VARIABLE FLEXIBILITY TETHER

EXTRAVEHICULAR EQUIPMENT DEVELOPMENT BRANCH
CREW SYSTEMS DIVISION
NASA MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

CONTRACT MONITOR: GERALD ARMSTRONG

PREPARED UNDER CONTRACT NAS9-7336

BY

DAVID J. WITHEY
GENERAL ELECTRIC CO.
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ABSTRACT

A prototype restraint and positioning system for use by an astronaut during EVA has been designed, fabricated and assembled. The system utilizes two variable flexibility tethers, one mounted on each hip, to form a double hip tether restraint system. The unique feature of the system is that the tethers may be selectively rigidized to varying degrees in any random curvature or shape as required by the astronaut. The tether is constructed of many ball and socket links, strung over a central cable. To rigidize the tether, the astronaut cranks the handle of a hip mounted controller which applies tension to the cable, and a compressive load to the ball/socket joints. The resulting friction between the balls and sockets maintains the tether rigidity, the degree of rigidity being a direct function of cable tension. To relax the tether, a quick release mechanism is incorporated into the control handle. The distal ends of the tethers consist of modified "vise grip" pliers suitable for attachment to a variety of work stations.

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INTRODUCTION

Problems encountered in past brief experiments with astronaut extravehicular activity (EVA) have been related to the zero-g, or "weightlessness", phenomenon and the restricted mobility inherent in a pressurized space suit. Weightlessness radically alters the normal procedures for doing useful work, i.e., applying forces or torques, by requiring the astronaut to "hold on" or be otherwise restrained. The decreased mobility of the pressure suit greatly increases the effort required by the astronaut to merely "hold on" or move from one position to another. Under these conditions, even relatively simple tasks leave the astronaut exhausted and unable to work effectively.

The variable flexibility tether system described in this report is designed to alleviate the above problems by providing a restraint and positioning system for the astronaut. Torques and forces applied by the astronaut will be reacted by the tether system, thus keeping the astronaut "on station" with a minimum of effort. The tether can be selectively made limp, like a rope, or rigidized in any particular shape or curvature. "Vise grip" clamps at the distal end of the tether can attach to a great variety of work stations. The prototype system developed is intended to demonstrate the feasibility, practicability and performance of this unique astronaut restraint and positioning concept.

SYSTEM DESCRIPTION

Figure 1 shows the design concept of the variable flexibility tether system. Figures 2 and 3 show the actual tether system hardware developed in this program. As shown, there are two tethers utilized for astronaut positioning and restraint, one mounted on the right hip, and the other on the left hip.

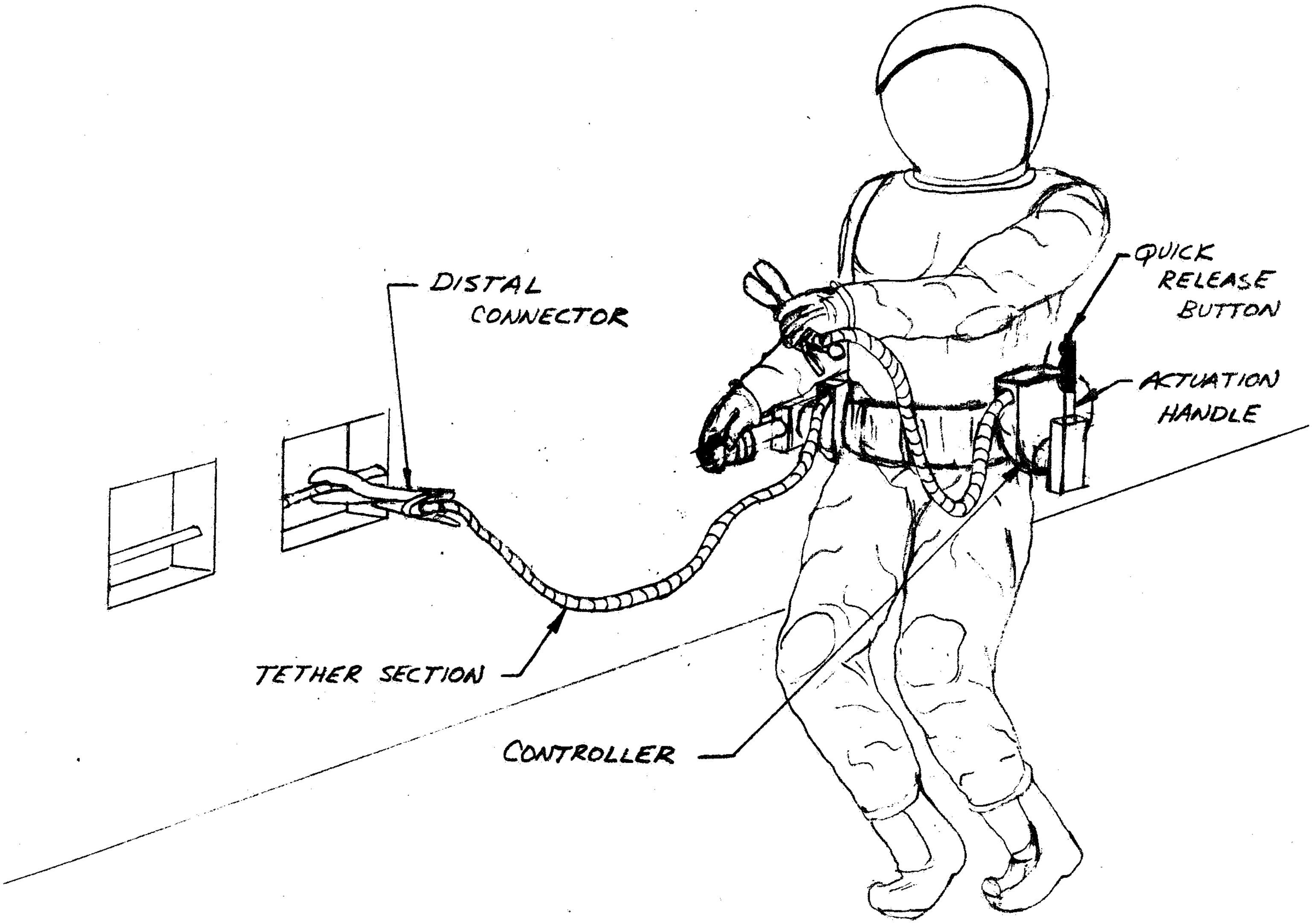


Figure 1. Variable Flexibility Tether System

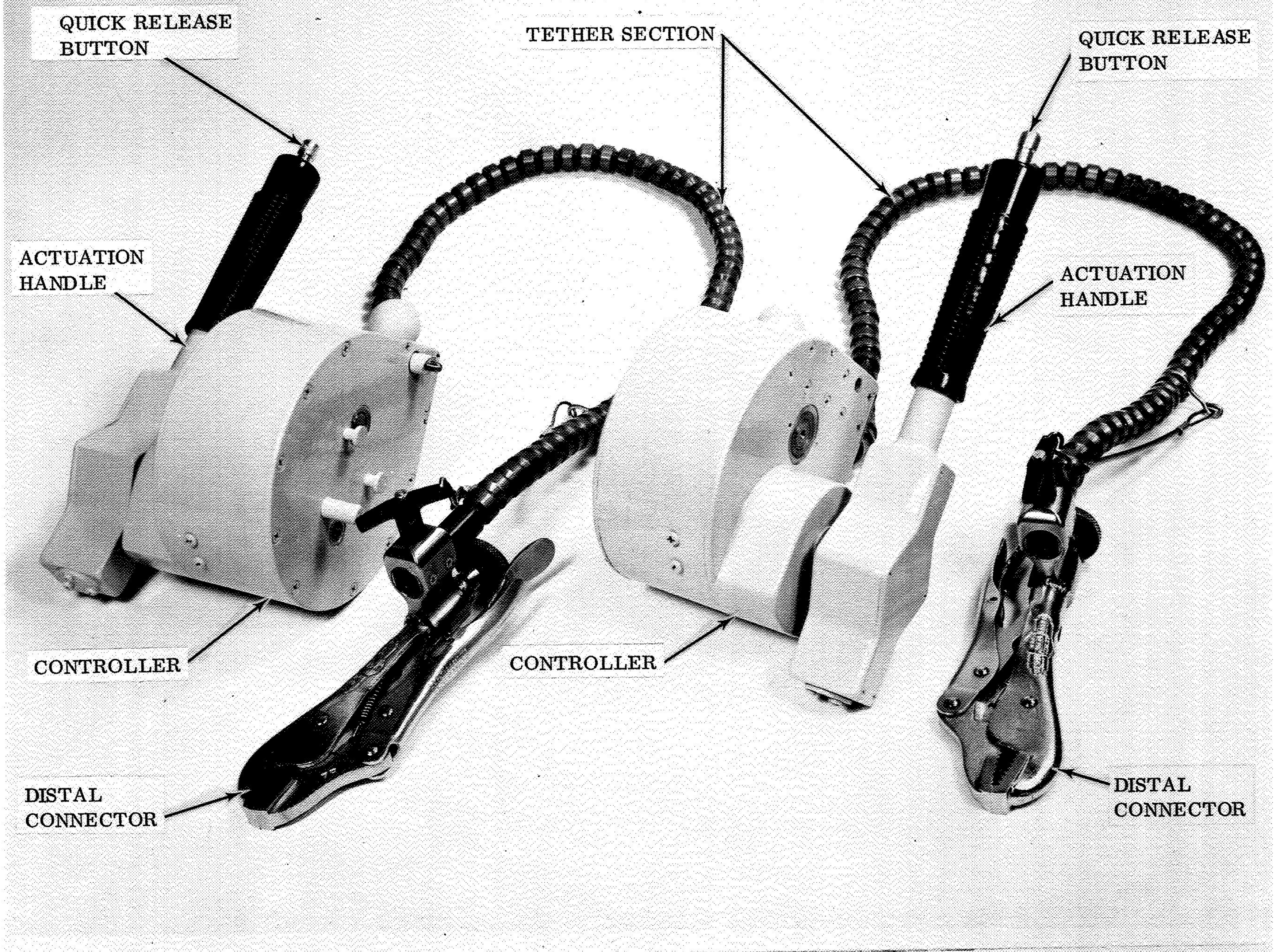


Figure 2. Variable Flexibility Tether System (Tethers Relaxed)

