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7. METAL WITH A MEMORY PROVIDES USEFUL TOOL FOR SKYLAB ASTRONAUTS

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SUMMARY

In 1970, Skylab planners decided to use extendible booms to convey film cassettes weighing 56.7 kg (125 lb) between the Airlock Module and the Apollo Telescope Mount. This paper describes the boom and its dispensing mechanism, and discusses problems encountered with the mechanism during the test program. These problems were mainly associated with operation in cold temperature, lubrication, and the motor/gearhead assembly. Another set of problems which arose during crew training in the MSFC water tank is also discussed.

Experience from this program leads to the conclusion that attention to detail is the cardinal rule for mechanisms designers. Such things as the correct choice of lubricant, the build up of tolerances, and the affect of differential contraction of metals can make or break a design.

INTRODUCTION

Two film transfer booms were used during six separate EVA's over the almost nine-month Skylab mission. At these times, film for five solar physics experiments was replenished and retrieved from two work stations on the Apollo Telescope Mount (ATM), and the touch of a button sent extendible, stainless steel booms carrying bulky cassettes at 0.15 m/s (6 in/s) across 9.1-m (30-ft) of space. One of the booms also performed an unscheduled task when it helped to salvage the mission by transferring foot restraints, clamps and a sunshade at the time the second protective cover was erected over the crippled spacecraft.

The booms and their dispensing mechanisms remained fixed to the shroud surrounding the Airlock Module (AM) throughout the mission, one boom's line of travel being between the AM and the Center Work Station (CWS), and the other between the AM and the Sun Work Station (SWS). Figure 1 diagrammatically shows the relative positions of the booms and the ATM.

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BOOM DESIGN SPECIFICATION

The specification for the film transfer boom (which included the dispensing mechanism) was detailed and rigorous. Some of the general requirements are shown in Table 1 below:

TABLE 1

FILM TRANSFER BOOM SPECIFICATION

- The total weight of the boom and its dispensing mechanism shall be no greater than 39 kg (185.9 lb).
- The overall size of the boom and mechanism with the boom stowed, shall be no greater than 38 cm x 38 cm x 51 cm (14.9 in x 14.9 in x 20 in).
- The length between the base of the mechanism housing and the tip of the fully extended boom shall be 8.3 m (27.2 ft).
- The mechanism shall be motor driven, from a 26 ± 4 Vdc supply. The maximum power available will be 210 watts at 30 Vdc in a -29°C environment.
- The speed of boom extension and retraction shall not exceed 22.9 cm (8.9 in) per second at 30 Vdc and at a temperature of 71°C, and shall not be less than 7.62 cm (2.9 in) per second at 22 Vdc at a temperature of -29°C.
- At full boom deployment, a limit switch shall deactivate the motor. Similarly, a limit switch shall deactivate the motor at full retraction of the boom.
- The fully extended boom shall not deflect more than seven inches due to the temperature differential created by solar radiation on one side of the boom and shade on the other.
- The fully extended boom shall withstand a bending moment of 238 N -m (2100 in-lb).

In addition, the specification included the following unique requirements:

- It was required that the boom should be easily grasped by a gloved astronaut. (A 5.08-cm (2-in) diameter was regarded as a maximum size to grip.) This requirement also meant that no exposed sharp edges were allowed on the boom for fear of cutting a glove.
- The maximum temperature of the boom due to solar radiation was not to exceed 121°C. This limit was imposed to prevent damaging the astronaut's clothing.

- A 0.99 probability of completing a service life of no less than 200 cycles under any combination of specified environment was required of the boom and its dispensing mechanism.

- In the event of a motor failure, a back-up operational mode was required such that the boom could be extended and retracted by a hand crank. The torque required to operate the crank was to be no greater than 22.6 N-m (200 lb-in.).

- It was a requirement that a pressure-suited astronaut should be able to remove a boom unit from its location outside the Airlock Module and replace it with the spare. This was to be a one-handed operation.

DESIGN DESCRIPTION

Boom

Here was an obvious application for a tubular extendible element (TEE), the principle of which is to heat-treat a thin strip of metal such that it takes a tubular form when it is unrestrained. The technique of storing this type of tube is well known. It is simply opened out flat and rolled round a spool inside a dispensing mechanism.

It quickly became clear that the 238 N-m (2100 in-lb) bending moment requirement was a critical design parameter. Trade-off studies showed that to retract a steel boom thicker than 0.02 cm (0.008 inch) and wrap it flat around a spool required more power than was available, and the size of the dispensing mechanism would exceed the specified envelope. But, if 0.02-cm stainless steel strip was used, a conventional boom with a circular cross section would have too large a diameter for the astronaut to grip.

It was with these requirements in mind that the final boom configuration was designed as shown in Figure 2. This twin-lobe boom with its 5.08-cm (2-in) diameter lobes can be gripped by the astronaut, and the required strength is obtained by nesting two 0.02-cm elements one inside the other. The edges of the outer element that run the length of the boom were rolled inward slightly and dressed with an abrasive to eliminate the risk of cutting or snagging the beta cloth of the astronaut's glove.

Thermal considerations dictated a polished outer surface of the boom to achieve a low emittance (0.13) so that the temperature should be no higher than 121 °C, and a black coating on the inside of the boom to achieve a high emittance (0.86) to keep the thermal gradient as low as possible across the boom and therefore to reduce thermal bending to a minimum.

DISPENSING MECHANISM

Mechanism Design

Figure 3 shows the envelope dimensions of the film transfer boom located in its funnel-shaped adapter that was permanently attached to the airlock shroud. A simplified internal view of the mechanism is shown in Figure 4.

