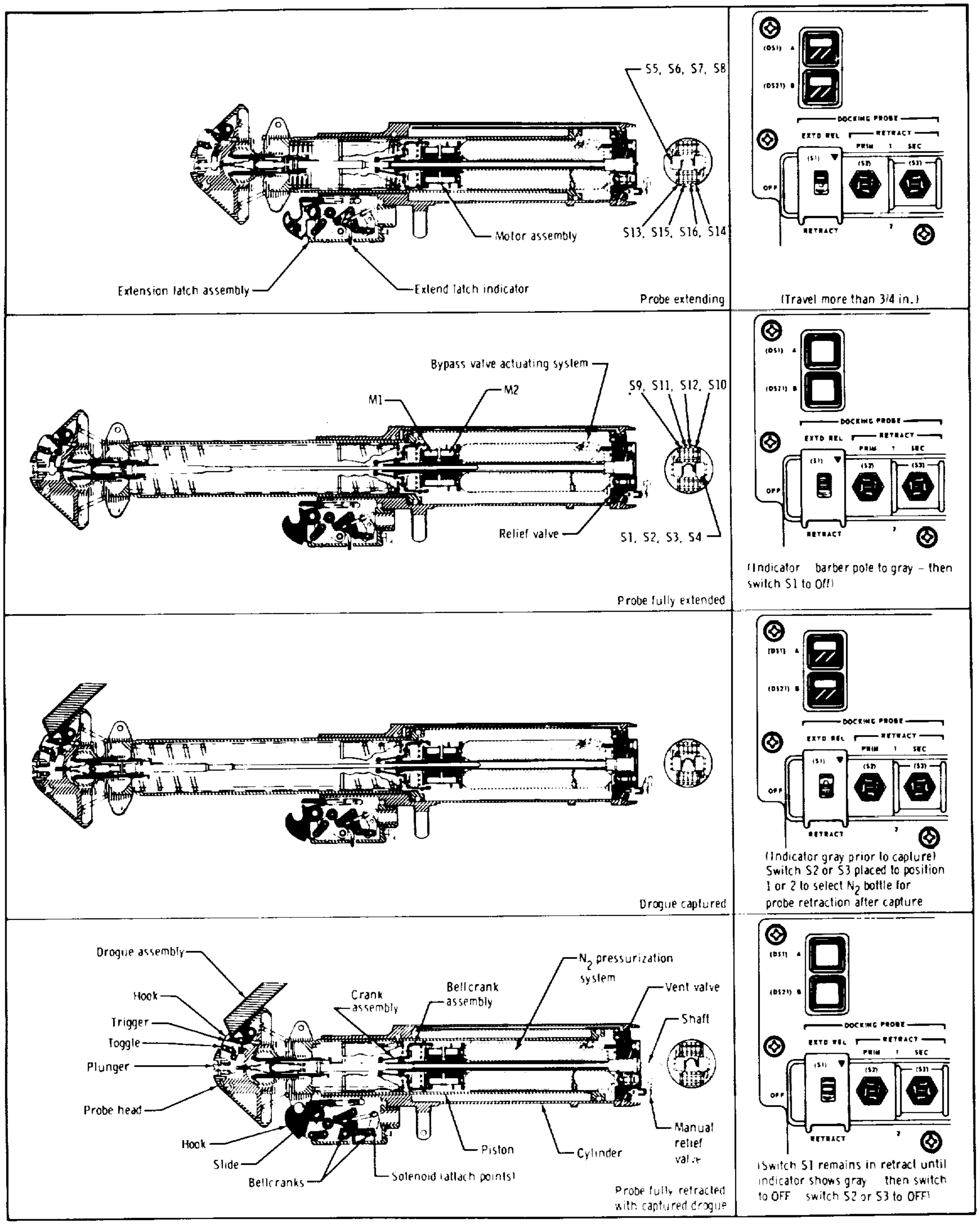
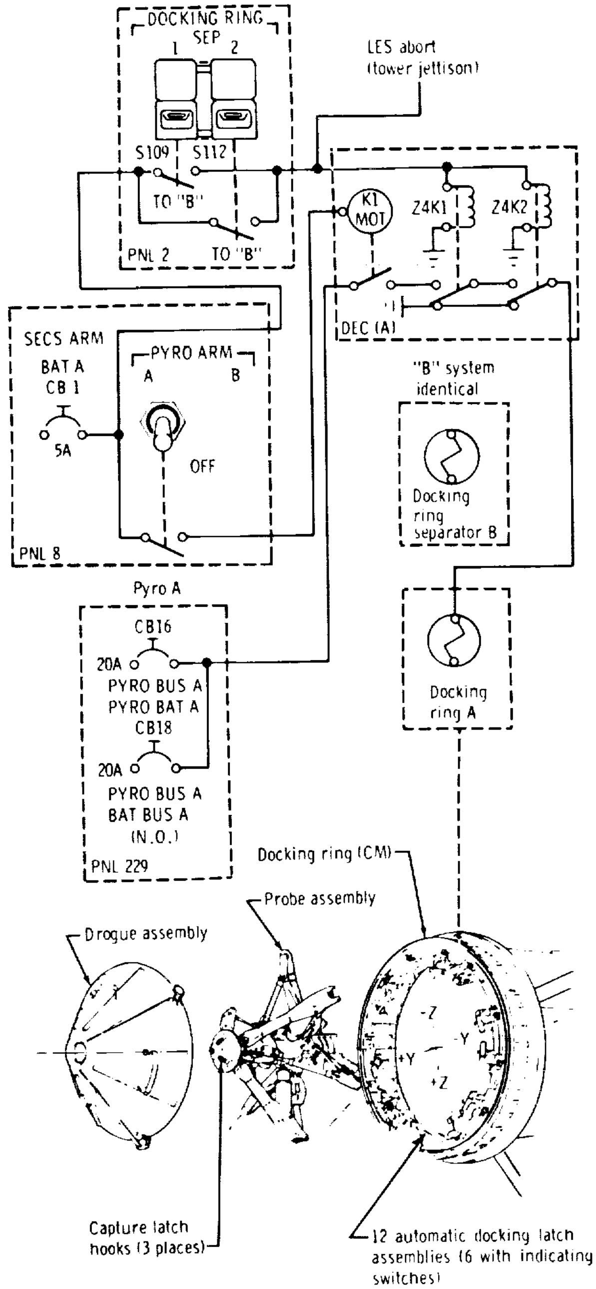
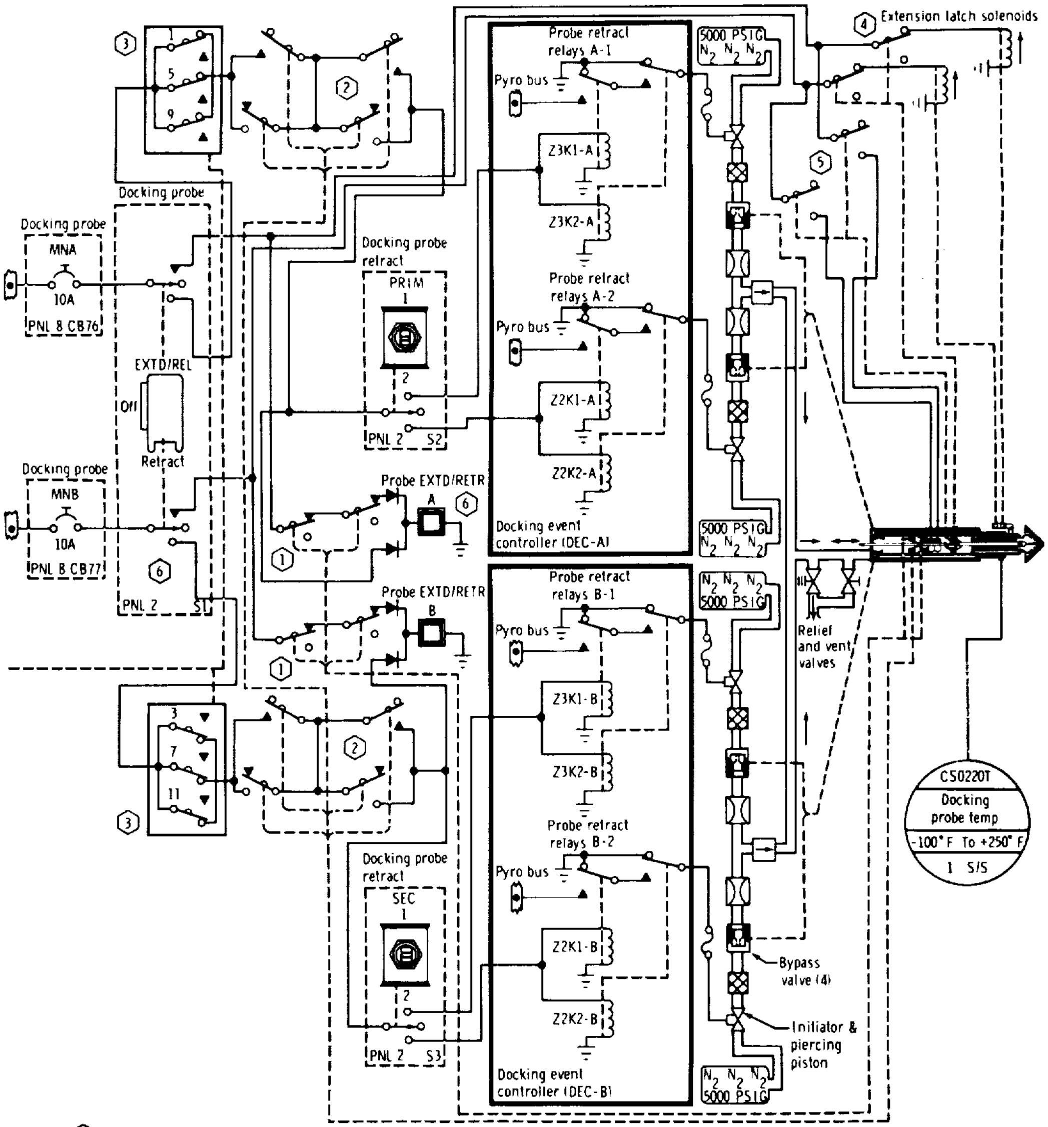


Figure A-6. - Probe extension, capture, and retraction sequence.



(a) Separation switches and mechanical assembly.