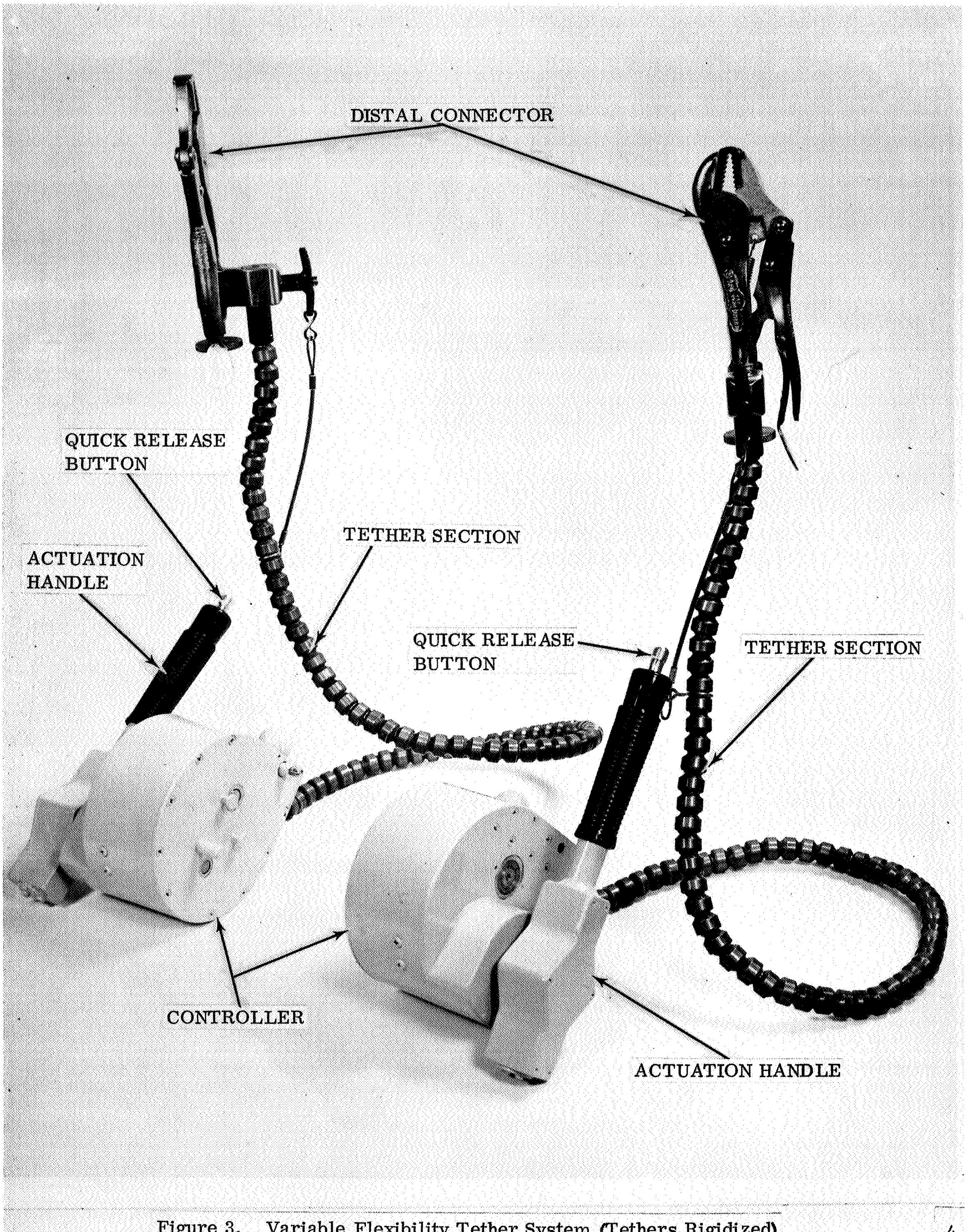


Figure 3. Variable Flexibility Tether System (Tethers Rigidized)

Each tether consists of a controller, a tether section, and a distal connector. The tether section consists of multiple links having a ball at one end and a socket at the other end and a central cable. The dimensions and materials of the link are shown in figure 4. The tether section is assembled by stringing the links over the central cable so that the ball of one link nests within the socket of the next link. Each socket is then swaged over the adjacent ball to prevent the tether from separating should the central cable break. The cable is then connected to the controller and distal connector. When the actuation handle of the controller is pushed forward, internal gearing applies tension to the central cable. This applies a compressive load to the ball/socket link joints and rigidizes the tether, with the degree of rigidity dependent on the amount of tension in the cable. The tether is relaxed, to a free "rope like" condition by pressing the quick release button on the actuation handle, and pulling the handle back. The distal connectors are modified "vise grip" pliers suitable for attaching the tether system to a variety of work stations.

Either tether, therefore, can be selectively rigidized or relaxed (at any degree of rigidity up to the maximum) as desired by the astronaut. Due to the ball/socket link configuration, the tether will rigidize in whatever shape or curvature it happens to be in at that particular time. When rigidized, the system will resist forces and torques acting upon the astronaut. This restraint system allows the free use of both hands for useful work by the astronaut, while maintaining the astronaut in a fixed position.

SYSTEM DESIGN REQUIREMENTS

The design requirements for the variable flexibility tether system are as follows:

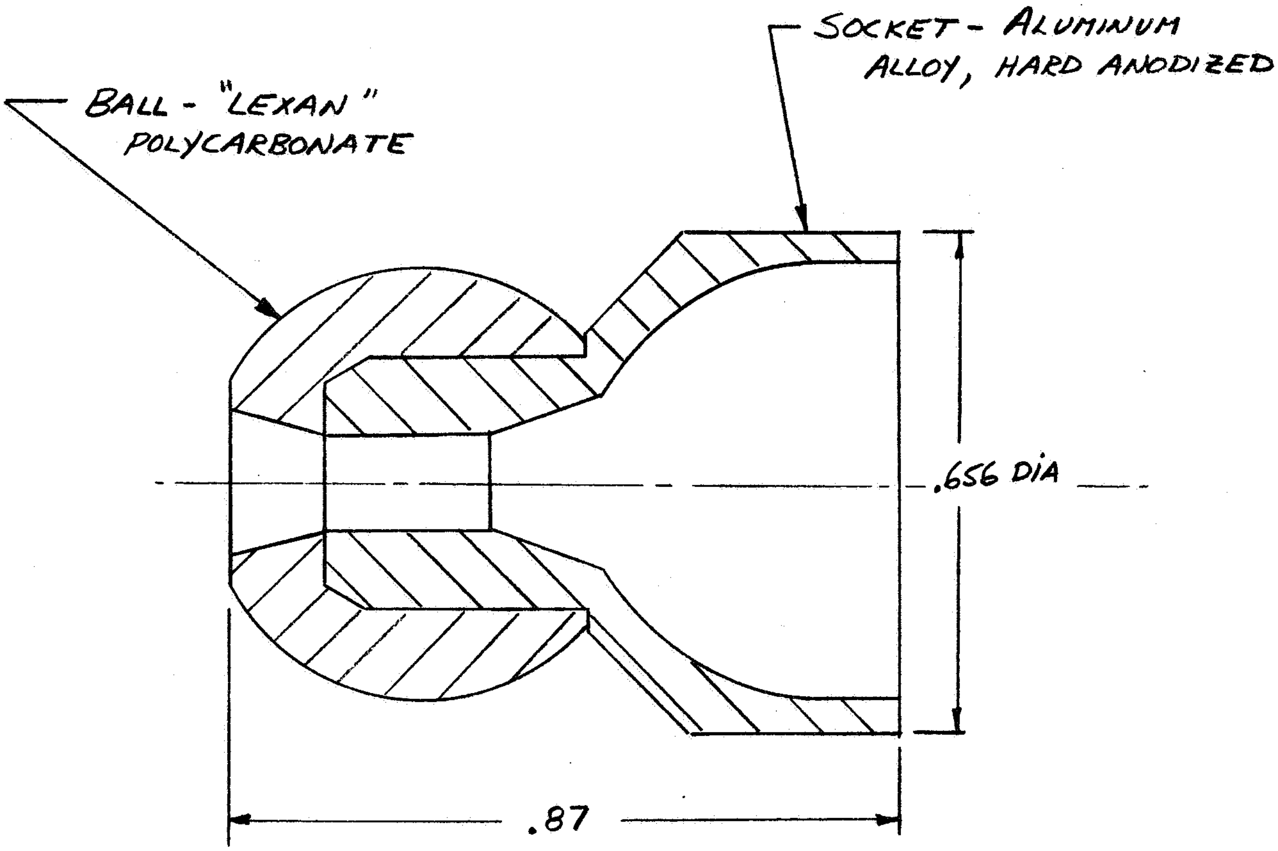


Figure 4. Tether Link - Scale 4:1

1. In case of failure of any link, or of the central cable, the tether will not separate to decouple the astronaut and permit him to drift away.

2. In an emergency, the astronaut may detach either, or both, the distal connector from the tether section, or the controller from the astronaut. No failure of the tether will prevent the astronaut, at his option, from decoupling from the work station.

3. A failure of the controller will not sever the cable or detach the controller from the astronaut.

4. Materials will be chosen to minimize cold welding in space and will be compatable with 100 percent oxygen up to 7 psia.