A dc motor provides, through gearing, the necessary torques to extend and retract the boom. In the extend mode, each boom element is unreeled from a separate spool by an identical pinch drive system, which consists of an RTV-coated drive roller and a hard anodized, aluminum backup roller. Each boom element leaves its spool flat and passes round a drive roller where it is pinched between the drive and backup rollers. Both the spool and drive roller are driven, but the backup roller free-wheels.

When the boom is fully retracted, the combined diameter of an element and spool is greater than the diameter of the drive roller. Therefore, at the beginning of boom deployment, the drive roller has a tendency to turn faster than the spool. To prevent this and preclude the drive roller from slipping on the element, the spool is driven through a slip clutch. By this means, the high initial torque placed on the spool by tension in the element overrides the torque setting of the slip clutch, and the angular velocity of the spool approaches that of the drive roller. The slip clutch material, which bears against the stainless steel of the spool drive gear, is a teflon/molybdenum/lead composite which is stable over a wide temperature range.

When the boom elements leave the pinch drive rollers, they immediately start to assume their tubular shape. During the transition phase, when the boom elements are going from the flat to the formed twin-lobe configuration, they are very susceptible to buckling if subjected to a bending load. In this critical phase, they are supported by a fiberglass "shoe" molded to the natural shape of the element during its transition stage. The two elements extend, one on each side of the tapered shoe, and by the time they exit from the mechanism through a delrin collar, they have nested one within the other and are approximately 60% towards the final formed dimensions of the boom. The delrin collar gives external restraint and, together with the shoe, provides adequate support at the root of the fully deployed boom to withstand the 238 N-m (2100 in-lb) bending moment requirement.

To retract the boom, the polarity of the motor is reversed. During boom retraction, the spools are driven through one-way sprague clutches which free-wheel during boom deployment. To ensure a tight wrap on the spool, tension is maintained in the element by a technique similar to that used during boom deployment, only this time the slip clutch is on the drive roller.

The dispensing mechanism is normally driven by the motor. However, the motor can be isolated by operating a lever on the side of the mechanism housing which disengages a crown-toothed clutch in the mechanism's gearbox. The boom can then be extended or retracted using a manual crank handle. This was a contingency mode for operating the boom in case of a motor failure.

Three film transfer booms were located on the Skylab airlock shroud. Two were operated throughout the mission and the third was a spare that was not used. Because the two working units were exactly positioned to line up with their respective work stations, it was necessary to be able to replace either unit in the event of a failure. The specification required this to be a one-handed operation. To accomplish this, a latching handle was provided as shown in Figure 4. The handle can be gripped by one hand and a delrin trigger squeezed against a spring load, thereby lifting long aluminum links attached to the trigger and running down through the handle supports and to the base of the mechanism housing. The lift was transmitted to a horizontal load through a bell-crank, and the horizontal load, which pulled two scissor links whose four extremities were attached to pawls that traveled along slider blocks. The four pawls engaged in cutouts in the adapter funnel that was permanently attached to the shroud. The trigger was locked during launch to prevent the pawls from being dislodged due to vibration.

Motor/Gearhead Design

Power to extend and retract the boom was supplied by a dc motor. To meet the deployment and retraction speeds of the boom, and to produce sufficient torque to wind the boom into the mechanism (the boom has a natural tendency to self-deploy, and therefore the torque and power are higher in the retract mode), it was determined that the motor should deliver a minimum of 8.15 N-m (72 in-lbs.) of torque over a voltage range of 22 to 30 Vdc. In this voltage range, the speed of the motor/gearhead output shaft was required to be between 17,000 and 31,000 rad/s (45 and 82 rpm) for any temperature between -29 and 71 °C. To achieve low output speeds, the motor was geared down through a four-pass planetary gearhead.

The motor/gearhead characteristics shown in Figure 5 indicate how well the assembly met the requirements at room and high temperature. However, at -29 °C the motor did not supply quite enough torque at 17,000 rad/s and 22 Vdc. This affected the speed of boom deployment and retraction, about which more will be said later.

Various studies have been performed on motor brush materials suitable for a space environment, and with some success. But it has been found that these same brushes will not perform well in an earth environment because they are susceptible to oxidation and are hydroscopic. Therefore, dc motors with space-rated brushes fail repeatedly during testing in an earth atmosphere.

Unfortunately, brushes that are normally used for ground applications, lose moisture in space and become abrasive. They then score the armature, and curtail the motor's operating life in a space environment. In the case of Skylab, the motor was required to operate intermittently in space over a period of several months. It was decided therefore, to install space-rated brushes and find a way around the ground testing problem. This was done by sealing the motor in a can. The can was evacuated and back-filled with helium in order that a leak test could be performed after final assembly. The drive from the motor to the output shaft was effected through a nutating metal bellows, as shown in Figure 6.

DESIGN PROBLEMS AND THEIR SOLUTIONS

When first assembled, the qualification unit required the motor to deliver almost 22.6 N-m (200 in-lb) of torque to extend the boom at -29°C. It can be seen from the speed/torque characteristics that the motor/gearhead speed at 22.6 N-m is extremely low. Therefore, the boom deployment rate was lower than required, and the corresponding current of 10 amps at 22 Vdc exceeded the specified power budget. Furthermore, the output shaft and shaft bearings were not designed for this high load and both bearing and shaft failures occurred.

The problem was tackled in two ways; to reduce the loads in the mechanism at cold temperature, and to increase the torque-carrying capability of the motor/gearhead.

