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Design, Development and Testing of the X-Ray Timing Explorer High Gain Antenna System

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Abstract

The High Gain Antenna System (HGAS), consisting of two High Gain Antenna Deployment Systems (HGADS) and two Antenna Pointing Systems (APS), is used to position two High Gain Antennas (HGA) on the X-Ray Timing Explorer (XTE). A similar APS will be used on the upcoming Tropical Rainfall Measuring Mission (TRMM). Both XTE and TRMM are NASA in-house satellites. The salient features of the system include the two-axis gimbal and control electronics of the APS and the spring deployment and latch/release mechanisms of the HGADS. This paper describes some of the challenges faced in the design and testing of this system and their resolutions.

Introduction

The XTE spacecraft will be launched late in 1995 on a Delta II expendable rocket. The primary mission objective is the study of broad-band spectral and temporal phenomena associated with stellar and galactic systems. To provide a high scientific data rate communication linkage between the spacecraft, the Telemetry and Data Relay Satellite System (TDRSS), and the Ground Tracking Stations, the spacecraft employs two HGAs. Each HGA is stowed during launch, deploying into its operating configuration after the spacecraft finalizes its orbit. Each HGADS utilizes spring/damper hinges, aluminum booms, and pyrotechnic pin puller release mechanisms to stow and deploy each HGA. The function of the gimbal is to track TDRSS and to transfer 2.287 GHz radio frequency (RF) data across the moving interface, maintaining less than 1.5 dB insertion loss through the gimbal. The Gimbal and Solar Array Electronics (GSACE) provide control, commands and telemetry for the gimbal and the solar array drives.

Antenna Pointing System Description

The two-axis gimbal is shown in Figure 1. Each axis is driven by an actuator having a stepper motor with incremental position sensing and absolute home and endpoint reference sensing. The gear reduction is accomplished using a Silk Hat type harmonic drive, in which the mounting flange flares outward to accommodate a larger center hole for harness feedthrough. The 200:1 drive provides 0.0075 degree output motion per motor step. Each actuator has a minimum of 45 N•m of unpowered holding torque.

To accommodate both the XTE and TRMM missions, the X axis cable/harness wrap, shown in Figure 2, is designed to pass 76 shielded #22 and #24 gauge wires and two 4.88-mm-diameter, low-insertion-loss RF cable assemblies through the rotating interface with minimal stress, wear and torque. The rotation range is ±100.5 degrees and the envelope is 184 mm outer diameter and 62 mm in length. The cable wrap was

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designed to be modular for accommodation of future missions. For XTE and TRMM the harness is divided into 5 bundles each encased in an outer jacket; one motor, two encoder, and two thermal system bundles. Each bundle and RF cable passes through the 25-mm-diameter throughhole and spirals into its own annular compartment, completely separated from the next harness by a 1-mm-thick plate which forms the bottom of the next compartment. At either end of the cable wrap are caps which provide 0.76-mm-wide labyrinth paths to exclude particulate contamination. Each harness bundle or RF cable is held in place by Uralane 5753, potted into grooves at the rotor entrance and housing exit, and moves in a planar spiral between the two grooves. Prior to assembly, each harness and RF cable is wrapped around a 76-mm mandrel and heated overnight to 70° C to pre-form it into a spiral shape. The Y axis cable wrap is similar to the X axis, but passes fewer wires.

The primary function of the GSACE is to position the two HGAs and the two solar array panels. To minimize cost and complexity, the actuators to be driven are almost identical. The XTE spacecraft attitude and orbital position, along with other required orbital data, is supplied to the Attitude Control System (ACS) computer in the Spacecraft Data System (SDS). The ACS computer determines the desired pointing information and provides this input to the GSACE over the 1773 bus. The key components in the fully redundant GSACE are the MIL-STD-1773 interface and the ACTEL gate arrays. The GSACE was designed in modules to facilitate testing of the gimbals and the solar array. As shown in Figure 3, the box contains a 1773 remote terminal module, primary and redundant modules for the solar array drive, and primary and redundant modules for each of the HGAS systems. Each drive module consists of two Printed Circuit (PC) boards, one of which provides two totally independent paths of 24 volt regulation (one for each motor), as well as motor drive electronics (low power MOSFET). The other PC board contains the command decoding, telemetry buffers, position sensing logic, encoder interface, motor sequencer, and housekeeping logic.