5. The distal connector will permit ready disconnect by a gloved astronaut. The attachment between the tether section and distal connector will permit use of alternate devices other than the modified "vise grips" provided.

6. The attachment of the controller to the astronaut will utilize the present pin and lock concept of the Apollo Block II Suit emergency oxygen supply (EOS) disconnect.

7. The controller will have a spring loaded quick release mechanism, which, upon activation, will make the tether fully flexible.

8. All designs and manipulative features will be appropriate for use by a gloved, pressurized astronaut.

9. The tether section will be 36 inches long and the system (both left and right assemblies) will weigh approximately eight pounds.

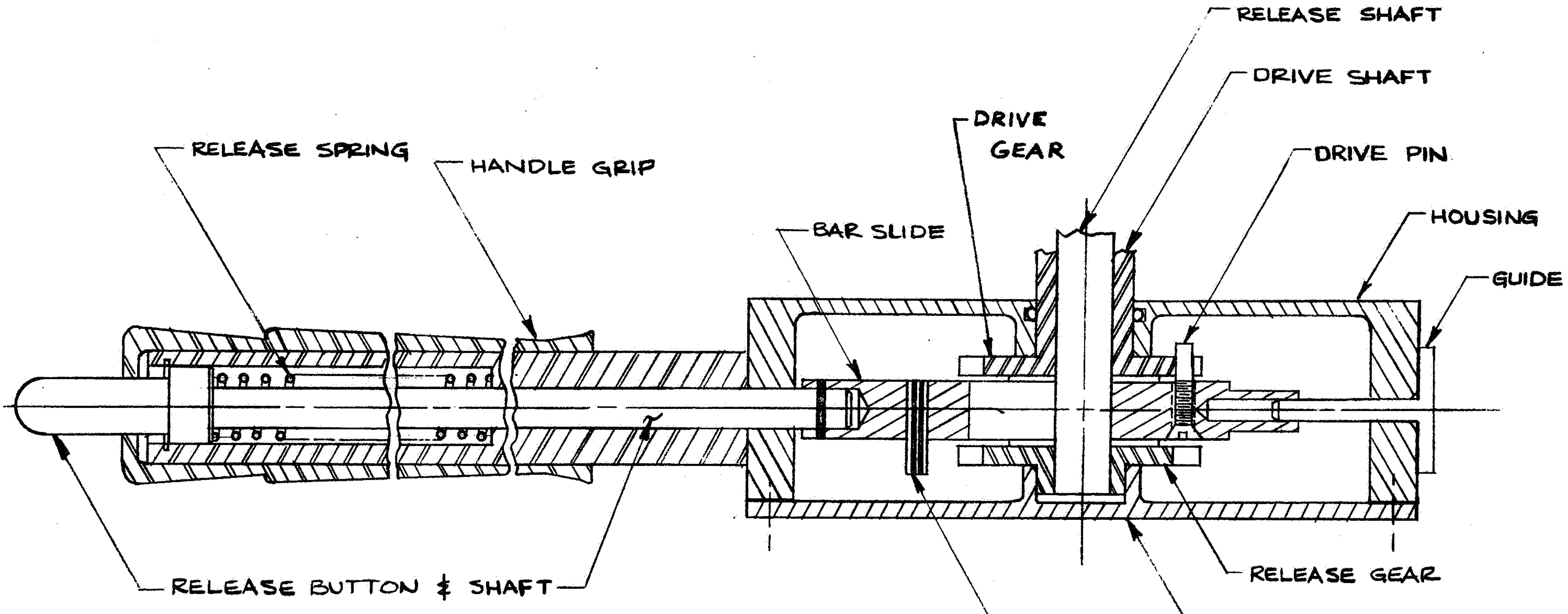
10. The tether section shall be approximately 5/8 inch diameter.

COMPONENT DESIGN

CONTROLLER

The function of the controller is to provide the astronaut with the means to apply or relax the cable tension in the tether section, thus rigidizing or derigidizing the tether. The controller consists of two major subassemblies, the actuation arm, or handle assembly (see figure 5) and the control box itself (see figures 6 and 7). When it is desired to rigidize the tether, the handle is pushed forward. The torque developed by this motion is transmitted to the drive gear and drive shaft by means of a pin, fixed to the bar slide, which engages the drive gear. The drive gear thus rotates with the handle. In the control box, the drive shaft is connected, through a one way drive indexing type clutch, to the drive pinion. The pinion turns the larger spur gear and shaft, which causes the rack and pinion, affixed to the spur gear shaft, to apply tension to the tether cable. A spring loaded pawl, which engages the drive pinion, is used to maintain the cable tension when the force on the handle is released, i.e., the pawl prevents reverse motion of the cable tensioning gear train components.

The indexing clutch allows the handle to be cranked, back and forth, in a manner analagous to a ratchet wrench as opposed to a continuous circular rotation, when rigidizing the tether. When the handle rotation is reversed, i.e., brought back toward the operator, the clutch is free wheeling and thus allows the drive shaft in the handle to rotate. (The remaining drive components in the control box cannot reverse direction, due to the holding action of the pawl, as mentioned above). Thus the degree of cable tension, and thus also tether rigidity, is controlled up to the maximum limit, by the number of cranks (i.e. sum total of angular displacements given to the handle in forward movements) applied to the handle. The maximum cable tension that can be applied



NOTE: HANDLE IS SHOWN IN DRIVE POSITION

Figure 5. Actuation Handle

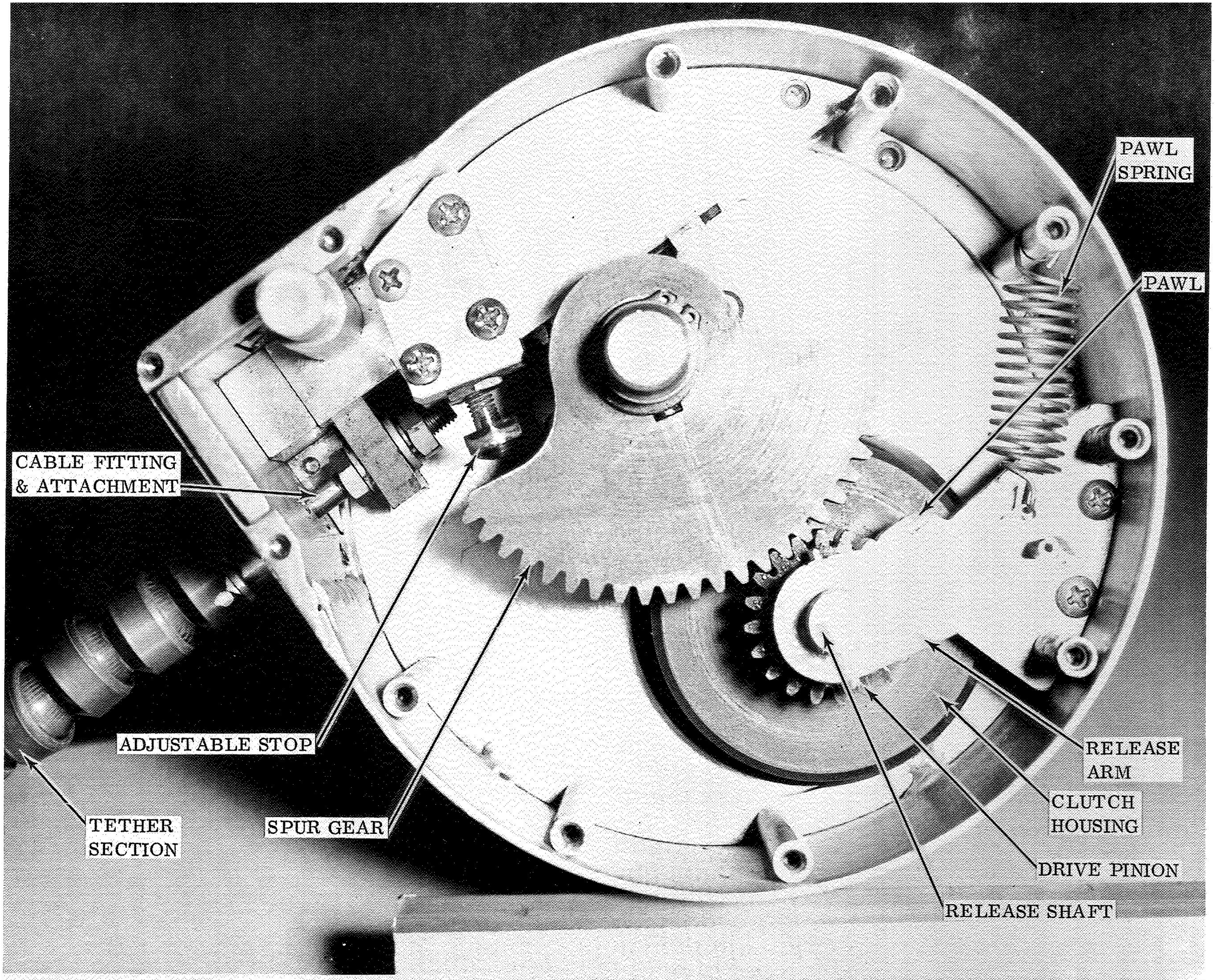


Figure 6. Controller Assembly (Cover Removed)