In the case of the mechanism, there were three main causes of high loading at -29°C.

a. The delrin collar contracted round the boom at the point of exit from the mechanism housing. This forced the boom elements hard against the shoe and resulted in excessive drag.

b. Considerable stiction forces became apparent in the gearbox at low temperatures. Gear-carrying stainless-steel shafts were supported in side plates which were separated by aluminum stand-offs and the differential contraction of the aluminum and stainless steel resulted in shaft seizure.

c. Increased drag of the slip clutches on the spools and drive roller.

Problems (a) and (b) were readily overcome by increasing the clearance of the delrin collar, and increasing the end-play in the gearbox shafts. Several environmental tests were performed to arrive at the optimum dimensions so that operation at 71°C would not be impaired.

Problem (c) was not so easy to resolve. Belleville washers were used behind the slip clutches to set the clutch torque values, and it was found that the spring force for any given deflection increased significantly at low temperatures. Therefore, a clutch set at room temperature would produce excessive drag at -29°C. To overcome this, the belleville washers were replaced by conical washers made from bimetallic strip, which have a more constant spring characteristic over the temperature range of interest.

The combination of these three fixes reduced the drive torque in the mechanism to 17.5 N-m at -29°C.

With regard to increasing the torque-carrying capability of the motor/gearhead, it was considered impractical to increase the size of the gearhead, for weight and cost reasons, so a closer look was taken at the mechanical design of the gearhead assembly. At high torque, the bearings on the output shaft were marginal, but more seriously, the dry film lubricant used was overstressed and broke down under load. Bearings packed with Braycote 803 grease were substituted. This grease has good outgassing characteristics and a higher load-carrying capacity than the dry film lubricant. One of its main disadvantages, however, is that it becomes too viscous below -29°C for most practical purposes.

With the change in lubricant, a problem in the output shaft itself became apparent. High loads at cold temperature snapped the shaft at its root. A step, designed to position the shaft against a bearing, had been machined at the root of the shaft. A classic stress raiser! The stainless-steel material was optimum, and an increase in shaft diameter would have necessitated a significant redesign. As an alternative solution, the shaft was machined to remove the step and leave as large a radius as possible. The step was replaced by a fitted washer.

As a further precaution, a solid-state circuit breaker was installed in the mechanism which limited the steady-state motor current to 12 amps. The breaker was designed to pass current spikes as high as 25 amps for up to 150 milli-seconds, but would open circuit when more than 12 amps were applied for longer periods. In this way, the torque on the motor output shaft, which is proportional to current, was limited to a safe level. Higher torques, which resulted from transient start-up currents, would not be transferred to the shaft because of the inherent spring-constant of the motor gearhead.

A combination of all of the above modifications produced an entirely reliable mechanism. The start-up torque in the mechanism at -29°C was reduced by approximately 25% and the motor torque-carrying capability was improved. But, more important, if for any reason a high start-up torque was called for, the motor would be shut down before a catastrophic failure occurred.

Other problems encounted during qualification testing centered around the pawls that latched the film transfer boom unit to its funnel-shaped adapter.

During Y-axis random vibration, the pawls intermittently unlatched. The causes of this anomoly were traced to two factors:

a. Flexibility of the linkage connecting the latch handle to the pawls.
b. An adverse tolerance build-up in the latching design.

The linkage was not modified, but a positive lock was designed into the latch handle to prevent the trigger from moving during vibration. In addition, a minimum acceptable engagement of each pawl in the adapter was established, and verified in a vibration retest. This minimum engagement was assured in flight units by following a detailed rigging procedure.

Another problem with the latching also occurred as an outcome of the vibration test. The pawls slide along stainless steel guides as they latch and unlatch, and originally, the guides were dry film lubricated. After vibration, the qualification unit was subjected to a 10-day temperature-humidity test. At the conclusion of the test, the guides were found to be corroded, and the pawls and guides had to be forced apart. It was determined that the guides had suffered surface damage during the 34 GRMS qualification level vibration and corrosion had set in over the damaged areas. Although a very effective lubricant, the process for applying the dry film changes the surface characteristics of steel and destroys its "stainless" qualities. Therefore, if the lubricant is removed, corrosion is likely. This was overcome by making new guides and coating them with 803 Braycote grease.

CREW TRAINING

Crew Extravehicular Activities (EVA's) were practiced in the water tank at the Marshall Space Flight Center, Huntsville. This alone presented a new set of problems, for now space hardware had to be adapted to an underwater environment. Figure 7 shows crew training in progress.

Because the training units had to be identical in external configuration and performance to the flight units, a simplistic approach was taken, namely to remove and/or replace all electrical components and to eliminate potential corrosion mechanisms wherever possible.

In the case of the electrical components, both extend and retract limit switches were permanently removed, and the limits of boom extension and retraction were controlled by hand valves. The electric dc motor was replaced by an air motor. An exhaust manifold was designed around the motor;

and air supply, and return and exhaust lines were routed from an external source.

To counteract the onset of corrosion as much as possible, aluminum parts were hard anodized (on the flight units many aluminum components were iridited to conduct electricity for electro-magnetic considerations). Stainless steel components were passivated. In addition, the one-way sprague clutches on the spools and drive rollers were packed with grease.

Problems occurred immediately when the mechanisms were first tested in a water tank. The RTV-coated drive rollers skidded on the boom elements and boom deployment was erratic. It was found that oil and grease were migrating to the elements from the air supply line, exhaust manifold, and sprague clutches.