Figure A-7. - Probe electrical schematic.



1. Extend indicating switches open when piston has extended 9.25 inches
2. Switches close when capture latches are in the locked position (probe locked to LM drogue) - (last 16° to 18° of shaft rotating CW)
3. Switches open when automatic docking latches are actuated (docking rings approximately 0.1 inch apart)
4. Switches open removing power from solenoids when shaft extends 0.75 inch
5. Switches close activating capture latch release motor when shaft extends 0.75 inch (either motor rotates shaft unlocking capture latches)
6. Talkback indication "A" system (B would be identical)

Switch position EXT/REL-retract	Retracted	Intermediate	Extended		Remarks
EXT/REL (momentary)			GRAY	Release SW	Failure to hold SW will allow capture latches to recapture MDA before separation takes place
OFF	GRAY	GRAY	GRAY		
RETRACT	GRAY Docking latches activated		MDA captured Probe will retract if PRIM 1 or 2 bottle is selected	MDA not captured GRAY	

(b) Schematic.

Figure A-7. - Concluded.

Capture Latch Release Handle

The capture latch release handle (fig. A-8) is located on the aft end of the probe and provides a means for manual release of the capture latches when the probe is in the retracted position. The probe must be retracted for the capture latch torque shaft to mate with the keyed female telescoping drive shaft. The release handle is secured on the pyrotechnic cover by spring clip detents and a manual locking lever. Prior to folding the probe for removal from the CM tunnel, the release handle is unlocked and pulled from the spring clips. As the probe is folded, the sliding collar travels aft, contacts the release handle, and extends the telescoping drive shaft. The handle is then accessible for manual rotation to release the capture latches.

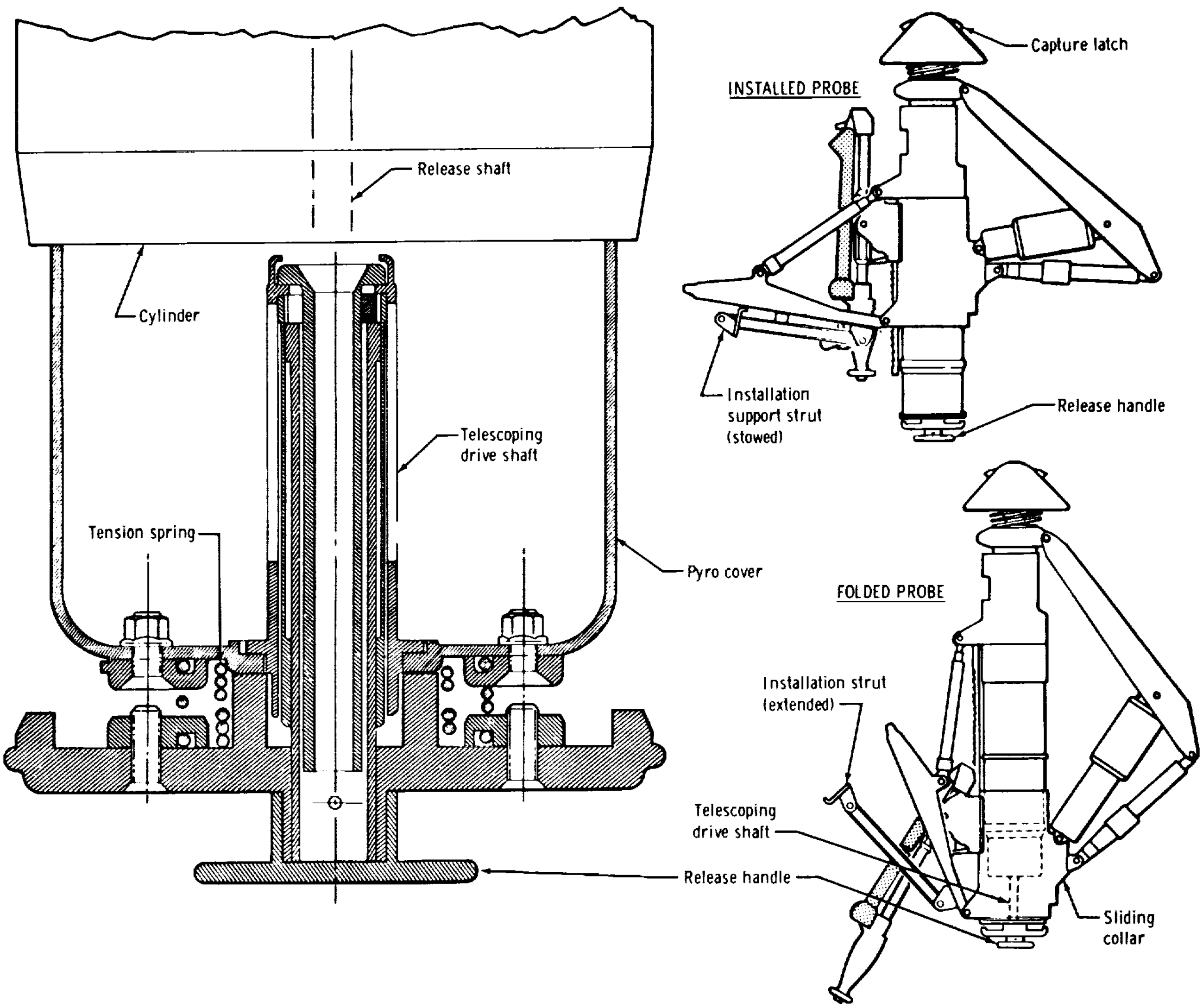


Figure A-8. - Capture latch release.

Nitrogen Pressure System

The nitrogen pressure system (fig. A-9) consists of four pressurized bottles and a manifold assembly installed in the aft end of the probe cylinder and retained by a threaded ring. Each bottle is hermetically sealed, contains nitrogen gas pressurized to 5000 psi, and is socket mounted to the manifold assembly. The system is actuated by firing a pyrotechnic initiator that drives a piercing plunger through a metal diaphragm in the neck of the bottle. The nitrogen gas flows through a primary orifice (0.005-inch diameter) in the manifold, opens the check valve, goes through a passage in the probe cylinder, and pressurizes the volume between the probe piston and the forward end of the probe cylinder. This pressure, acting on the 4.73-square-inch area of the piston, moves the piston toward the aft end of the cylinder. When the piston is approximately 1 inch from full retraction, the bypass actuating mechanism is depressed. This action opens the secondary orifice (0.013-inch diameter) in the manifold to provide a minimum retraction force of 1000 pounds to effect final closure of the CM to the LM, compress the interface seals, and actuate the automatic docking latches.

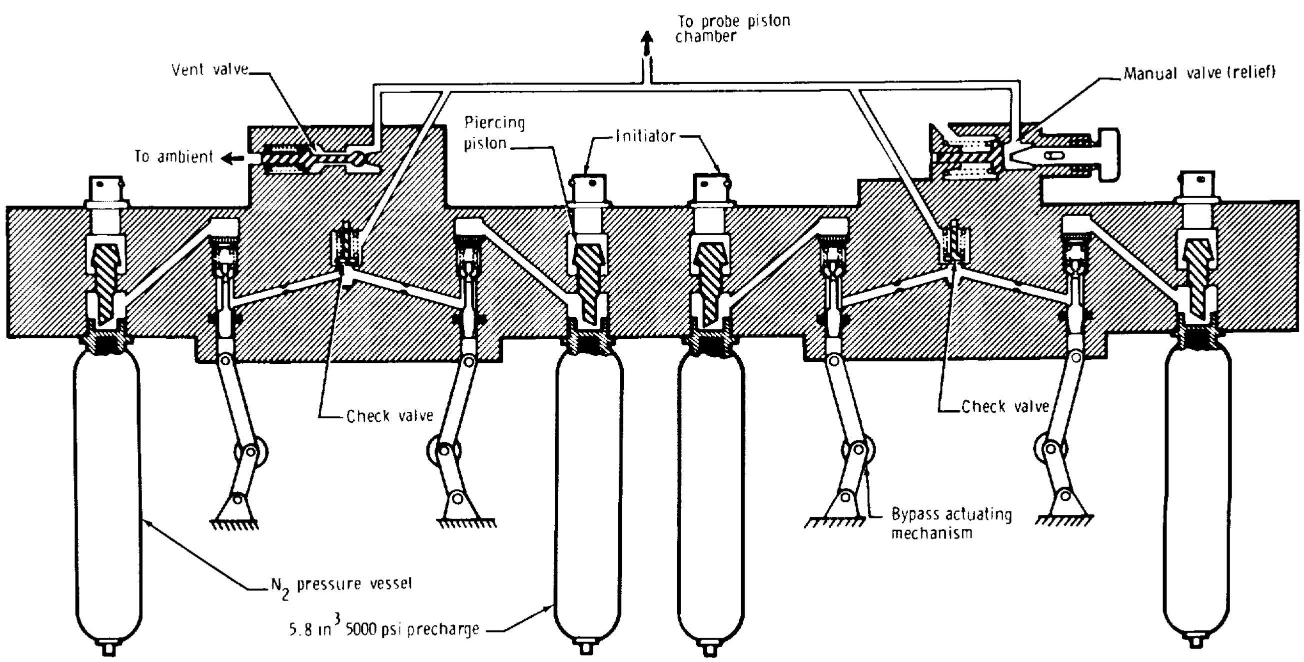


Figure A-9. - Nitrogen pressure system.

Other features of the system include a normally open vent valve and a manual vent valve. The vent valve is necessary to bleed the trapped sea-level air from the system during the spacecraft ascent boost phase. The manual relief valve is actuated by the crewmen after transposition docking to bleed the high-pressure nitrogen gas from the system to allow subsequent probe extension. This valve also serves as a relief valve for the system and opens automatically if the pressure exceeds 350 psig.