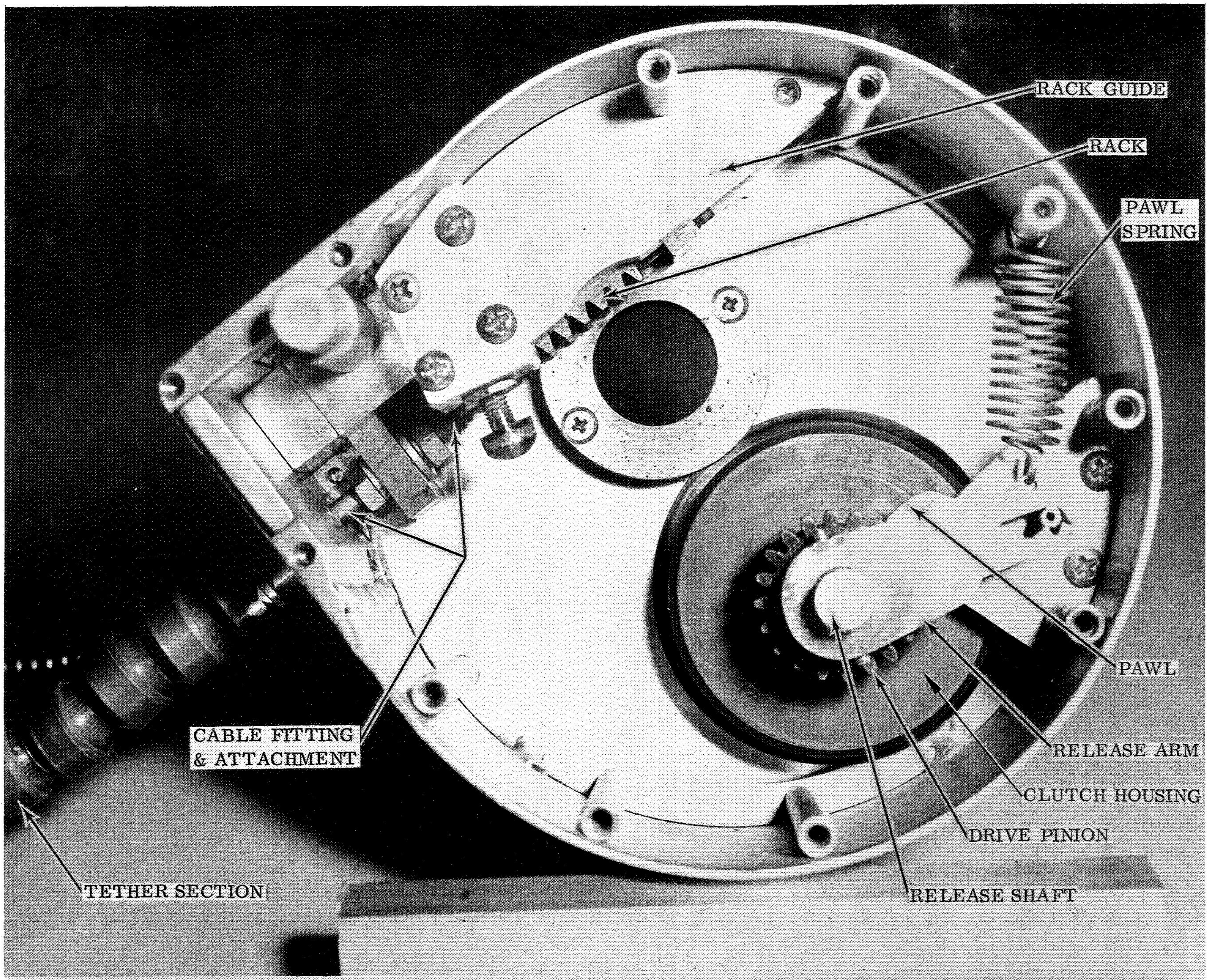


Figure 7. Controller Assembly (Cover, Spur Gear, Pinion and Shaft Removed)

is set by an adjustable mechanical stop which limits the rotation of the drive gear. This is set during system check out to provide a maximum tension of 500 lbs (see tether design section). A total angular displacement of the handle of about 260 degrees is required to take the tether from completely relaxed to fully rigidized.

When it is desired to relax the tether, i.e., release the cable tension, the button on the end of the handle is depressed and the handle is pulled back toward the operator. The spring loaded button is, in reality, the end of a shaft which is attached to the bar slide in the handle. Thus, when the button is depressed, the bar slide moves. This takes the one pin, attached to the bar slide, out of engagement with the drive gear and forces another pin into engagement with the release gear in the handle. (Figures 8 and 9 show the handle in the drive and release positions, respectively.) Thus, when the handle is pulled back, the release gear and release shaft rotate. An arm at the end of the release shaft, in the control box, then moves the pawl out of its engagement with the drive pinion. With the pawl released, the gear train is then free to move, in a reverse direction, releasing the cable tension.

The gear ratio selected for the controller was based on a desire to minimize the number of cranks required on the handle to rigidize the tether, while keeping the applied force on the handle at a reasonable value. Discussions with human factors personnel, knowledgable in space suit mobility problems led to the selection of 15 lb. as a reasonable value for this force. Further preliminary design steps led to the selection of a handle moment arm length of 6 inches and a gear ratio of 3:1. Thus a force of 15 lbs. applies a torque of (15)(6) = 90 inch-lbs to the drive shaft in the handle. This torque is multiplied by the gear ratio to give (3)(90) = 270 inch-lbs available to drive

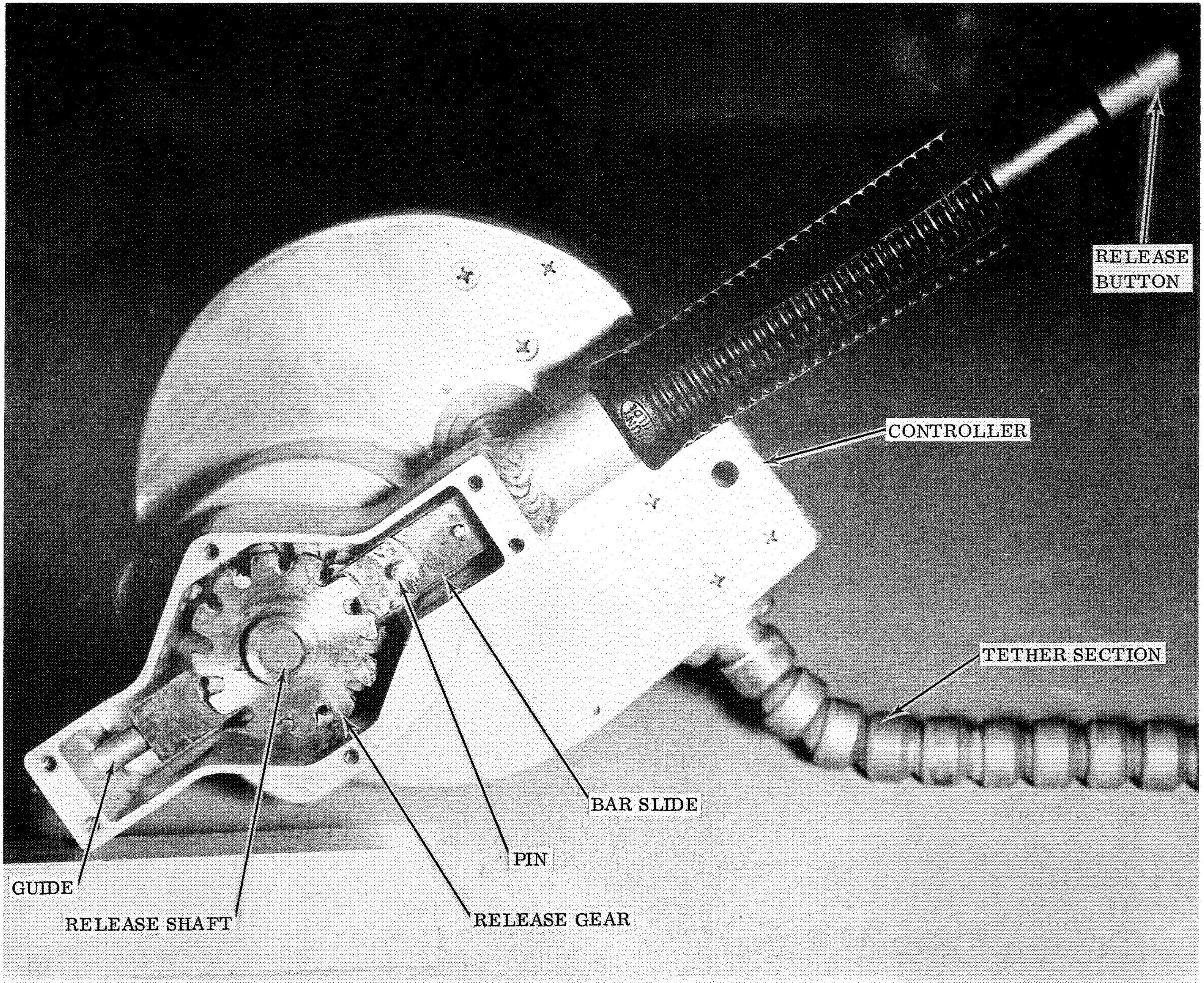


Figure 8. Handle, Drive Position (Cover Removed)