High Gain Antenna Deployment System Description

Both HGADS are shown in Figure 4 in their stowed and deployed configurations. The Upper High Gain Antenna Deployment System (UHGADS) consists of a single linkage boom, a spring/damper base hinge assembly, four snubber/kick-off spring assemblies, and two cone and V-guide combinations of release mechanism assemblies. The boom rotates 94.35 degrees about its base hinge during deployment.

The Lower High Gain Antenna Deployment System (LHGADS) consists of a double linkage boom assembly, a spring/damper base hinge assembly, a spring/damper elbow (boom-to-boom) hinge assembly, four snubber/kick-off spring assemblies, and three cone and V-guide combinations of release mechanism assemblies. It also has a cable to synchronize the rotation the of two linkage booms 135 degrees about their hinges during deployment. The cable moves on a pulley built in to the hinge assembly.

The three hinge assemblies on the XTE HGADS are based on the same design principles. The differences are in the interface and deployment rotating angles. Each assembly is powered by a set of five constant spring leaves. Each set generates about 8.5 N•m of torque. To minimize the deployment impact force at the end of boom travel, a viscous rotary damper is used for dynamic damping. Heaters, thermostats, and multiple layer insulation blankets provide each damper with active thermal control. A torsional-spring-loaded latch is employed in each hinge to provide positive mechanical locking in the deployed configuration. The locking latch also provides additional working energy to the assembly during the last five degrees of rotation. Primary and redundant potentiometers coupled to the rotating shaft of each assembly provide deployment telemetry. A cut-away view of an assembly is shown in Figure 5.

The differences between the three release mechanism assemblies are in the interface and number of degrees of freedom. The main components on each are the housing, the tension/release rod with conical end, redundant release jaws, and two pyrotechnic pin pullers. In the restraint configuration during launch, the tension/release rod is held in place by the two jaws, which are in turn held in place by the two pin pullers. In normal operating mode, both pin pullers are actuated by a pair of pyros to release the two jaws, which release the tension/release rod. Once the rods on all release mechanism assemblies are free, the hinge assemblies rotate the booms into their deployed configurations. Mechanical redundancy ensures that the successful actuation of either pin puller will release a jaw and thus the tension/release rod. Each pin puller is powered by a single pyro (pressure cartridge) having double bridgewires for electrical redundancy. A cone and V-guide release mechanism assembly combination is used for each deployment system to minimize the induced launch and thermal loads on the deployment systems. A release mechanism assembly is shown in Figure 6.

The snubber/kick-off spring assembly, shown in Figure 7, provides overall system stiffness at the stowed configuration, as well as extra kick-off energy at the beginning of the deployment process. Each snubber kick-off spring assembly provides approximately 26 N of deployment (kick-off) force. The position of the four snubber kick-off assemblies are selected to provide maximum stiffness of the HGADS.

HGAS Qualification Testing

Qualification testing included pointing, electromagnetic interference and compatibility, vibration, thermal vacuum, deployment, range of motion, and threshold torque.

One of the challenges to the testing program was the development of a gravity (G) negation system which allows economic and efficient deployments of the two HGAS without the costly and time consuming optical alignment operation usually required for each test. The primary function of the HGADS G-Negation System is to null the gravity force on the system during deployment tests. It is comprised of three assemblies; the honeycomb table, the air pad assembly, and the active air piston suspension assembly.

The honeycomb table provides the required flat and level surface for the air pads. Its features include adjustments for local flatness and table height, overall table leveling, light weight, and flexibility of size and configuration. It is also relatively inexpensive to fabricate and assemble. Each table module is made of a 1.2 m x 2.4 m honeycomb panel, a support structure, 15 flatness adjustment mechanisms, and an overall table leveling mechanism. The honeycomb panel is commercial, readily available at various distributors around the country. The table support structure is a welded Aluminum 6061 frame which includes 15 pads with flatness adjustment mechanisms for mounting the honeycomb panel. Each of the four table legs has overall table leveling and height adjustment (both coarse and fine) mechanisms. The total weight of each honeycomb G-negation table assembly module is about 311 N. Multiple honeycomb table modules can easily be joined in various configurations to meet the demand of the complex test configurations of other spacecraft deployable systems.