Every last drop of oil and grease was removed from the boom and mechanism and tests were performed on an air motor using dry, oil-free air. But the motor, which was a standard off-the-shelf unit, relied on oil in the air supply to lubricate its bearings and the bearing life was severely curtailed as a result. The motor exhaust manifold was sealed and immediately the increased back pressure in the motor reduced efficiency. It was eventually decided to live with some leakage from the motor exhaust, but to limit the oil in the air supply and have spare motors on hand. This together with the following modifications enabled an effective training program to be fulfilled:

- The diameter of the back-up roller was increased and another back-up roller located next to it. Deploying the boom elements was like squeezing clothes through an old-fashioned wringer.

- To compensate for the increased load on the back-up roller, the hard-anodized hollow aluminum roller used in flight units was replaced by a solid shaft made of stainless steel.

- A silastic stripe was painted along the center of each boom element to increase the element's thickness at that point. This compensated for the fact that the boom elements tended to dip in the middle and assume their formed shape even when passing between the drive and back-up rollers.

- One last modification was to provide the drive rollers with "snow-treads". Grooves 3 mm (0.118 in.) wide by 1.5 mm (0.059 in.) deep were ground in the RTV, parallel to the roller axis and spaced 19 mm (0.74803 in.) apart round the circumference.

CONCLUDING REMARKS

It can be concluded that attention to detail is the cardinal rule for mechanisms designers. The boom mechanism design concept was sound from the outset and it was found to be adaptable to such opposite environments as space and water. But it was the seemingly small things that proved to be important--such things as the correct choice of lubricant, the build up of tolerances, and the effect of differential contraction of metals. The design of mechanisms is not for those who lack an eye for detail.

ACKNOWLEDGMENTS

The author wishes to thank the Fairchild team, and in particular James M. Talcott, for their contributions to a successful program. Thanks are also due to MDAC-E for their cooperation in this endeavor.

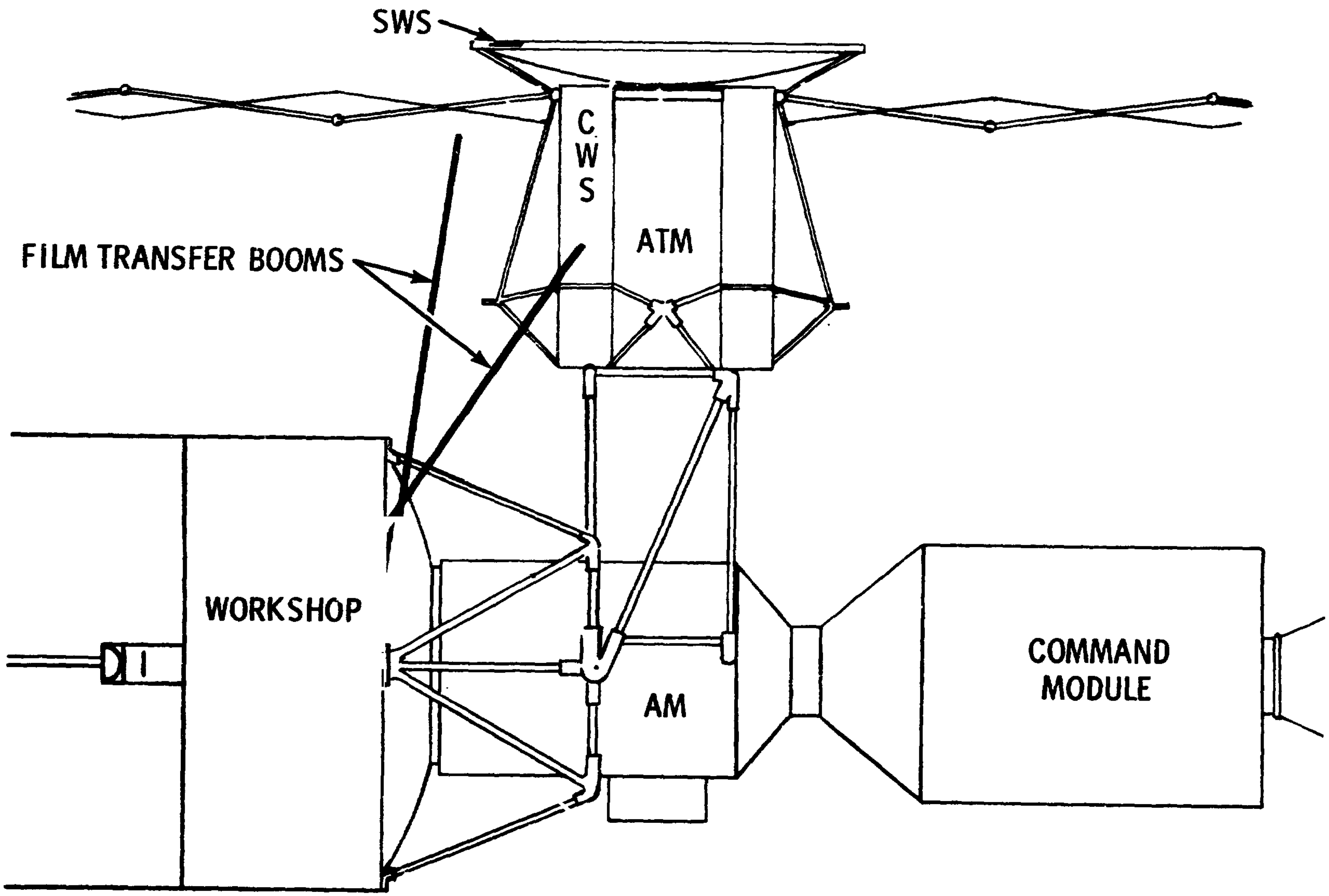
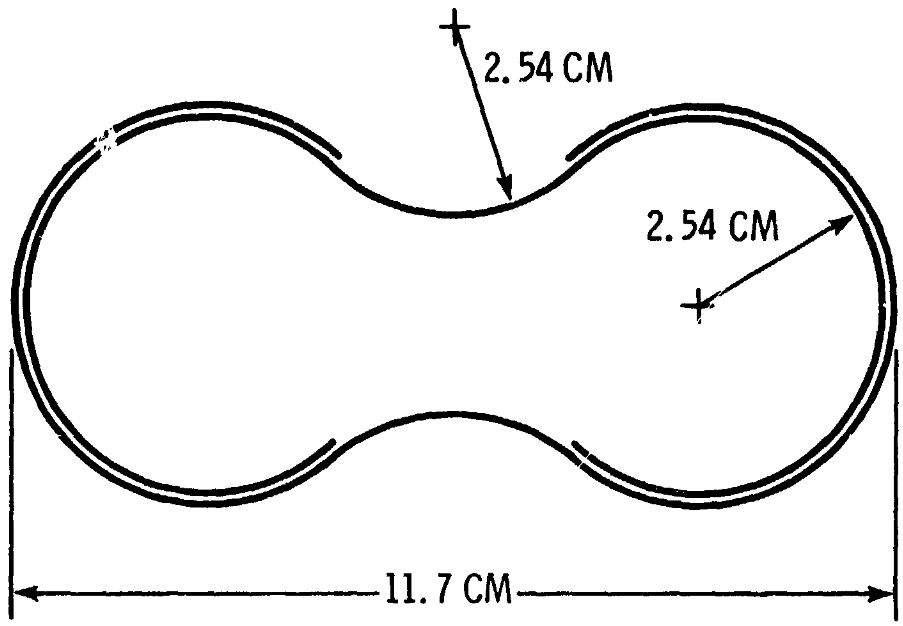