Ratchet Handle Assembly

The ratchet handle assembly (fig. A-10) serves as the structural tie between the probe collar and the cylinder and provides a means for removal and installation of the probe. Mechanically, the assembly consists of the handle, a ratchet housing, the ratchet mechanism, and a rack. The rack is attached to the probe cylinder, and the

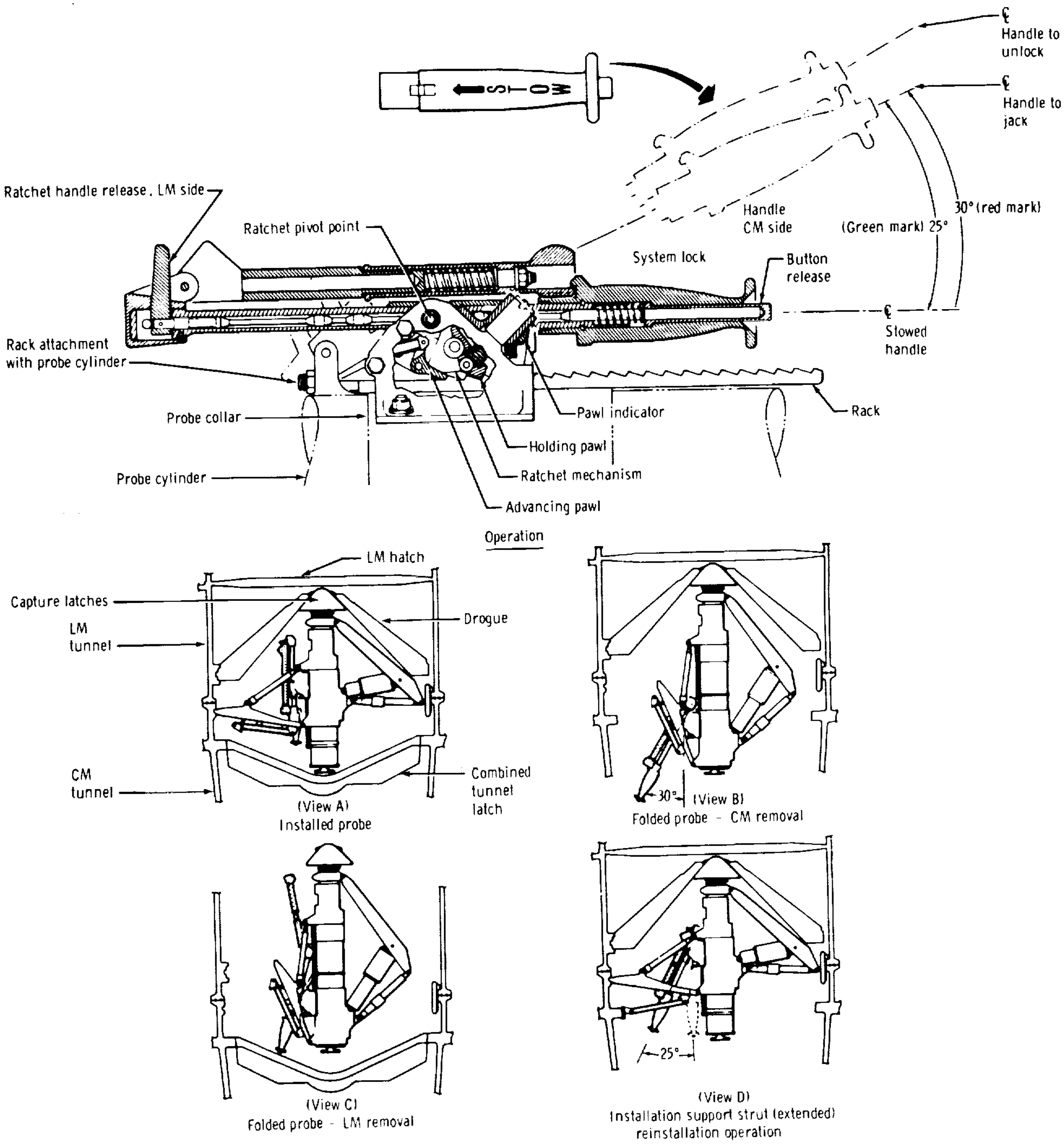


Figure A-10. - Ratchet handle assembly.

ratchet housing is bolted to the probe collar. Because the probe support arms, attenuators, and tension links are attached to the probe collar (fig. A-10 view A), the position of the collar with respect to the cylinder determines the installed or folded configuration of the probe. If the collar is released, the gas pressure in the attenuators will cause the collar to slide aft and the support arms to withdraw from the mounting sockets in the docking ring and achieve a folded configuration (fig. A-10 views B and C).

The ratchet mechanism consists of an advancing pawl that is keyed to the pivot point shaft and a holding pawl that simply pivots about the shaft. Release of the collar is achieved by rotating the pivot point shaft 30° counterclockwise. This action will lift both pawls from the rack and allow the collar to slide aft. To install the probe (fig. A-10 view D), the pivot point shaft is rotated 25° counterclockwise and returned (20 strokes) to jack the mechanism and collar along the rack. Each 25° counterclockwise stroke simply advances the spring-loaded holding pawl to the next tooth, and each return stroke (25° clockwise) moves the advancing pawl to the next tooth. The eyebolt that is attached to the holding pawl serves as an indicator and a tension load link. When the indicator is flush with the housing, the crewman is aware that the holding pawl is properly engaged with the rack tooth, while the tension link optimizes the load vector.

The device that allows the crewman to select the desired rotation of the shaft and accomplish the task with minimal effort is the handle assembly. The handle assembly slides within a collar that is attached to the pivot shaft. To operate the handle, the crewman must depress a button on the handle axis and slide the handle aft to either the probe installation detent (25°) or the probe removal detent (30°), grasp the handle, and push the handle away from the probe axis. With the handle at the installation detent, the handle is limited to 25° rotation by an adjustable bolt. The installation strut (fig. A-10 view D) is used to stabilize the probe during installation. To provide a means for removing the probe from the LM side (fig. A-10 view C), the release handle on the LM side is unstowed, rotated to position, and pulled.

Extension Latch, Torque Shaft, and Preload Handle

The extension latch (fig. A-11) is mounted on a track on the probe cylinder. The latch automatically engages by cam action as the probe retracts. Release of the latch to allow probe extension is achieved by applying electrical power to either of the two solenoids.

Prior to undocking, the probe is preloaded to 5900 ± 200 pounds of tension to allow the subsequent unlatching of the 12 docking ring latches and to maintain tunnel pressurization. Preload is achieved by rotation of the torque shaft, which mates with the floating extension latch by an Acme-threaded screw, to move the extension latch in the aft direction. To ensure

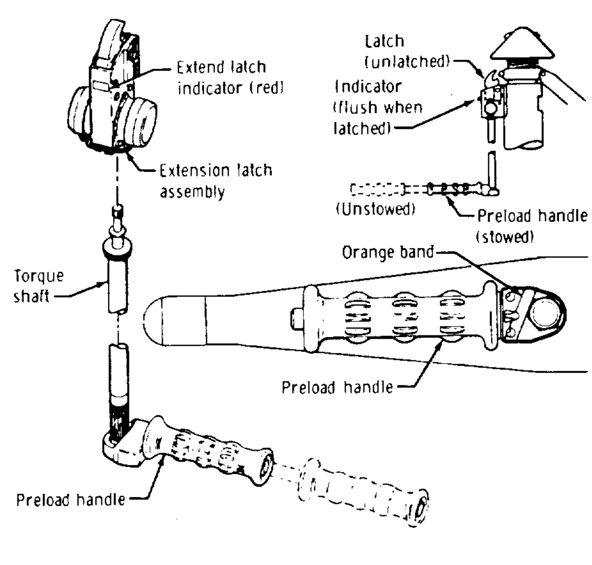


Figure A-11. - Extension latch assembly.

proper preload, the handle assembly contains a preset clutch limiter that allows the handle to slip, relative to the shaft, when the prescribed torque is achieved. Other features of the assembly include a preload select lever to allow either clockwise or counterclockwise rotation of the shaft, a telescoping handle to allow the crewman to increase the moment arm, and the splined torque shaft to allow fore and aft movement of the handle assembly.

Shock Struts

The shock struts are relatively stiff devices connected between each of the support legs and the probe cylinder to aid in energy attenuation. Each strut contains 154 Belleville washers that allow the strut to compress, thereby decreasing the probe lateral-load spring rate.

Shock Attenuators

A shock attenuator is attached between each of the probe pitch arms and the collar so that compression of the probe piston or any of the pitch arms will cause the attenuators to stroke. The attenuators (fig. A-12) are gas and oil, fluid displacement dampers

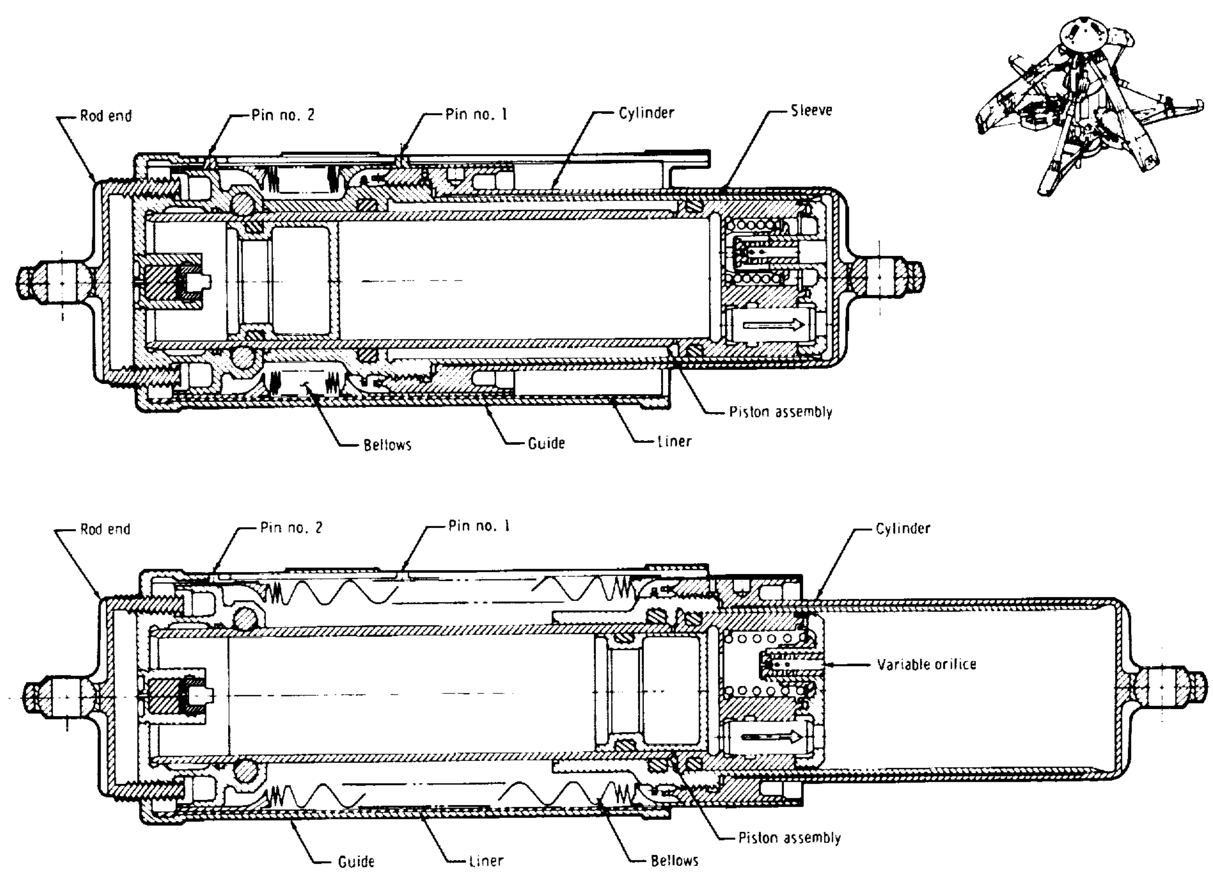


Figure A-12. - Docking probe attenuator assembly.