The main function of the air pad (or air bearing) assembly is to provide the necessary lift to minimize travel friction for the deployment systems. Air pad assemblies are very compact and light weight, have high but efficient lift, and are self aligning. Each air pad is about 76 mm in diameter and has a center air feed through a custom-made spherical bearing which provides self alignment. The air-pad surface is coated with a layer of dry lubrication. An extensive development program optimized the air pad size, weight, lift, and air flow efficiency. Multiple air bearings can be combined to provide greater lift for supporting the deployment tests of larger or heavier deployable systems.

The active air piston suspension system provides a constant negative gravity force and actively compensates for high and low points on the surface of the G-negation table. Previous air pad G-negation systems required a critical optical alignment operation for each test set up to ensure that the deployment system is precisely parallel to the surface of the table throughout the deployment path. The active air piston suspension system was designed to relax the parallelism requirement (tolerates up to 6.35 mm), eliminating the need for alignment for each test set up. A simple mechanical air flow closed-loop feed back system is used. The system has a built-in load cell and can be easily adjusted to compensate for gravity for various deployable system weights. Figure 8 shows an active suspension air pad assembly.

.The active suspension air pad, the flexible and light weight honeycomb table, and the overall design of this G-Negation system have enabled the economic and efficient performance of the qualification and acceptance testing program on the HGADS.

Actuator Life Testing

The original actuator included a Silk Hat type harmonic drive comprised of a 304L stainless steel (SS) flex spline, 17-4 PH SS circular spline, and 440C CRES wave generator bearing. Based on successful heritage using Pennzane 2000X oil with 7% lead napthenate by weight on harmonic drives using these materials, this same oil/additive combination was chosen to lubricate the gear mesh, the flexspline bore, and all of the bearings and phenolic retainers. As most of the previous data had been accumulated on Cup-type harmonic drives, a life test of an actuator was performed. The results of this life test demonstrate the value of early life testing of mechanisms at the component level. It is fortunate that a life test was performed in time enough to recover with minimal impact to the overall program schedule.

The qualification actuator underwent all required environmental testing. It then accumulated 1,250,000 degrees of output travel, 1.25 times the expected XTE mission life. The stepping pattern simulated operation: a tracking motion of 0.0026 $^{rad}/_{s}$ was swept ±10 degrees 13 times followed by a slew at the maximum speed of 0.026 $^{rad}/_{s}$ to both ends of travel. The thermal vacuum chamber was cycled every 3 to 4 days between 0°C and 40°C. The actuator passed all post-life test functional tests, including threshold voltage. Upon disassembly of the unit, a large number of metal particles were found in the flexspline bore and teeth, as well as particles that migrated elsewhere. There were two heavily gouged lines in the flexspline bore where it contacts the wave generator bearing outer diameter. The lines ran the entire circumference of the bore, located approximately at the bearing corners (Figure 9). Except for some darkened lubricant in the gouge marks, the rest of the bore surface looked dry. The bearings had no visible particles inside and their lubricant looked good: all surfaces were wet and undarkened with a good meniscus at the contact. It was also noticed that the wave generator bearing had moved approximately 2.5 mm axially inward, drawn toward the diaphragm end of the flexspline. The gear teeth also showed excessive wear. The most severe wear was near the location of the wave generator bearing outer corner (nearest the gear end of the flexspline), where the teeth were only about half their original thickness. The wear grew progressively less in both axial directions. The teeth were wet with lubricant, but some of it was darkened.

A detailed investigation determined this information:

1. The Cup type harmonic drive which spawned most of the heritage assumptions had a flexspline made of drawn 304L SS tubing already half hardened through cold working (no longer available). The still relatively soft 304L flexspline was further hardened using proprietary processes that did not significantly affect the dimensions. This process is not available to the manufacturer of the Silk Hat type harmonic drive. Consequently, the flexsplines used were very soft for a gear application using space lubricants.

2. The wear mark for a Cup type harmonic drive is generally a single wear path near the edge of the splines, a faint mark where run-in occurs and a deeper mark further in where operation occurs. None of the experienced harmonic drive consultants had ever seen a two path wear mark such as had occurred. Later tests using different materials showed the same two path pattern. The phenomenon is not completely understood.

3. The 440C wave generator bearing had many inclusions on the outer diameter surface and the corners were chamfered instead of rounded.