Figure 1. Skylab Orbiting Configuration with Film Transfer Booms Partly Extended



MATERIAL DESCRIPTION

STAINLESS STEEL CARPENTER CUSTOM 455
26.7 CM WIDE X .02 CM THICK

Figure 2. ATM Film Transfer Boom Configuration

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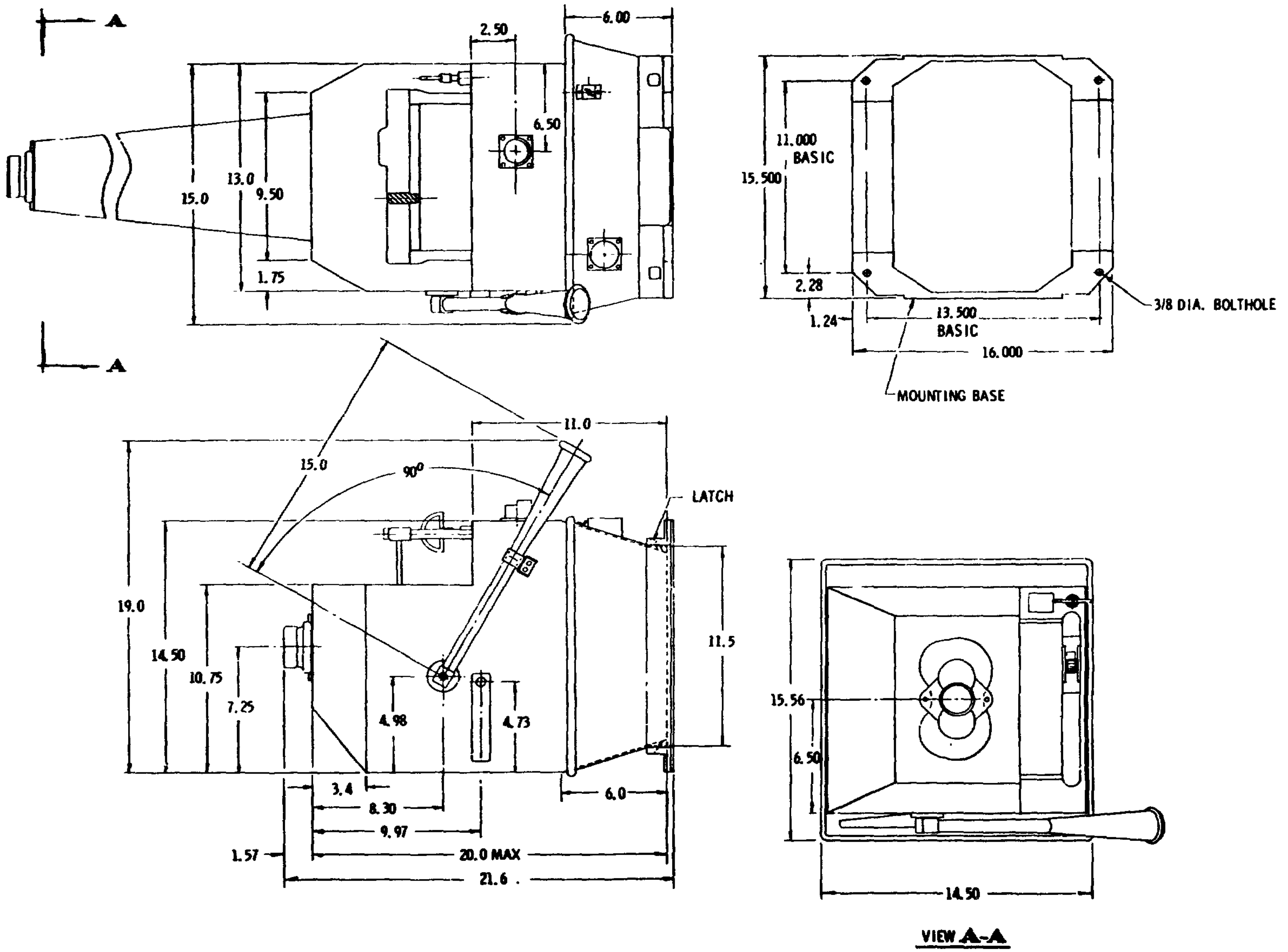