that have been certified by test for a temperature range of -80° to +250° F. Energy attenuation is accomplished as the piston strokes and displaces the Orinite 70 fluid through a velocity-sensitive variable-metering orifice. The gas in the assembly is pressurized to approximately 30 psig at 70° F (with piston extended) and provides the force necessary to extend the attenuator. This gas energy aids the probe center spring during undocking and also provides the force necessary to collapse the probe for removal from the tunnel. To prevent possible contamination of the CM with hydraulic fluid, each attenuator is hermetically sealed by a welded metal bellows.

DROGUE ASSEMBLY

The drogue assembly (fig. A-13) is a truncated cone structure that is installed in the LM tunnel and serves as the guide and the receiver for the probe head. The drogue consists of 1-inch-thick aluminum honeycomb (sandwiched between aluminum face sheets), three main support beams, and six stringers. The drogue mounting lugs are part of the main support beams and mate with drogue mounting pads in the LM tunnel. One of the drogue pads contains a latching mechanism that provides rotational constraint and can be actuated by the crewman during installation or removal of the drogue from either the CM or the LM side of the transfer tunnel.

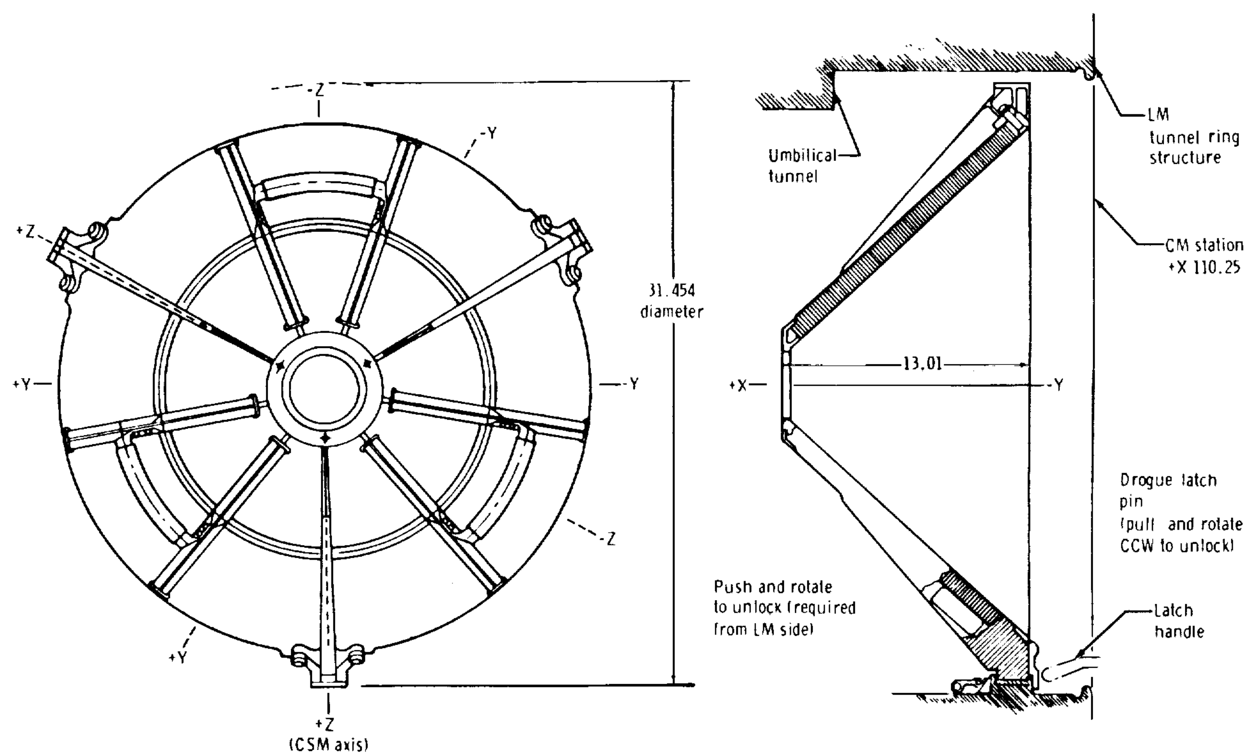


Figure A-13. - Drogue assembly. Dimensions are in inches.

APPENDIX B

APOLLO 14 MISSION FAILURE TO ACHIEVE DOCKING PROBE CAPTURE LATCH ENGAGEMENT

By Mission Evaluation Team

STATEMENT

Six docking attempts were required in order to successfully achieve capture latch engagement during the transposition and docking phase after translunar injection. After docking, the probe (fig. B-1) and drogue (fig. B-2) were examined by the crew. Probe operation appeared normal, and radial marks were noted on the drogue. During all subsequent operations, the probe operated properly.

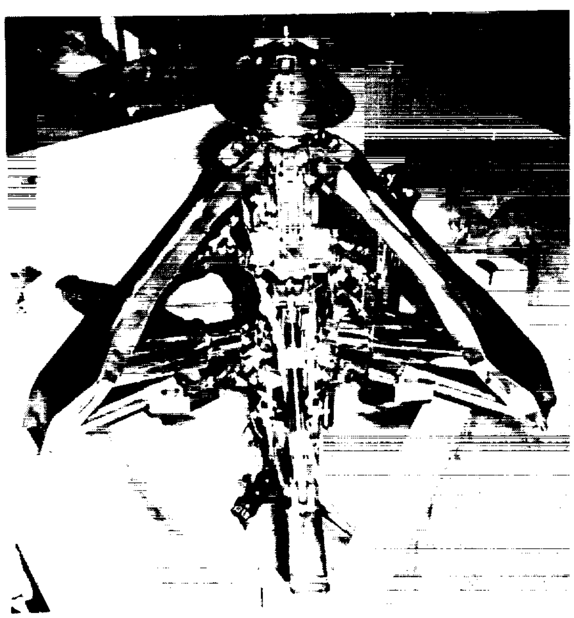


Figure B-1. - Apollo 14 probe assembly.

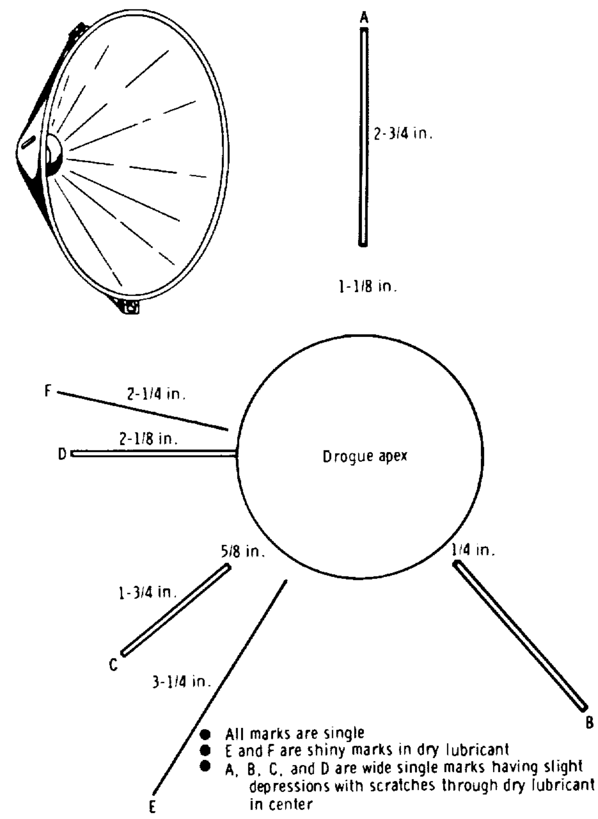


Figure B-2. - Drogue assembly and location of radial marks.

DESCRIPTION AND SYSTEM OPERATION

During prelaunch operations of the Apollo spacecraft, the docking probe assembly is installed in the CM docking ring in the retracted and cocked configuration and is attached to the boost protective cover by a tension tie mechanism. If an LES abort of the CM is required during ascent, the docking ring is severed from the CM by an explosive charge and the docking ring and probe assembly are jettisoned with the launch escape tower and boost protective cover (fig. B-3). However, for normal ascent, the docking ring is not severed. Instead, the tension tie shear pins shear when the launch escape tower and boost protective cover are jettisoned; thus, the tension tie is pulled out of the probe head by the launch escape tower, leaving the docking ring and probe assembly intact. The tension tie is shown in figure B-3. After docking has been accomplished, the probe is removed from the CM tunnel for access to the LM. The probe is normally jettisoned with the LM ascent stage. (The Apollo 14 probe was returned for failure analysis.)