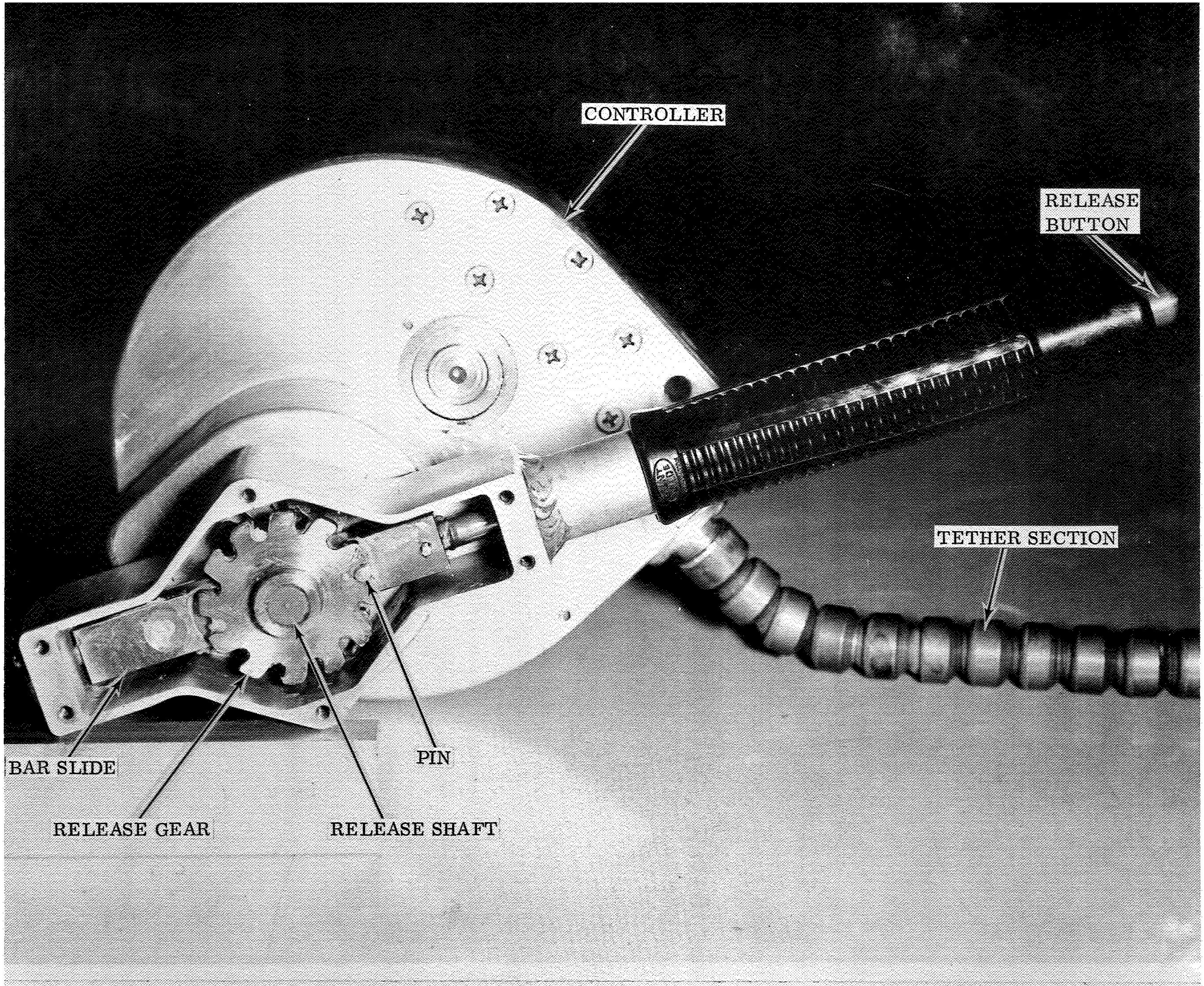


Figure 9. Handle, Release Position (Cover Removed)

the pinion and rack. The force exerted on the rack gear is, then, $\frac{270}{R}$ where R = the pinion radius of 1/2 inch, or force = 540 lbs. This is higher than the desired maximum cable tension of 500 lbs., however, gear train inefficiencies will reduce this load to close to 500 lbs.

The amount of movement required by the rack was estimated as 0.75 inches, consisting of 0.5 inches for cable stretch over 0 to 500 lbs. and 0.25 inches for excess slack in the cable. To move 0.75 inches, the pinion must rotate through an angle of $\frac{(0.75)\ (360)}{\pi d}$ (where d = pinion dia. = 1 inch) $= 86^{\circ}$. Multiplied by the 3:1 gear ratio, the total handle angular displacement $= (3)(86) = 258^{\circ}$. This means that less than three 90° cranks of the handle are required to take the tether from completely relaxed to fully rigidized.

Following establishment of the design concept for the controller, the component parts were designed and materials selected based upon strength requirements and the desire to minimize cold welding in a space environment. Each major part was subject to stress analysis. Where the stress analysis and cold welding characteristics permitted, aluminum alloy was chosen for the material of construction in order to minimize weight. In many cases, however, stress levels and size limitations did not permit use of aluminum, and heat treated stainless steel was used for these components. Consideration was given to minimizing size and weight also subject to the schedule and funding constraints of the contract.

The materials selected were reviewed for minimizing cold welding in the space environment and compatability with a 7 psia, 100% oxygen atmosphere. The results of this investigation indicated that the materials utilized should not give any problems in these areas. In general, cold welding occurs under application of pressure and is dependent on the hardness and composition of the materials in contact. Similar materials will cold weld more readily than dissimilar materials, with certain alloys of aluminum in contact with aluminum, particularly bad offenders. Cold welding should not occur between ferrous parts, unless contact pressures are very high or the parts operate at elevated temperatures. In the design of the controller (and tether system as well) contact of aluminum parts on other aluminum parts, under dynamic loading conditions was avoided. Parts in contact under dynamic loadings were fabricated from dissimilar materials where possible (e.g. steel shafts in bronze bearings, lexan ball in hard anodized aluminum socket). Where this was not possible, due to strength requirements (e.g. rack and pinion, spur gears) hardened ferrous parts were utilized.

All features of the controller were reviewed and discussed with human factors personnel, to assure ease of operation by a suited pressurized astronaut. A pair of heavy, stiff, rubberized gloves, simulating the hand mobility of the Gemina EVA suit, were utilized to check the suitability of the handle/quick disconnect button concept. Operation of the handle and quick release was easily accomplished, in the following manner:

Cranking the handle forward and rigidizing the tether can be accomplished by extending the hand and catching the handle in the "V" formed between the fleshy base of the thumb and the fingers (which are bent slightly, in a natural position) and pushing forward. Returning the handle is simply a matter of bringing the hand back until the handle bears on the inside of the fingers. To operate the quick release, and relax the tether, the hand is slid down over the handle until the thumb depresses the button. Then, when the hand is brought back, force is applied to the handle by the inside surface of the fingers, which should be cupped slightly. The handle itself has numerous annular ridges, to provide a non skid surface. Because of the indexing clutch in the control box, the handle can be rotated 360° to any convenient location for applying the cranking motions. This also allows the handle to be rotated out of the way when not used.

The controller utilizes the same disconnect concept as the Apollo Block II Suit Emergency Oxygen Supply for attachment to the astronaut. This disconnect utilizes a fixed round pin, two retaining studs, and a spring loaded locking pin. The controller would thus mate on a plate or mount affixed in some manner to the pressure suit or a harness on the astronaut. To connect the controller to the plate, the fixed pin and retaining studs are engaged in the matching holes in the plate. The controller is then rotated about 13°. This locks the retaining studs to the plate and permits the spring loaded locking pin to drop into its mating hole in the plate. (The controller pivots about the axis of the fixed pin. The studs are "T" shaped and engage keyhole type slots in the plate).

To remove the controller, the knob on the top of the controller is pushed outward, withdrawing the locking pin from its hole in the plate. The controller can then be rotated, in a reverse direction, and removed. The critical dimensions for the location and size of the fixed pin, retaining studs and locking pin were taken from Hamilton Standard Drawings SV715420, "Plate, Mounting, E.O.S., PLSS" and SV594200, "Supply, Emergency Oxygen".

TETHER SECTION

The tether section consists of ball and socket links strung over a central cable as shown in figure 10. End fittings, swaged on the cable, are fastened to the rack gear in the controller and the adaptor at the distal end, so that, as the cable is tensioned, a compressive load is applied to the link ball and socket joints. Under this condition, tether rigidity is maintained by the static friction between each ball and socket. In the design of the links for the tether section, the following considerations

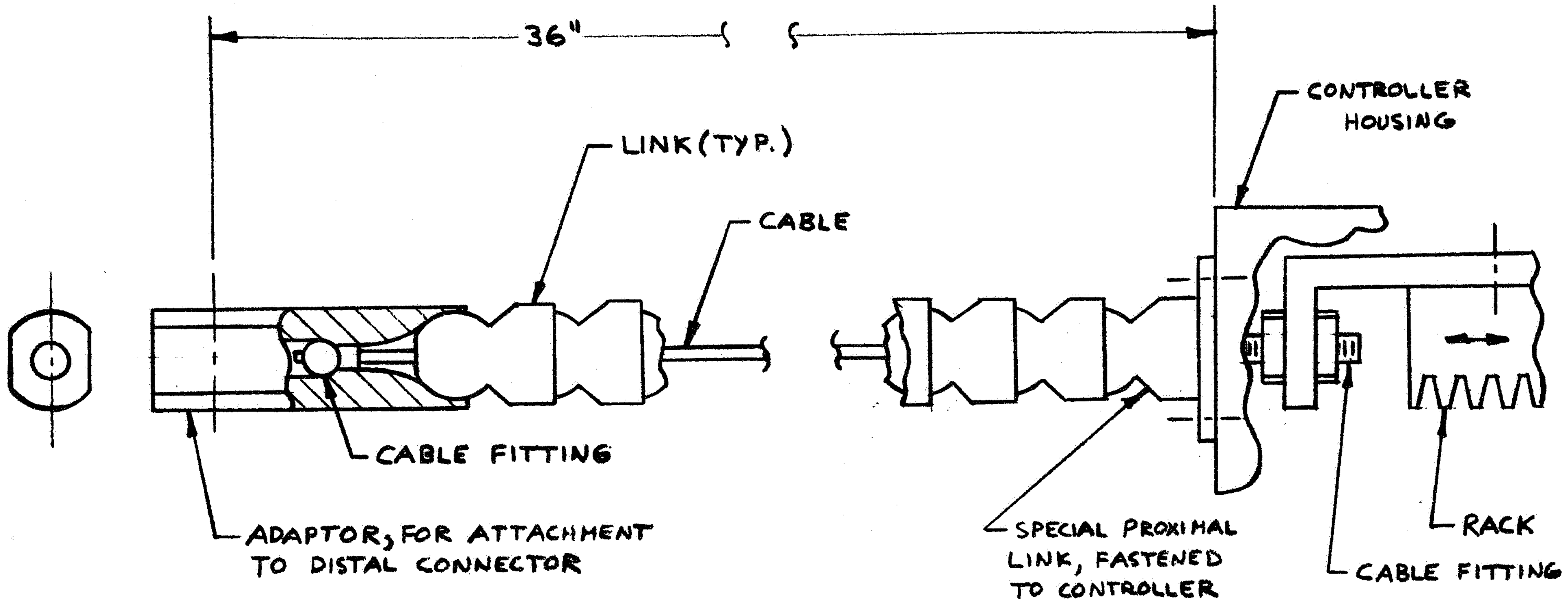


Figure 10. Tether Section

were made:

1. It was desired to fabricate the ball and socket from dissimilar materials, to minimize the possibility of cold welding.