4. A torsional stiffness greater than 13558 $^{N \cdot m}/_{rad}$ (120,000 $^{in \cdot lb}/_{rad}$) was originally requested. The qualification actuator stiffness was 28246 $^{N \cdot m}/_{rad}$ (250,000 $^{in \cdot lb}/_{rad}$). This higher stiffness may be a life limiting factor. It was determined that stiffness could be as low as 9039 $^{N \cdot m}/_{rad}$ (80,000 $^{in \cdot lb}/_{rad}$) and maintain acceptable performance.

5. The Cup type harmonic drive has a shoulder to limit the axial motion of the wave generator bearing. The original Silk Hat design had no such shoulder.

It was decided to pursue two parallel paths. The first was to test a redesigned Silk Hat drive and the second to test a T-Cup type harmonic drive design, similar to the Cup design except that the output flange first turns inward and then flares outward to accommodate a larger throughhole. Included in each specification was a one hour each direction run-in at 178 $^{rad}/_{s}$ in transmission fluid. The parameters of each design are:

Redesigned Silk Hat

- 4340 vacuum melt flex spline, Rockwell hardness between 34 and 38.
- 17-4 PH SS circular spline, Rockwell hardness between 28 and 32.
- 52100 steel wave generator bearings, outer diameter Rockwell hardness of 57 to 60.
- 13558 $^{N\bullet m}/_{rad}$ (120,000 $^{in\bullet lb}/_{rad}$) ±30% stiffness, agreement to work to low end.
- Addition of a shoulder at the wave generator inner race to limit axial motion.
- Could not get rounded corners on wave generator bearings - straight chamfers.

T-Cup

- 15-5PH SS flex spline.
- 15-5PH SS circular spline, melonited for additional hardness.
- 440C CEVM SS wave generator bearings, with radius.
- Desired low stiffness, but could not get tight tolerance; stiffness ranged from 15818 to 39544 $^{N\bullet m}/_{rad}$ (140,000 to 350,000 $^{in\bullet lb}/_{rad}$).
- Bearing shoulder.

The lower stiffness harmonic drives of both the redesigned Silk Hat and the T-Cup showed some evidence of a small varying amount of backlash as received. In the present case the amount was acceptable for the program requirements.

The two designs were first tested against each other at ambient pressure and temperature with a reversing load, ±20 degrees travel at 0.026 $^{rad}/_{s}$ over a total of 500,000 output degrees. At this point in time, production of a grease version of the Pennzane, Rheolube 2000, had matured. Based on previous experience with harmonic drives and other lubricants, it was decided that the grease version might be more successful than oil at the flexspline bore and gear mesh. Therefore, Rheolube 2000 with 3% lead napthenate by weight was used in the gear mesh and on the flexspline bore and wave generator outer diameter. The bearing internal lubrication scheme remained unchanged. The redesigned Silk Hat tested had a stiffness of 11298 $^{N\bullet m}/_{rad}$ (100,000 $^{in\bullet lb}/_{rad}$). After the test, its mesh looked good with plenty of grease evident, but the grease on the bore had disappeared. The surface felt somewhat oily but no film was evident. Other than the lack of oil, the bore looked fine. There was a two band pattern but it was a very light burnish (like a run-in mark), and there was no darkened oil. The first T-Cup design tested was one of very high stiffness, 39770 $^{N\bullet m}/_{rad}$ (352,000 $^{in\bullet lb}/_{rad}$). After 500,000 output degrees, the lubrication in the flexspline bore was extremely dark brown and analysis showed the presence in the oil of many 0.127 micrometer (5 micron) flat particles of 15-5PH SS. The grease at the ends of the teeth was darkened but was normal within the mesh.

Based on the poor performance of 100% grease at the flexspline bore (disappearance of grease on the Silk Hat and severe darkening on the T-Cup), the lubrication at the bore was changed to a 50/50 grease/oil slurry with a grease dam outside the contact area. The gear mesh was lubricated with 100% grease. The redesigned Silk Hat was relubricated and accumulated a subsequent 1 million output degrees. The bore and bearing outer diameter came out looking nicely wet with only slightly darkened oil (as the test was done in atmosphere, depletion of antioxidants may have caused the darkening). The gear mesh had an ample supply of grease of a good oily texture and there was no visible wear on the teeth. The lubricant was slightly darker at the teeth edges than in the mesh. The two band burnish marks had become slightly more prominent, but there was no serious wear. A lower stiffness T-Cup, 17626 $^{N\bullet m}/_{rad}$ (156,000 $^{in\bullet lb}/_{rad}$), was also tested with a 50/50 slurry at the bore. After 1 million output degrees, the lubricant in the bore was slightly darkened but oily in texture. The mesh lubricant was also slightly darkened but oily, being somewhat darker at the edges of the teeth. There was no evidence of tooth wear. This harmonic drive also had a two band burnish pattern corresponding to the wave generator bearing corners, but the marks were extremely light and the original machine finish was still evident.