Figure 3. ATM Film Transfer Boom Envelope Dimensions

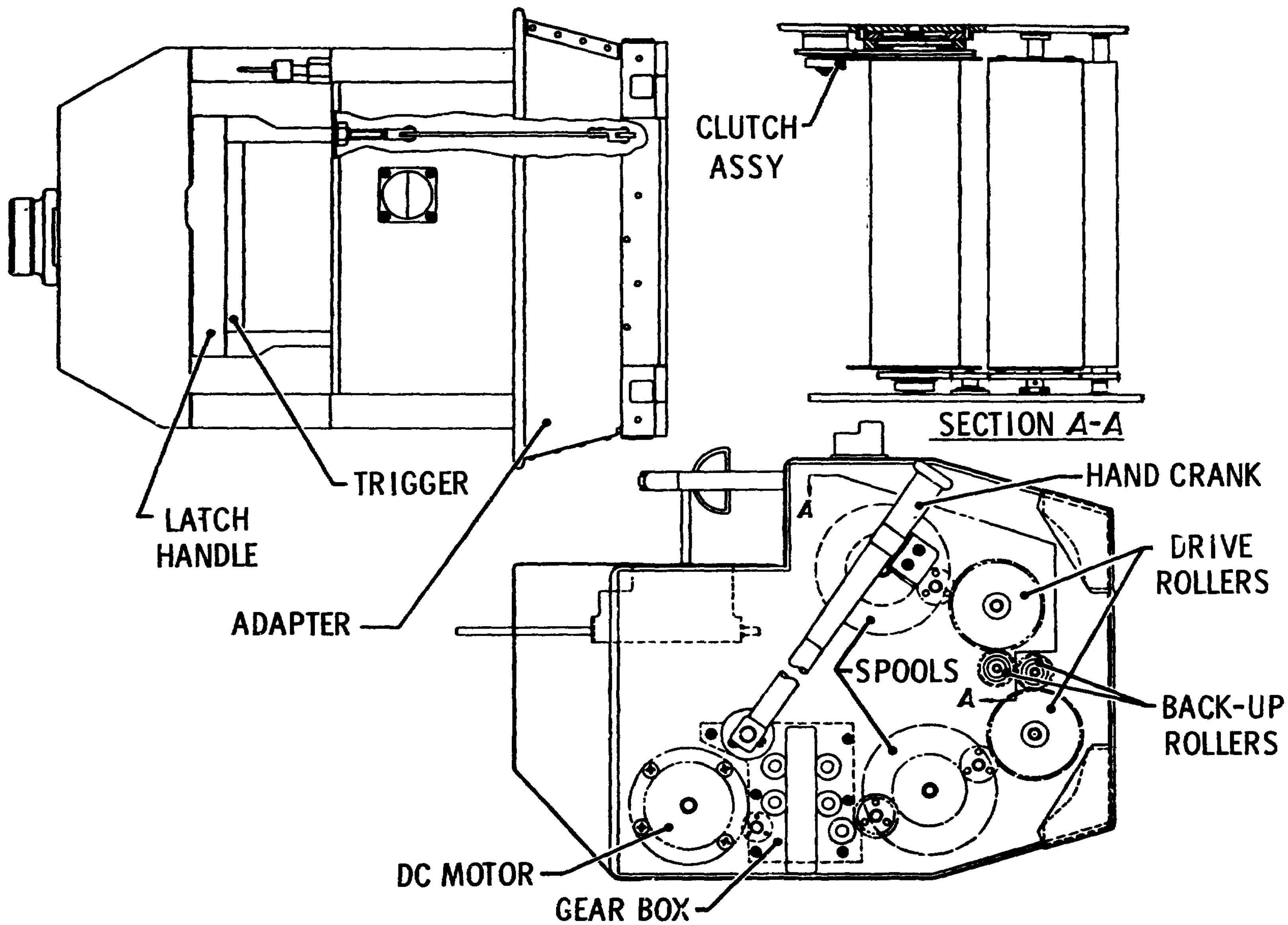

Figure 4. ATM Film Transfer Boom Internal Layout