2. The use of a metalic socket was desired, so that upon assembly, each socket could be swaged over an adjacent ball. This would provide tether integrity should the central cable break.

3. The materials utilized for the ball and socket should exhibit a relatively high coefficient of friction. This will enable the tether to withstand high loads before relative motion occurs between the links.

4. The links should be designed to minimize weight.

Conditions number 2 and 4 were best satisfied by utilizing aluminum for the socket material, because of its relatively light weight and ability to be crimped or swaged. Selection of the ball material was more involved. Previous testing had been conducted at General Electric Co., on many different materials to determine the frictional characteristics of the ball/socket joint. In these tests, the candidate links were subjected to a known compressive load, and a force was applied perpendicular to the axis of the links, at a known distance from the ball and socket joint. The force required to rotate the joint was measured, and a moment was calculated. This moment is the maximum restraint moment exhibited by the particular materials under the test conditions. The general results of these tests can be stated as follows:

1. The restraint moment increases with increasing ball/socket diameter, and increasing compressive load.

2. A relatively soft material ball against a relatively hard material socket yielded better results than a hard ball against a soft socket.

3. The restraint moment is greatly influenced by the cleanliness of the balls and sockets, with clean surfaces exhibiting much higher moments.

4. The effect of wear at the ball/socket interface generally increases the restraint moment of the joint, but can lead to galling and binding of the joint.

Tests were also conducted on conical, instead of spherical, shaped sockets, in an attempt to increase the contact stress and gain an increase in restraint moment. It was found, however, that the restraint moment for these tests was worse, or no better than for the round sockets.

Aluminum links had been utilized in prior demonstration models of tethers fabricated at General Electric. Use of these demonstrators indicated that the aluminum balls and sockets tended to gall and bind with wear. Testing of hard anodized aluminum balls and sockets alleviated this problem, however, wear marks on the joints showed evidence of the anodic coating wearing away. With time, this would lead to aluminum in contact with aluminum, an undesireable condition. Testing of "Lexan" polycarbonate balls in aluminum sockets, freshly cleaned with alcohol, yielded restraint moments equal to any of the aluminum combinations tested. The final material selections were, therefore, a "Lexan" ball and a hard anodized aluminum socket. The hard anodized aluminum was selected to provide a relatively hard socket material in keeping with the test results above, and to minimize wear. Test results indicate that the restraint moment developed, with a cable tension (compressive load) of 500 lbs., should be from 50 to 80 in-lbs.

As noted above, tether rigidity increases with increasing cable tension, i.e., compressive load on the ball/socket joint. Thus it is desireable to utilize the maximum practical cable tension in the design of the system. The maximum cable tension is limited by the size of the cable, i.e., breaking strength, and the compressive strength of the links. Naturally, with 5/8" diameter links, there is a limitation on the cable diameter that can be utilized.

Achievement of maximum tether flexibility when unrigidized also favors a small diameter cable. The compressive stress on the links is difficult to assess realistically, due to the non-uniform cross sectional area, and the difficulty in predicting the area of contact between the ball and socket. Compressive stress on the lexan ball can be estimated, conservatively, by considering the load to be applied normal to the axis of the link, and using the contact area between the aluminum socket and lexan ball (within a single link) as the cross sectional area. In this case, the cross sectional area is 0.114 in^2. The maximum recommended working stresses for Lexan are given in Reference 1. The maximum working stress for compression loading for intermittent loads at room temperature is 6000 lb/in^2. Thus the recommended maximum cable tension, i.e., link compressive load, for these links is (0.114) (6000) = 685 lbs.

Consideration of the above factors led to the selection of a 3/32" diameter, stainless steel aircraft cable, made in conformance with MIL-C-5424A. The cable consists of seven strands of seven wires each (7 x 7 construction) and has a minimum breaking strength of 920 lbs.

In the tether design, the maximum cable tension was kept below the yield strength of the cable, in order to prevent a permanent deformation, or stretch, from occurring. Industry practice assigns a yield strength, for wire cable, of 60% of the breaking strength. Maximum design cable tension was therefore, theoretically limited to (60%)(920) = 550 lbs. As a practical limit, a value of 500 lbs. maximum cable tension was selected for the design of the system. This allowed a margin for error in the final adjustment of the mechanical stop, which limits the cable tension, in the controller. As seen, this cable tension value is also within the compressive strength capability of the links.

Tests were conducted with 3/32" diameter stainless steel aircraft cable to determine the actual elongation characteristics under tensile loads. This data was essential to the design of the controller cable take up mechanism. A conventional tensile test machine was utilized for this test. Figure 11 shows the results. Five "runs" were conducted on the cable, each consisting of slowly increasing the tensile load from 0 to 570 lbs. On the fifth run, the load was increased beyond 570 lbs. until the cable broke. Significant results are the following:

1. Permanent deformation, or "set", occurred during run 1. This was expected, since the cable had not been pre-stretched prior to the test. Pre-stretching the cable serves to remove any residual slack remaining in the individual wire strands after manufacture, and minimizes further permanent set in use. Run 2, therefore, can be considered the first valid test since the cable was essentially pre-stretched in run 1.

2. The stress/strain curves for runs 2 through 5 are essentially identical and indicate that the cable is operating within the elastic limit.

3. The low value for ultimate strength (690 lbs. versus the 920 lbs. guaranteed minimum) is due to the method utilized to hold the cable in the tensile test machine. Cable fittings were not utilized. Instead the raw cable ends were grasped between chuck jaws (similar to the devices used to grasp solid test specimens). This weakened the cable at these points, and resulted in premature fracture.

4. The strain, over a loading of 0 to 500 lbs., is 12.5 x 10^{-3} in/in. Multiplied by the tether length of 36 inches, gives a value of 0.45 inches for cable stretch. The controller must therefore provide sufficient travel to take up initial slack plus this cable stretch of 0.45 inches.

DISTAL CONNECTOR

The distal connectors are "vise grip" locking pliers, modified both

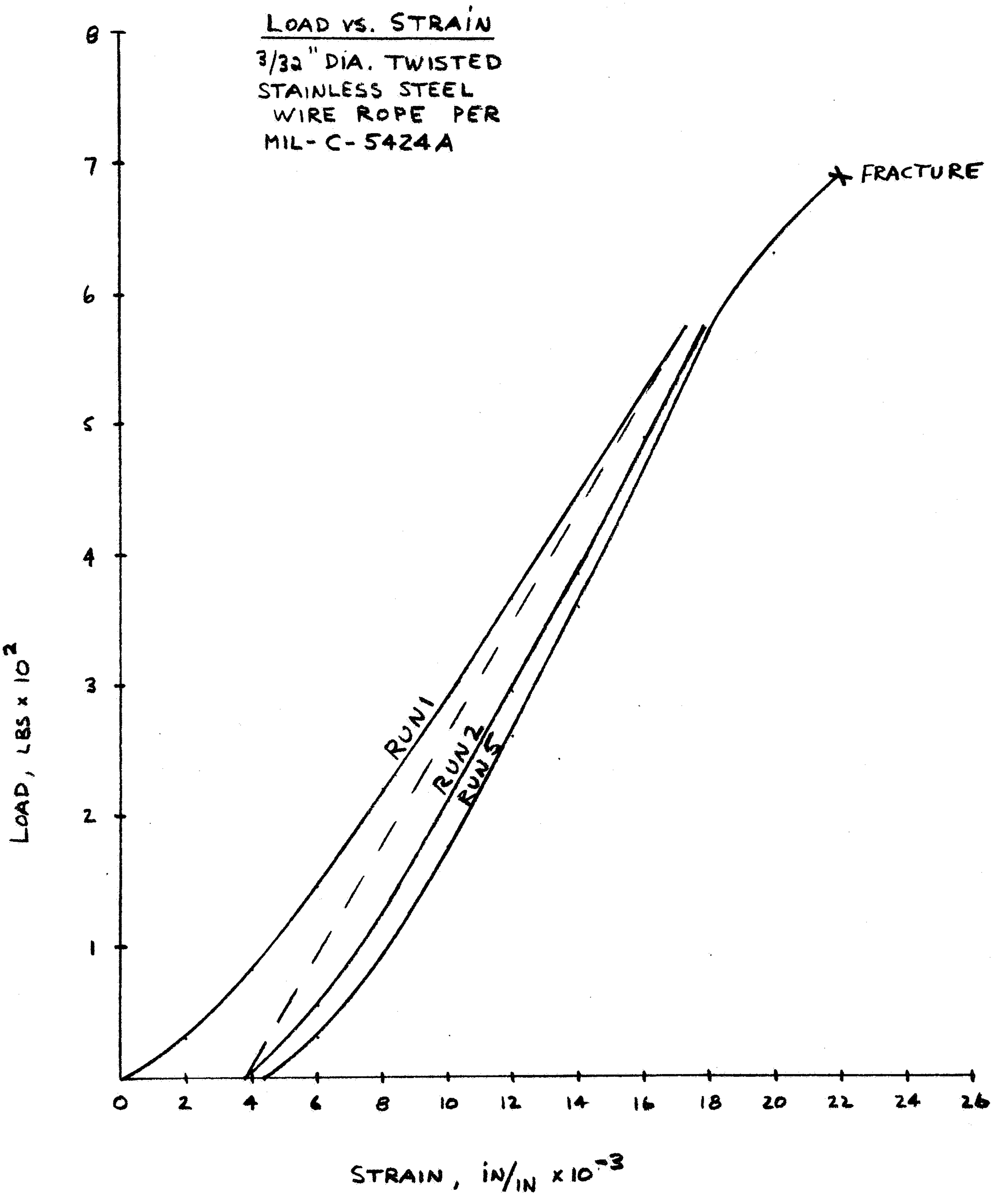


Figure 11. Cable Tension Tests

to permit use by a gloved, pressure suited astronaut, and to permit attachment to the end of the tether section. Figure 12 shows the distal connectors, the upper, right hand, connector shown attached to the tether section and the lower, left hand, connector shown disconnected from the tether section.