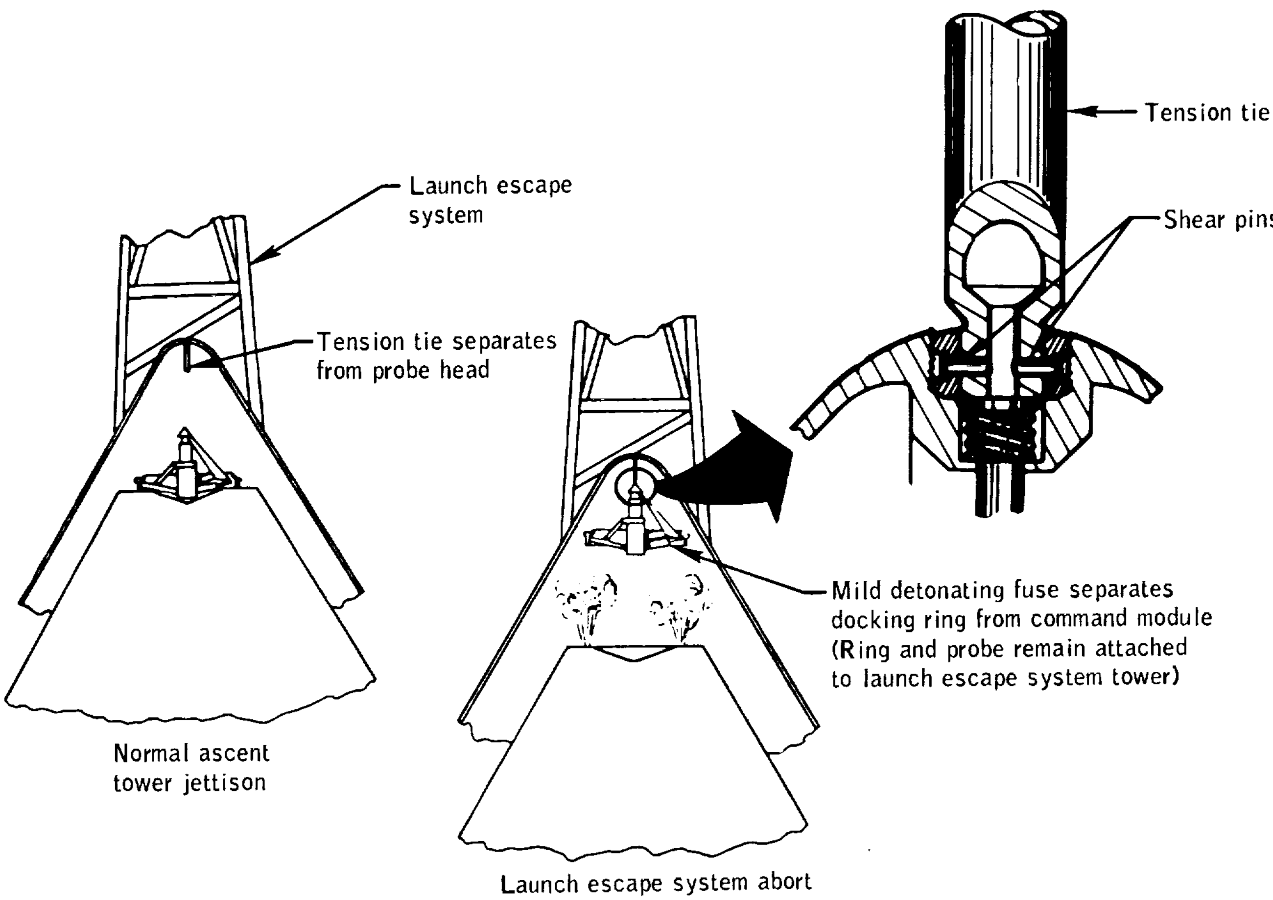


Figure B-3. - Tension tie operation.

The docking probe (fig. B-1) is a tripod-mounted device that serves as the active portion of the docking system. The probe incorporates provisions for the initial capture of the LM, energy attenuation, CM and LM retraction, relative vehicle alinement, and undocking. The three probe support arms are made of titanium and most of the remaining structure is aluminum with a nickel-plated exterior finish to provide passive thermal control. The structural items (fig. B-4) consist of the central cylinder, a piston, a collar, three pitch arms, three shock struts, and the three support arms. The primary subassemblies of the probe consist of the capture latch assembly, the actuator assembly, the capture latch release handle, the nitrogen pressure system, the ratchet handle assembly, the extend latch and preload assembly, the shock struts, and the attenuators.

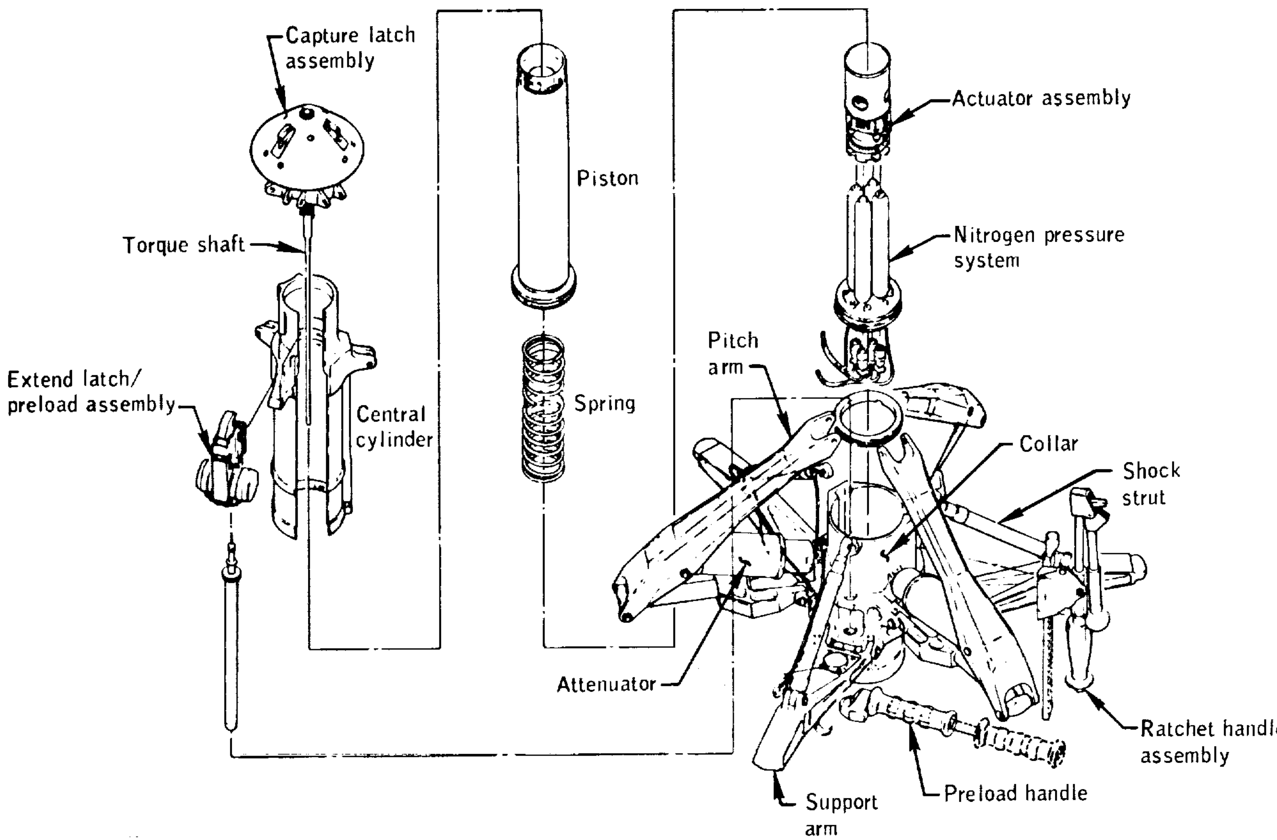


Figure B-4. - Structural items of probe assembly.

The probe capture latch assembly (fig. B-5) is contained within the probe head and is used for achieving the initial coupling between the CM and LM. In figure B-6, the probe latches are shown locked to a test tool in the same manner as they lock to the drogue. The capture latch assembly consists of three latch hooks (fig. B-7) that are pin mounted in the probe head and spring loaded so that the hook protrudes beyond the surface of the probe head. Opposite each of the latch-hook pivot points is a two-piece toggle link (fig. B-5) that connects the latch hook to a fixed point on the probe head.

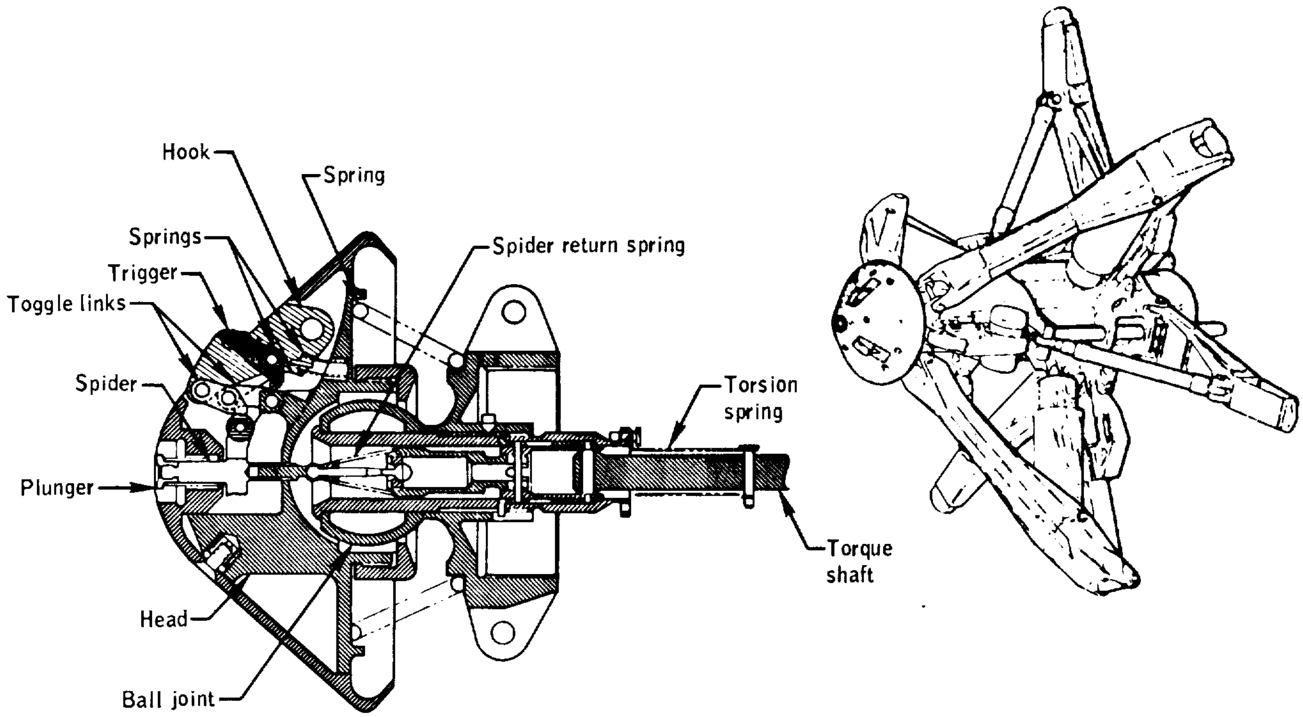


Figure B-5. - Probe capture latch assembly shown in locked position.