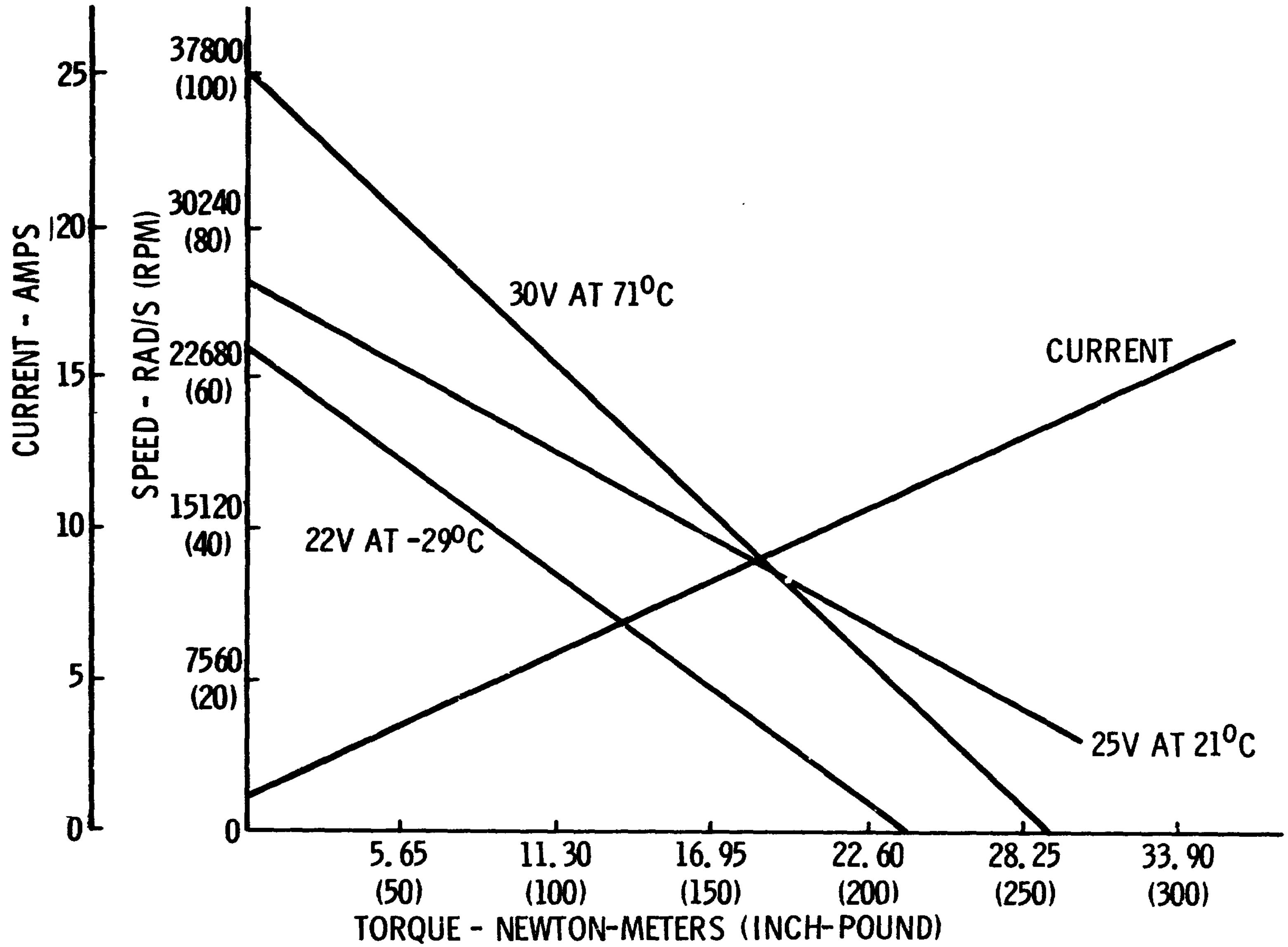

Figure 5. ATM Film Transfer Boom Motor/Gearhead Characteristics

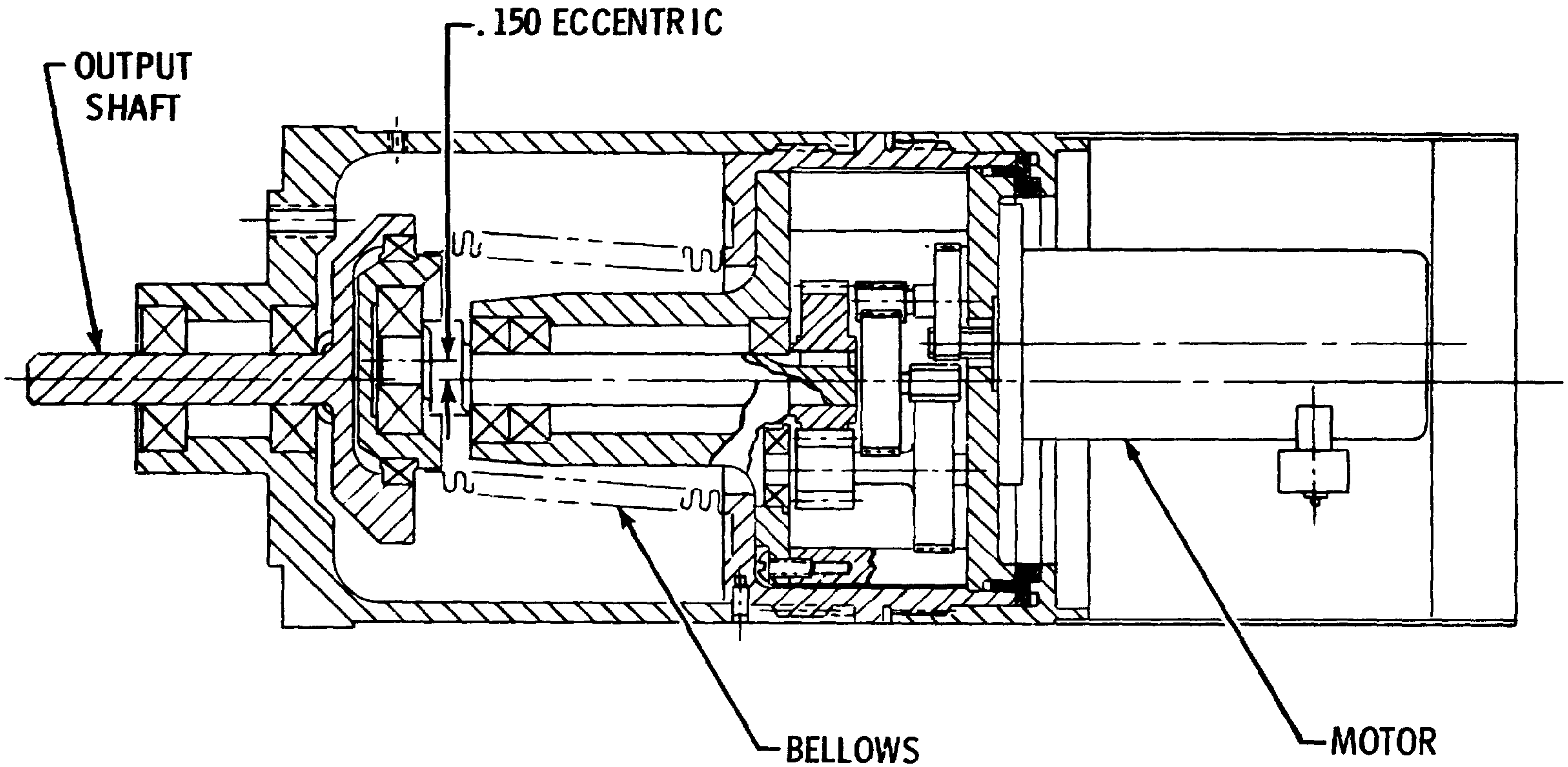