Two modifications were made to the "vise grip" pliers, as purchased, to permit ease of operation by a suited, pressurized astronaut. First, the diameter of the knurled adjusting bolt head was increased to 1.25 inch diameter. This enables the astronaut to more readily grasp and turn the bolt to obtain adjustment of the jaw spacing of the pliers. Second, the release toggle on the "vise grip" was lengthened, widened, and angled down to form a spoon shaped end. This enables the astronaut to release the "vise grip" from its locking position in the normal manner by pressing the end of the toggle with thumb or finger pressure.

The tether section is attached to the "vise grip" distal connectors by means of a sleeve, welded to the "vise grip" pliers, an adaptor attached to the end of the tether section, and a "Ball-Lok" detent pin. The adaptor, as shown in figure 10, also forms the termination for the central tensioning cable within the tether. To attach the tether to the distal connector, the adaptor is inserted into a mating hole in the sleeve, and the "Ball-Lok" pin is inserted, pinning the adaptor to the sleeve. Two flats on the cylindrical adaptor key to matching flats in the hole in the sleeve. This automatically lines up the holes in the sleeve and adaptor for insertion of the locking pin.

A double acting type "Ball-Lok" pin was selected in order to prevent accidental disconnection of the tether from the distal connector. To insert or remove this pin, the center button must be pressed down, which releases the two balls at the end of the pin. Thus, merely pulling on the "T" handle, either inadvertently or accidentally, will not release the

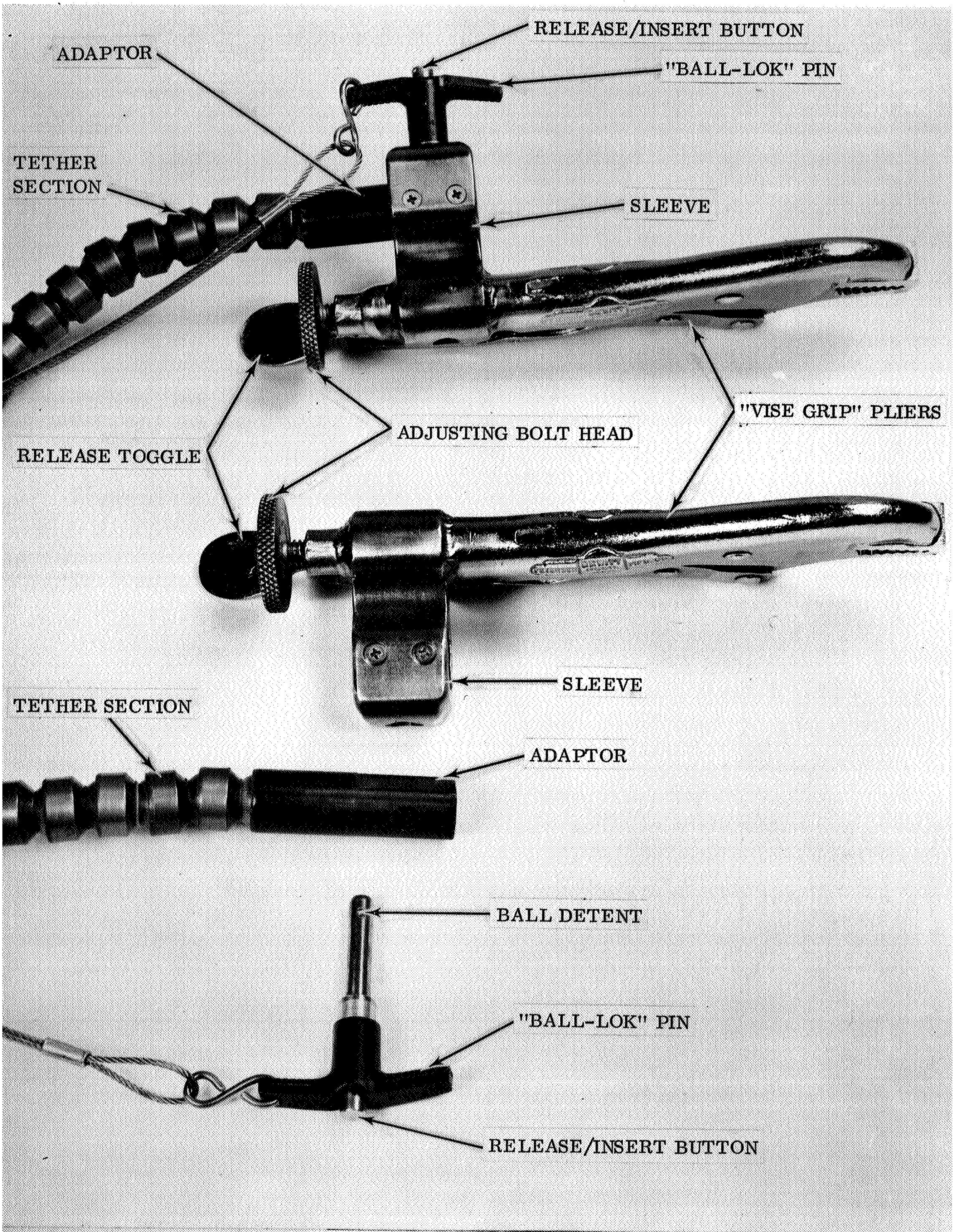


Figure 12. Distal Connectors

pin from the sleeve. The pin is safety wired to the end of the tether section to prevent loss when uncoupled from the distal connector.

FABRICATION, ASSEMBLY, CHECK-OUT

Fabrication and assembly of the component parts of the system was accomplished without the need for the development of new or unique manufacturing methods or processes. Most of the fabrication, and all of the assembly was accomplished under the direct control of the responsible design engineers. Changes and modifications to the engineering drawings of the components were made as required to facilitate either part manufacture, assembly or operation of the system.

Following assembly, the operation of the controller was checked out by utilizing a plexiglass cover to observe the working of the inner gear train components. This resulted in several minor modifications in the release arm and pawl which minimized the force required on the actuation handle to rigidize or release the tether. After these modifications, the controller was assembled and observed to operate satisfactorily.

It was necessary, next, to develop a method to readily determine the cable tension applied by the controller to the tether, in order to adjust the mechanical stop within the controller and prevent overtensioning the cable. This was accomplished by correlating the force applied on the actuation handle with the force applied to the cable. Since the gear ratio within the controller is constant, these forces are directly proportional to each other. One end of a bare cable, i.e., without tether links, was attached to the tensioning mechanism of the controller, and the other end fixed to a dynamometer, as shown in figure 13. The controller housing was clamped to the bench, and cable tension applied by actuating the controller

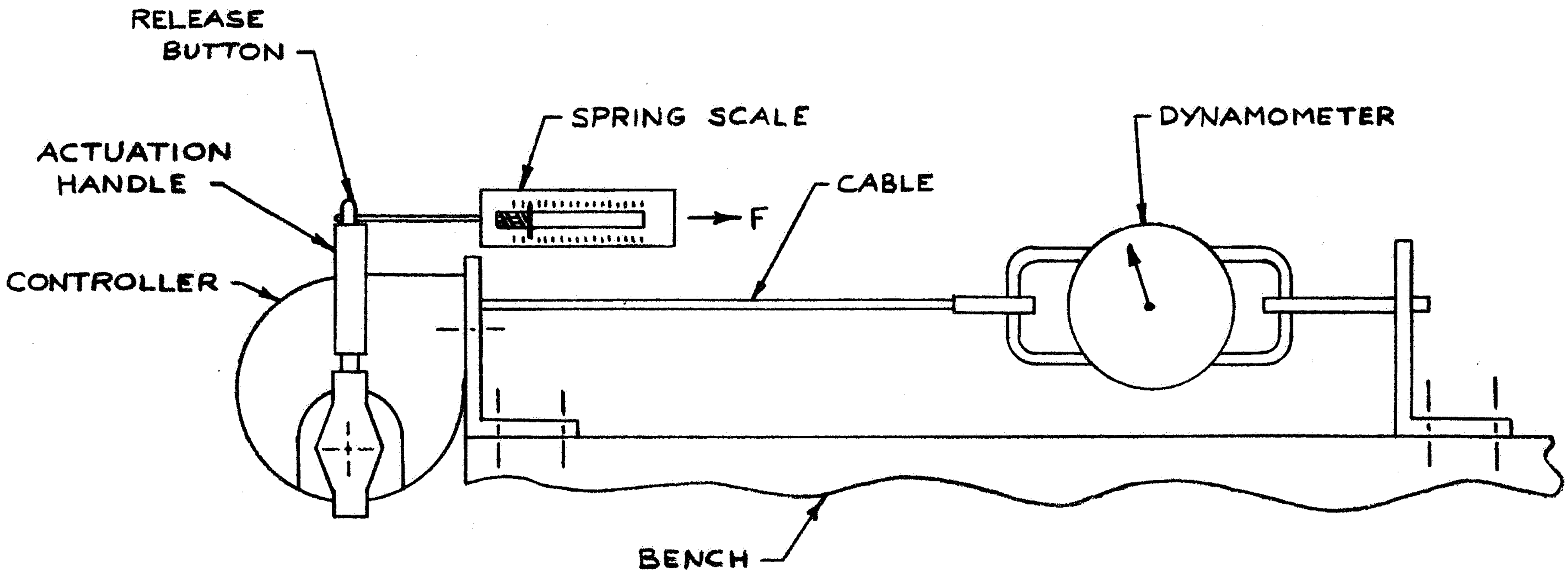


Figure 13. Test Setup: Cable Tension vs Handle Force

handle. Cable tension was read directly off the dynamometer. A spring scale, attached to the actuation arm at the intersection of the handle grip and quick release button, measured force applied to the handle. A force of 17 to 18 lbs. on the handle produced a cable tension of 480 to 520 lbs.