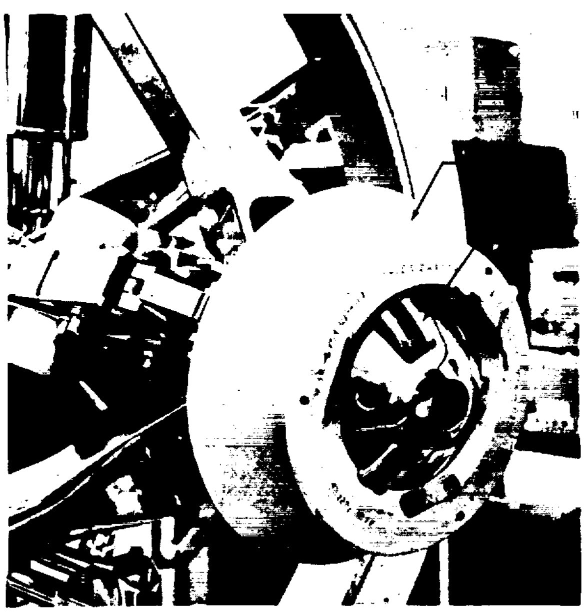


Figure B-6. - Probe latched to test tool.

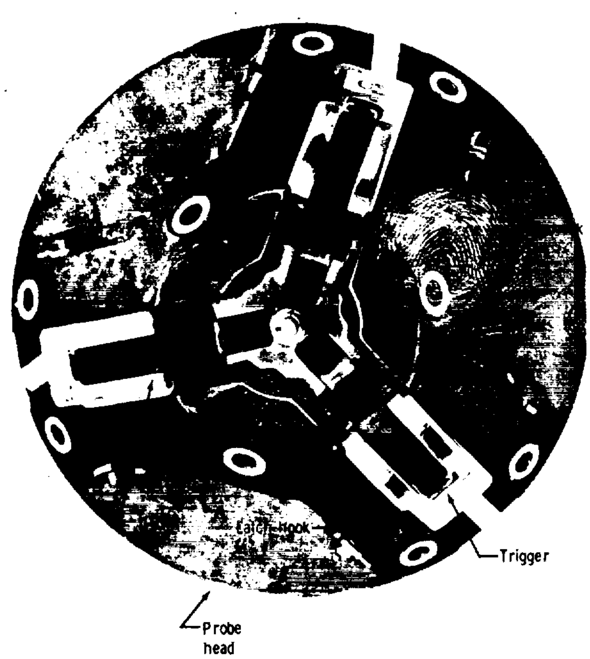


Figure B-7. - Capture latch assembly.

Locking and releasing of the latch hook is determined by the axial position of a single, symmetrical spider (fig. B-8) that is spring loaded to the full forward (locked) position (fig. B-5). In this position, a roller on the spider (fig. B-7) rests beneath each of the latch-hook toggle links so that the latch hooks cannot be depressed. To unlock the latch hooks, the spider must be moved aft and retained until a subsequent latch lock is required (fig. B-9).

Spider retention and release are achieved by triggers located within each of the latch hooks. When the spider is moved aft of the spring-loaded triggers and released, pins located on the outer tip of the spider (fig. B-9) bear against the back face of the trigger and thereby prevent forward travel of the spider. To release the spider, all three triggers must be depressed simultaneously because any one of the triggers will retain the spider in the aft position. The spider can be moved from the forward to the aft position by manually

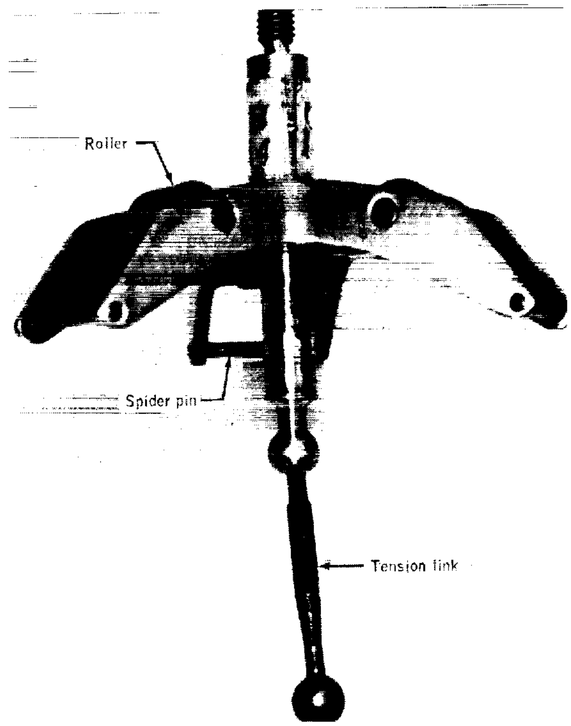


Figure B-8. - Spider assembly.

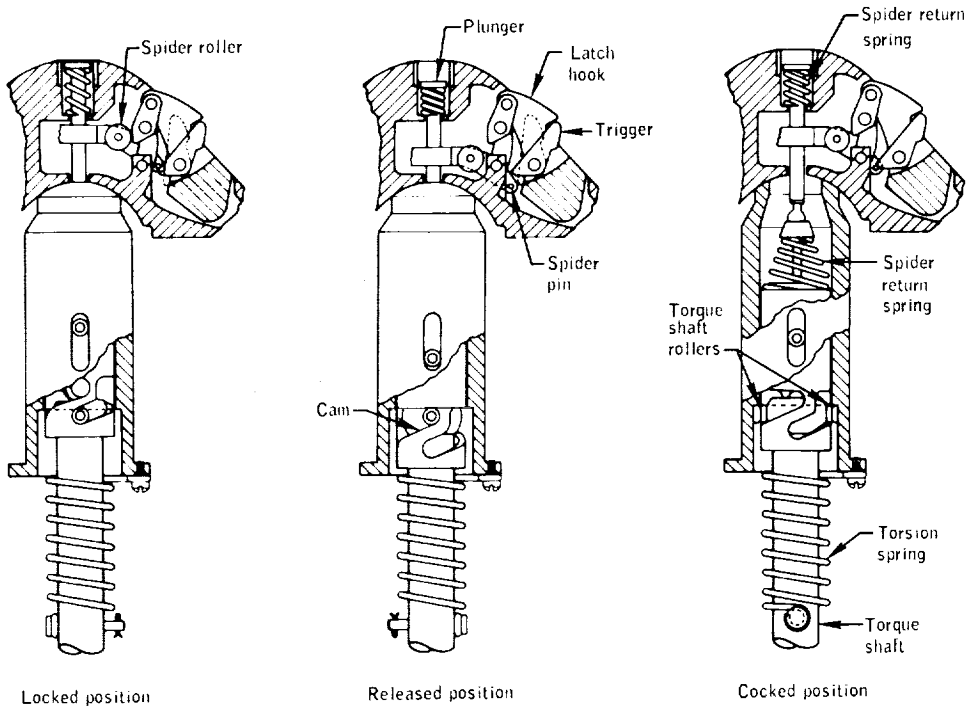


Figure B-9. - Relationship of probe latch and cam mechanisms.

depressing the plunger in the probe head or by rotating the torque shaft. The torque shaft has two rollers which ride in helical slots in a cam (figs. B-9 and B-10). The cam is attached to the spider with a tension link. When the torque shaft is rotated either by manually actuating the capture latch release handle or by powering the torque motors in the actuator assembly (fig. B-11), the rollers turn in the cam slots and force the cam and the spider aft (fig. B-9). When power is removed from the torque motors, the torsion spring on the torque shaft rotates the shaft back and allows the spider to move forward until cocked (i. e., the spider pins ride against the back of the triggers).

The actuator assembly (fig. B-11) consists of two tandem-mounted dc torque motors, 16 switches, and required electrical circuitry, all of which are located within the probe cylinder. The motor output is such that single-motor operation provides sufficient torque to unlock the capture latches. The drogue (fig. B-2), a truncated cone structure that is installed in the LM tunnel, serves as a guide and receiver for the probe head.