The decision to use the redesigned Silk Hat drive was based partly on the ease of retrofit and partly due to the difficulty of manufacturing low stiffness T-Cups. The final design implemented a 50/50 grease/oil slurry at the flexspline bore and all grease in the gear mesh. The qualification actuator was rebuilt using the same Silk Hat used in the ambient testing (relubricated) and this actuator was put through the original thermal vacuum life test. The gear mesh and the grease looked very good. The grease was oily in texture and only very slightly darkened. The bore had a nice oily film which was also nearly its original color. There was no evidence of a change in the two banded burnish marks. The unit was relubricated and closed up in order to accumulate the required travel for TRMM. It has presently accumulated 7 million output degrees out of the required 10 million with an inertial load in an argon purge at room temperature.

Radio Frequency (RF) Cable Wrap Life Testing

From the start there was a concern about the flexing of the RF cable assembly. To maintain the low loss performance of the assembly the manufacturer recommends that the bend radius be kept to greater than 25 mm for any flexing portion. In order to meet the range of travel and outer diameter requirements, the largest minimum bend radius possible is 38 mm. An extensive life test program was started to investigate the effect of this type of flexing. A cable was mechanically flexed for 80,000 cycles, a cycle being a sweep to both ends of travel and back (±100.5 degrees), at least four times the maximum life requirement of XTE or TRMM. The test fixture is shown in Figure 10. The test was run at ambient for the first 1000 cycles, 60° C for the next 24,000 cycles, and -10° C for the final 55,000 cycles.

Before and after cycling, the RF cable was subjected to visual (magnification X10) and X-Ray inspection, and insertion loss, voltage standing wave ratio (VSWR), time domain reflectometry (TDR), and DC resistance testing. The insertion loss, VSWR, and TDR tests characterize the cable's performance as well as the integrity of its shielding. A 50-ohm load placed at one end of the cable measured VSWR periodically during the test as well. There was no significant change in VSWR over the 80,000 cycle test or in the pre and post insertion loss, VSWR, TDR, and DC resistance measurements.

The most interesting results were seen in the X-Ray inspection. Figure 11 shows a section of cable under X-Ray prior to cycling. The shielding is wrapped helix fashion such that every inch of cable is covered with 2 to 3 layers of silver plated copper foil, which appears in the X-Rays as a very thin helical line as marked by the arrow. When a portion of the shielding begins to spread apart, the X-Ray shows it as a broader helical line. Figure 12 shows a portion of cable after 80,000 cycles. The arrow shows the location of the tightest bend radius. The cable to the left of the arrow was not bent as tightly. It can be seen that at the tight radius position the shielding wrap has begun to spread apart. The level of shielding at this point was still one to two layers at all places, which is enough to maintain the cable performance. No evidence was found of center conductor migration or crinkling.

Visually, the only evidence of some degradation in the cable was the appearance of some small dark spots between the weave of the outer mechanical braid. This also appears mainly in the areas of tightest flexing and is believed to be wear debris buildup from either the mechanical braid or the shield. There was also some wear debris of the outer Teflon jacket that came from the cable rubbing both against the flat fixture surface and against itself. The amount of debris was not excessive and was deemed acceptable. The outer jacket was not worn through in any location, nor was there any evidence of dents, kinks, or bent pins.

A subsequent test to 40,000 mechanical cycles was done on one RF cable in flight-like hardware, followed by a 40,000 cycle test of two RF cables and all of the harness bundles in flight-like hardware. The temperature was continuously cycled between 60°C and -10°C, soaking for one hour at each temperature. Approximately 70 thermal cycles were accumulated. The results were similar to the above except that there was less broadening of the helix pattern under X-Ray and less debris generated.

Harness Wrap Life Testing

To satisfy the size and motion requirements, the harness bundles had to be less than 8 mm in diameter. They also needed an outer covering which would remain flexible over the temperature and motion range. Three tests were run to determine a suitable candidate for Life Testing, using the same fixture as for the initial RF cable test. The temperature was cycled between -10°C and 60°C and the pressure was ambient.