Following this test, the tether section was connected to the controller. The handle was cranked until an actuation force of 17 to 18 lbs. was achieved. The mechanical stop within the controller was adjusted to prevent further rotation of the gear train at this point, thus limiting cable tension to 480 to 520 lbs., maximum.

The moment restraint exhibited by the tethers was also determined. Moment restraint is defined as the maximum moment load that can be resisted by the rigidized tether before slipping or sliding occurs between the ball/socket interfaces. The moment restraint was determined by rigidizing the tether, in a straight line, with the tether section resting on a bench (to eliminate force due to the tether weight) and the controller fixed to the edge of the bench (see figure 14). A force was exerted, by means of a spring scale to the distal end of the tether, until a tether ball/socket interface "broke the rigidity", i.e., rotated. The moment developed in the tether section by this applied load varies from zero at the distal end, to maximum at the controller end (i.e. M = Fd, where M = moment, in-lb, F = force, lb, d = distance, inches). The maximum moment restraint was determined to be between 40 and 60 inch-pounds.

Following check-out, the tether systems were painted and weighed. The controllers with attached tether sections weighed 13.44 lbs. (7.72 lbs., each) and the distal connectors weighed 3.16 lbs. (1.58 lbs., each), for a total

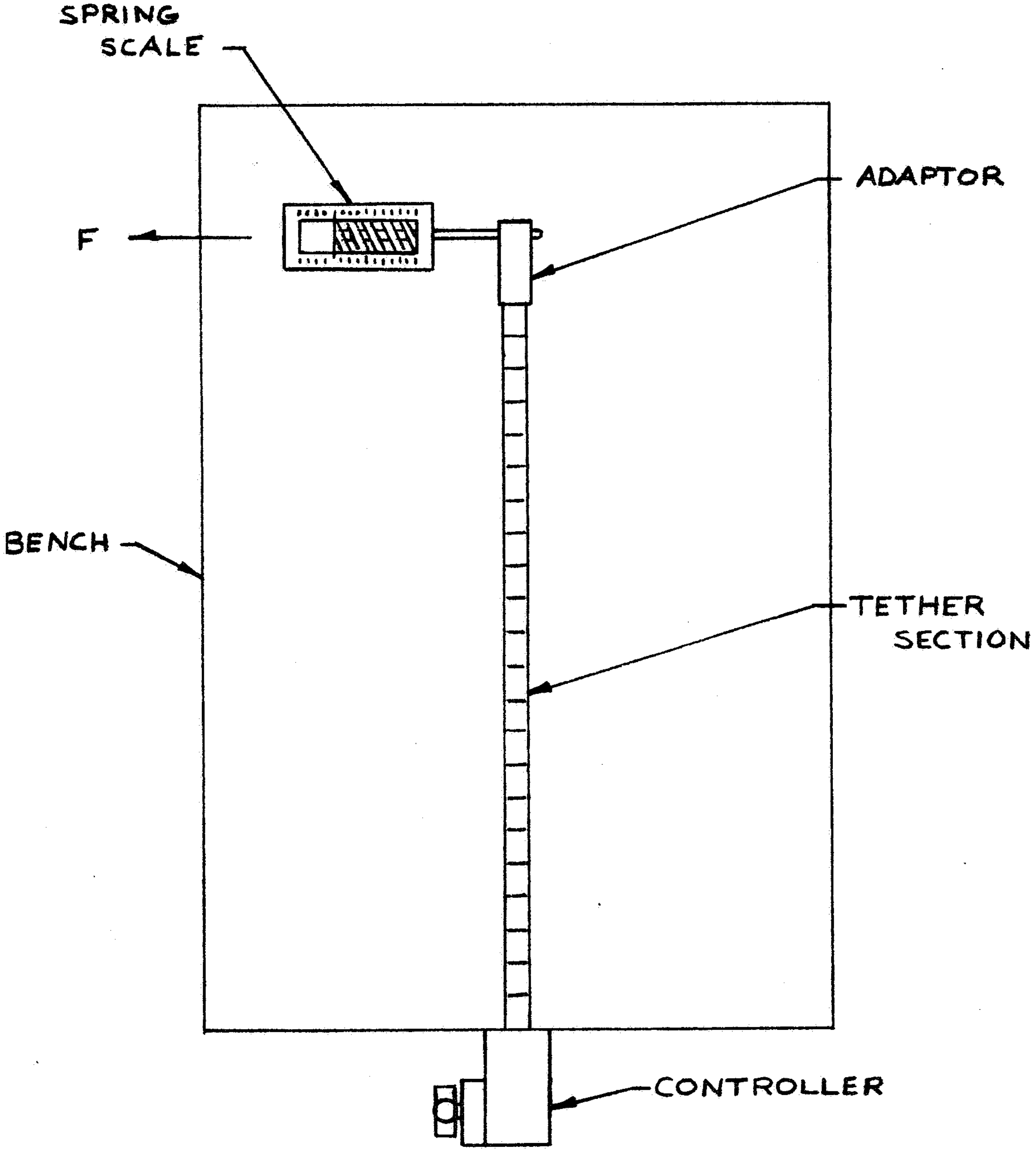


Figure 14. Test Setup: Moment Restraint

weight for both the right and left double hip tether restraint systems of 16.6 lbs.

RESULTS AND CONCLUSIONS

The prototype variable flexibility system described in this report is intended to demonstrate the feasibility, practicability, and performance of this unique astronaut restraint and positioning concept. All of the system design requirements stated at the beginning of this report, and described throughout, were met, with the exception of system weight. The system operated as intended, as demonstrated by the check out tests. No attempt was made, however, to assess the system performance as an astronaut positioning and restraint device. These tests will be carried out by the NASA, by zero-g simulation on the ground, underwater, or in aircraft. The conclusions as to the real value of this system, and recommendations for improvements, will result from these tests.

As stated previously, the system weight goal of 8 lbs. was exceeded by a significant amount. It was not practical, or necessary, within this program to exercise a rigorous weight reduction program since the hardware developed is for prototype, feasibility testing. Significant weight reductions could be attained, however, as routine tasks within a program for the development of a flight optimized system. For example, the "vise grip" distal connectors could be made considerable lighter if they were designed and fabricated from the start instead of purchased "off-the-shelf". The controller, which has the bulk of the system weight, is the prime candidate for weight reduction. Many steel components were required in the gear train to withstand the stress levels developed. A weight reduction program aimed at these components, to either substitute lighter more exotic materials, or simply minimize the bulk of material where stress levels permit by lightening holes, reduced cross sections, cutting corners, etc. would result in significantly lower weight. The controller case itself could be thinned in some sections by machining, chemical milling, lightening holes, etc.

RECOMMENDATIONS

Specific recommendations for improvements in the variable flexibility tether system required to enhance the practicality of or usefulness of the system will result from the future zero-g simulation test program. These tests will realistically exercise and evaluate the tether system as an astronaut EVA restraint and positioning device. The results of these tests will be factored into future designs to provide optimized flight hardware geared to specific programs.

There are two recommendations that can be made at this time, however. The first concerns investigating methods to increase the rigidity, i.e., moment restraint, of the tether without a corresponding increase in the size and weight of the links, or the controller. Such an increase in tether rigidity would have obvious benefits to the restraint system, by allowing the astronaut more freedom to exert significantly higher forces and torques, while still maintaining his position. Previous studies have centered on investigating ball/socket link joint rigidity as a function of compressive load, materials, and configurations. The results show, as expected, that increasing the ball diameter, and/or increasing the cable tension results in increased rigidity. This increased rigidity must be traded off against the increased size and weight of the links, and the penalties of providing a higher cable tension (heavier cable, higher loads on controller, increased gear ratios, etc.). Further studies are required to evaluate link joints other than the ball and socket. Various interlocking configurations are examples of other joint designs that should be considered. Other geometries, such as spherical shaped washers, that have a relatively large spherical radius may also improve rigidity. These analytical and experimental investigations could lead to the development of an improved tether section for the system. In this case, an improved tether section could be designed to be physically interchangeable with the existing tether section thus permitting a direct comparison between the two. The benefits gained by increased tether rigidity could then be evaluated through zero-g simulation testing.

The second recommendation is to consider the development of an electrically actuated controller. In such a system, the drive mechanism utilized to apply tension to the cable would be motor driven. The controller, in effect, would consist of a linear actuator with a manual override for emergency use. Astronaut energy input for operating the system would be minimized, and a significant reduction in the size and weight of the controller would result. Subminiature linear actuators capable of applying a 500 lbs. load typically weight about 3/4 lbs. and have dimensions of 1" x 2" x 4". The batteries could be contained within the controller housing, or the power could be taken from existing power supplies contained within other EVA systems, such as back packs, AMU's, etc. Again, as in the first recommendation, an electrically actuated controller could be developed to be interchangeable with the other existing system components. This would allow a direct comparison of the advantages to be gained from this modification.

REFERENCES

1. Lexan Design Manual, General Electric Co., Chemical Materials Department, Pittsfield, Massachusetts.