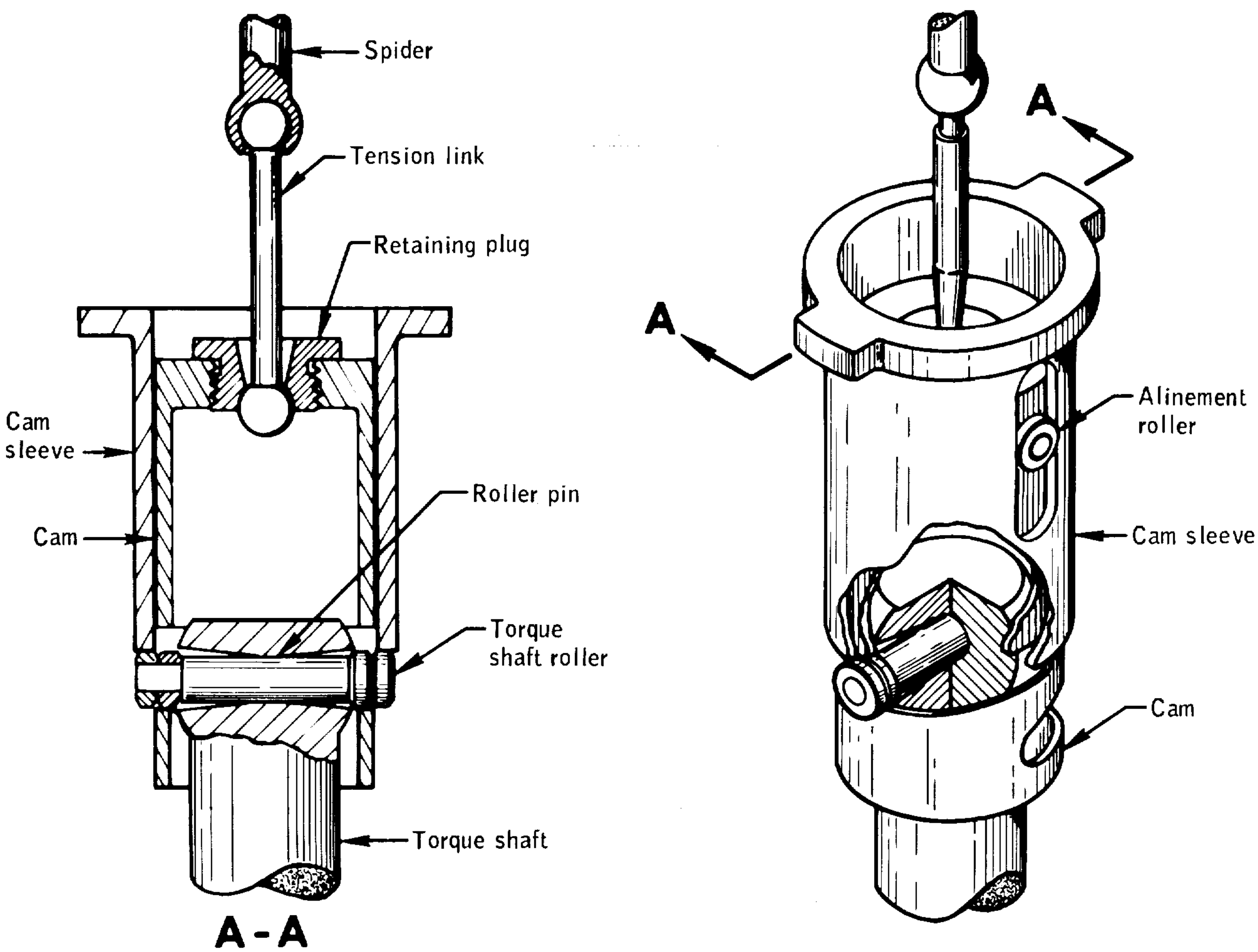


Figure B-10. - Cam actuating mechanism.

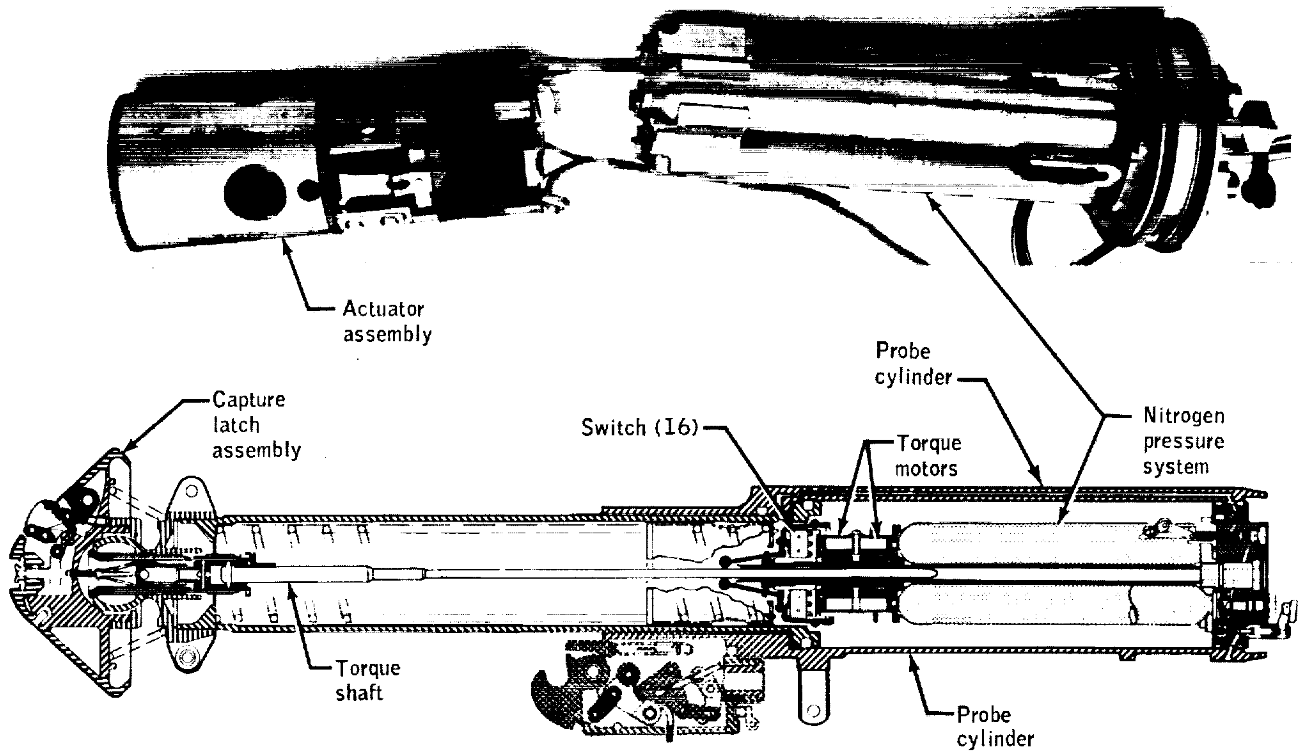


Figure B-11. - Cutaway of probe assembly in extended and cocked positions.

DISCUSSION

Data indicate that probe-to-drogue contact conditions were normal for all docking attempts, and capture should have been achieved for the five unsuccessful attempts (table B-I). The capture latch assembly must not have been in the locked configuration during the first five attempts based on the following:

1. The probe status talkback displays functioned properly before and after the unsuccessful attempts, thus indicating proper switch operation and power to the talkback circuits. The talkback displays always indicate that the capture latches were in the cocked position during the unsuccessful attempts (fig. B-9). (Note that no electrical power is required to capture the drogue because the system is cocked prior to flight and the capture operation is strictly mechanical and triggered by the drogue.)

2. The marks on the drogue noticed by the crew (fig. B-2) indicate that capture latch hooks were cocked as they should have been during the docking attempts. This confirms the talkback indications at the time of the docking maneuver. Also, after the flight, a drogue that had been used in dynamic testing with multiple marks, scratches, dents, and tears in the face sheet skin was examined by the CM pilot. The marks chosen by him to be most like those on the Apollo 14 drogue were caused by the capture latch hooks while operating normally (cocked position).

TABLE B-I. - RELATED DATA AND FILM INVESTIGATION RESULTS

Docking attempt	Contact, hr: min: sec	Estimated velocity,[a] ft/sec	Contact position, clock-oriented	Socket contact time,[b] sec	+X thrusting after contact, sec	Comments[a]
1A	3: 13: 53. 7	0. 1	11: 00	1. 55	None	1. No thruster activity 2. Contact moderately close to apex
1B	3: 14: 01. 5	. 14 max.[c]	9: 00	1. 65	None	Contact close to apex
1C	3: 14: 04. 45	. 14 max.[c]	4: 30	1. 4	0. 55	Contact close to apex
1D	3: 14: 09. 0	. 29 max.[c]	4: 00	2. 35	1. 95	Contact close to apex
2	3: 14: 43. 7	. 4 to 0. 5	8: 30	1. 7	None	Contact close to apex
3	3: 16: 43. 4	. 4	7: 00	2. 45	None	Contact close to apex
4	3: 23: 41. 7	. 4 to 0. 5	3: 00	6. 5	6. 2	Contact close to apex
5	4: 32: 29. 3	. 25	6: 00	2. 9	None	Contact close to apex
6	4: 56: 44. 9	. 2	7: 00	In and hard docked	14. 3	1. Contact moderately close to apex 2. Retract cycle began 6. 9 seconds after contact 3. Initial latch triggered 11. 8 seconds after contact

[a]System is designed to capture with closing velocities between 0. 1 and 1. 0 ft/sec and with initial probe contact within 12 inches of the center of the drogue. These criteria were met on all docking attempts.

[b]The maximum capture latch response time is 80 milliseconds.

[c]Estimated velocity from X-thruster activity time. These are maximums with some velocity being used to null out small separation velocity. Other velocities were estimated by film interpretation.

Because the latches were cocked, the problem was most likely caused by failure of the capture latch spider to reach the forward locked position.

A number of possible causes for preventing the capture latch spider from extending to the locked position were ruled out. A summary of these possible causes follows:

1. The tension tie shear pin remnants reentered the capture latch assembly during launch escape tower jettison. Tests show that the pin-remnant trajectories were such that the remnants would not reenter the probe head.

2. As a result of rain on launch day, water could have entered the probe head and frozen during the launch phase. This could cause the mechanism to bind. A maximum of 30 grams of ice could have formed; however, this amount would sublime within 15 minutes, well before the docking event which occurred about 3-1/2 hours after launch.

3. Extreme temperature effects could have caused the mechanism to bind. The temperature within the probe body was between 95° and 100° F at the time of the problem. The returned probe operated properly from +50° to +145° F.

4. A tolerance buildup in the latch mechanism combined with a normal thermal gradient between the parts caused binding. Analysis of the worst-case tolerance buildups, including thermal gradients and detailed inspection and measurement of the probe components, showed no interference.

Two possible causes remain that could prevent the capture latch spider from moving properly.

The first possibility is that of a side load being introduced into the torque shaft (fig. B-12) by the torsion spring or by other means; this may cause the ball end of the torque shaft to bind against the cam. This failure occurred on another probe during acceptance tests and it was possible to demonstrate this same failure on the Apollo 14 probe by applying a side load, but the failure did not occur consistently.

The second possibility is that some small foreign material may have been lodged in the probe in a manner that prevented operation of the mechanism. Burrs from an unknown source were discovered in the bore of the tension tie plug (fig. B-13). A foreign particle might have been lodged between the plunger and the plug and may have caused the problem.

During disassembly of the probe, 12 contaminant particles were found. Three materials foreign to the probe were iron oxide, double-back tape, and cadmium particles. The largest of the 12 particles was 0.060 inch long. Of the particles that were large enough to cause mechanical interference, none were strong enough to restrict the operations of the mechanism.