Figure 6. ATM Film Transfer Boom Motor Assembly

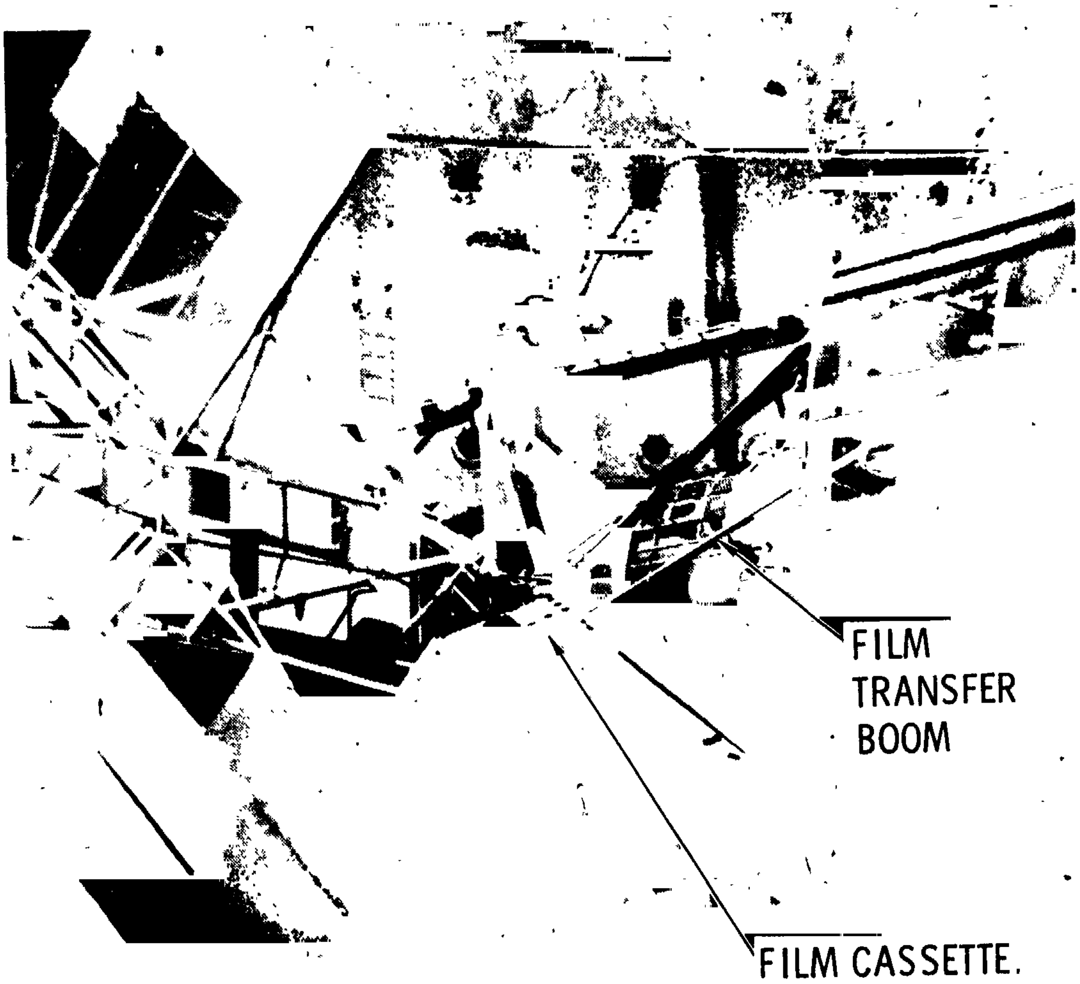

Figure 7. ATM Film Transfer Boom Underwater Testing