The first test used a netting type material called EXPANDO to jacket a bundle of twisted shielded pairs. At 20,000 cycles, tears had developed in the jacket, and at 27,500 cycles torn fragments of the weave were interfering with other layers of the spiral. The test was stopped. The second test case was a Viton heat shrink tubing over the bundle. The harness rotation at room temperature looked smooth. At cold and hot temperatures however the harness experienced continual hangups which stalled the 50 N•mm stepper motor. At the cold temperature, the harness spiral shrunk inward against the rotor piece, causing an inward force which increased torque as the motor tried to pull away from the tightest position. At the hot temperature, the spiral expanded against the outer wall, causing an outward force which increased torque as the spiral neared its fully unwrapped position. The test was discontinued at 13500 cycles.

The primary candidate had four shielded, polytetrafloroethylene (PTFE) covered bundles surrounded by an outer PTFE jacket. The harness reached 80,000 cycles without incident and periodic visual checks showed the behavior of the harness to be well defined and smooth. There was no significant change in maximum torque over cycling. The torque ranged from 16 N•mm to 24 N•mm over the temperature range before and after the 80,000 cycles. There was some PTFE debris, but at an acceptable level. The outer jacket had developed two very small holes and had a few flattened spots. Inspection showed no penetration of the inner PTFE jackets. There was no change in electrical performance, which included milliohm resistance and dielectric withstanding voltage.

The performance of the PTFE jacketed harness was deemed acceptable for the XTE/TRMM life and it was chosen for flight. Five harness and two RF cables were next cycled in flight-like hardware to 40,000 mechanical and 70 thermal cycles (Figure 13). Post test inspection found no degradation of electrical performance or holes in the outer jackets. Some PTFE debris was evident but minimal.

Gimbal Life Testing

A life test of a fully functional flight-like gimbal with equivalent inertia load is presently underway. The test is being conducted under vacuum conditions and the gimbal temperature is cycled between 5°C and 37°C. The X axis only is being rotated in a pattern representative of on orbit operation. The life test will be stopped periodically to do threshold and pull-in rate testing. After the accumulation of the XTE life, the X axis actuator will be removed and partially disassembled to ascertain the health of the unit. It will then be reassembled and continue until the TRMM life has been accumulated.

Conclusion

Testing is the key in every mechanism. Early Life Testing of mechanical components can uncover unforeseen problems while there is still flexibility for change. Keeping testing in mind during the design is also important. The GSACE modular design made the HGAS testing very time and cost efficient. Thorough and timely test planning can reduce overall schedule, as is shown in the case of the HGADS G-Negation system.