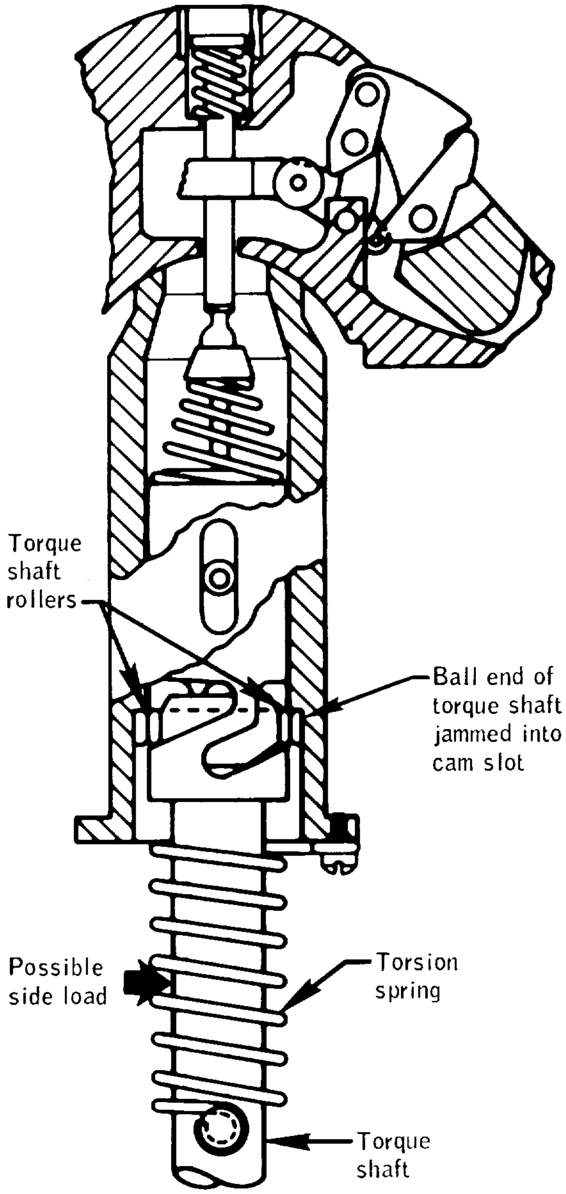


Figure B-12. - Side load reaction on torque shaft operation.

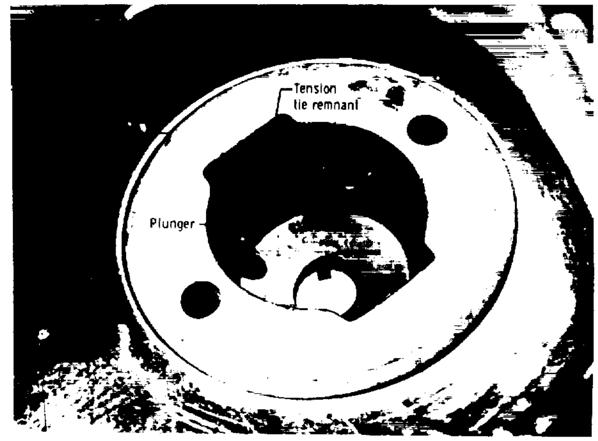


Figure B-13. - Scratches and burrs adjacent to capture latch plunger.

CORRECTIVE ACTION

The following changes have been made to prevent the introduction of foreign material into the probe mechanism.

1. A removable cover was provided for the probe head. The cover will be installed at the completion of acceptance testing and remain in place until the tension tie assembly is installed at the launch complex. It will be removed only when the probe is being tested.

2. Cleanliness requirements for all ground support equipment mating with the probe have been implemented.

3. Use of cleaners or primers when potting the tension tie nut during installation has been prohibited.

4. Shear pin remnants in the tension tie have been safely wired, and the potting holding the shear pins in place has been removed (fig. B-14).

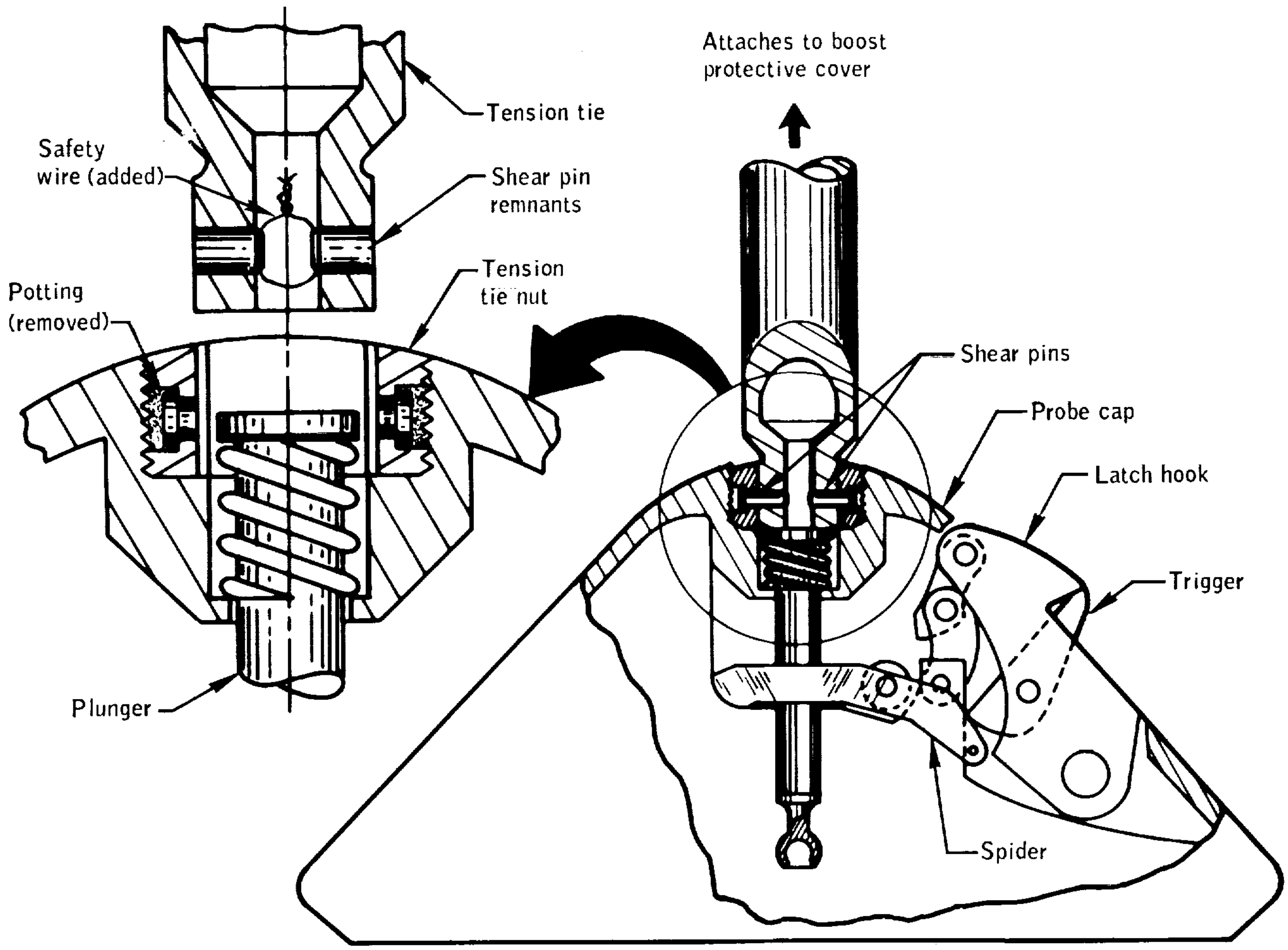


Figure B-14. - Probe tension tie changes.

The following changes have been completed to minimize the possibility of a translation cam malfunction.

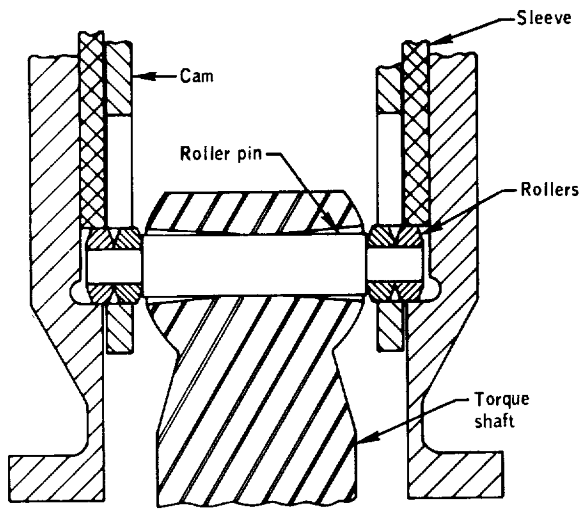
1. The probe translation cam assembly (fig. B-15) was modified to eliminate possible binding of the cam and spider.

a. The diameter of the ball machined on the forward end of the torque shaft was reduced.

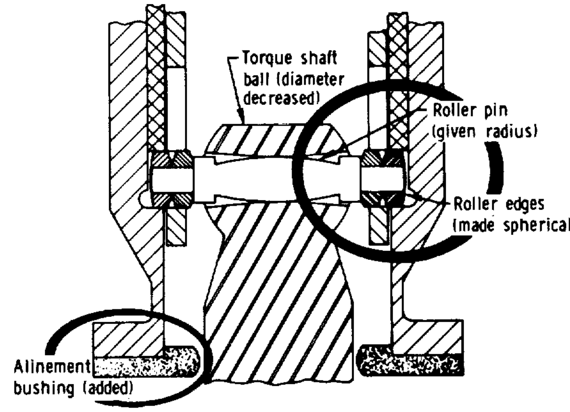
b. The roller pin surface was machined to allow a rocking motion between the roller pin and hole in torque shaft.

c. A spherical surface was provided on the roller ends and roller pin ends for improved clearance.

d. An alinement bushing was added to ensure proper torque shaft alinement.



(a) Apollo 14 cam assembly.



(b) Apollo 15 and subsequent cam assembly.

Figure B-15. - Cam assembly modifications.

2. A requirement was added to test the probe in the horizontal as well as vertical position during the capture latch timing test of the acceptance testing.

3. Capture latch timing tests were added just prior to the countdown demonstration test for the latest possible verification of latch operation in the spacecraft checkout flow.

CONCLUSION

The failure to achieve capture latch engagement has been narrowed to either foreign material restricting the normal function of the capture latch mechanism or jamming of the translation cam.