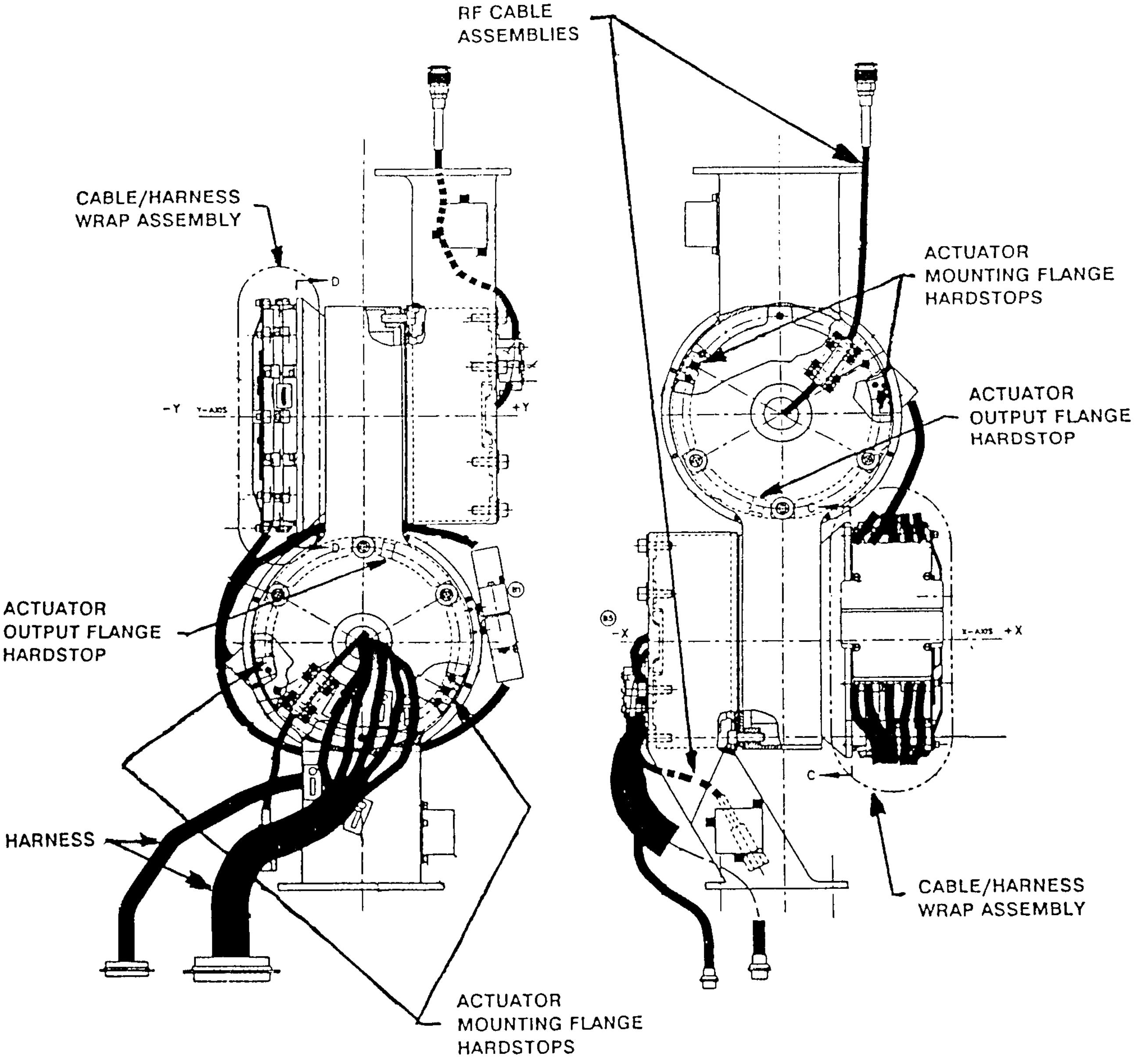


Figure 1. Two Axis Gimbal - XTE Configuration

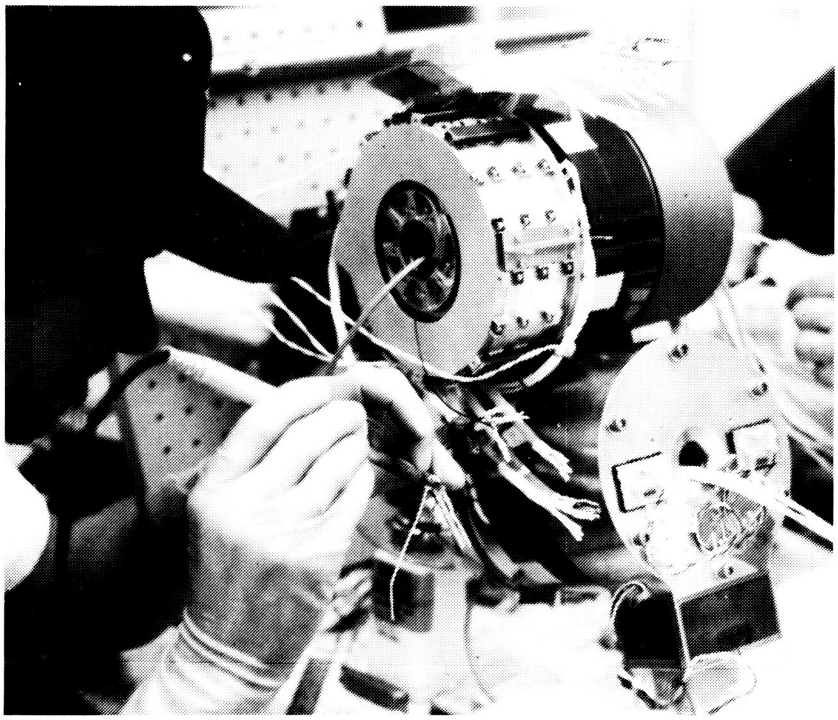


Figure 2. Gimbal Cable/Harness Wrap Assembly

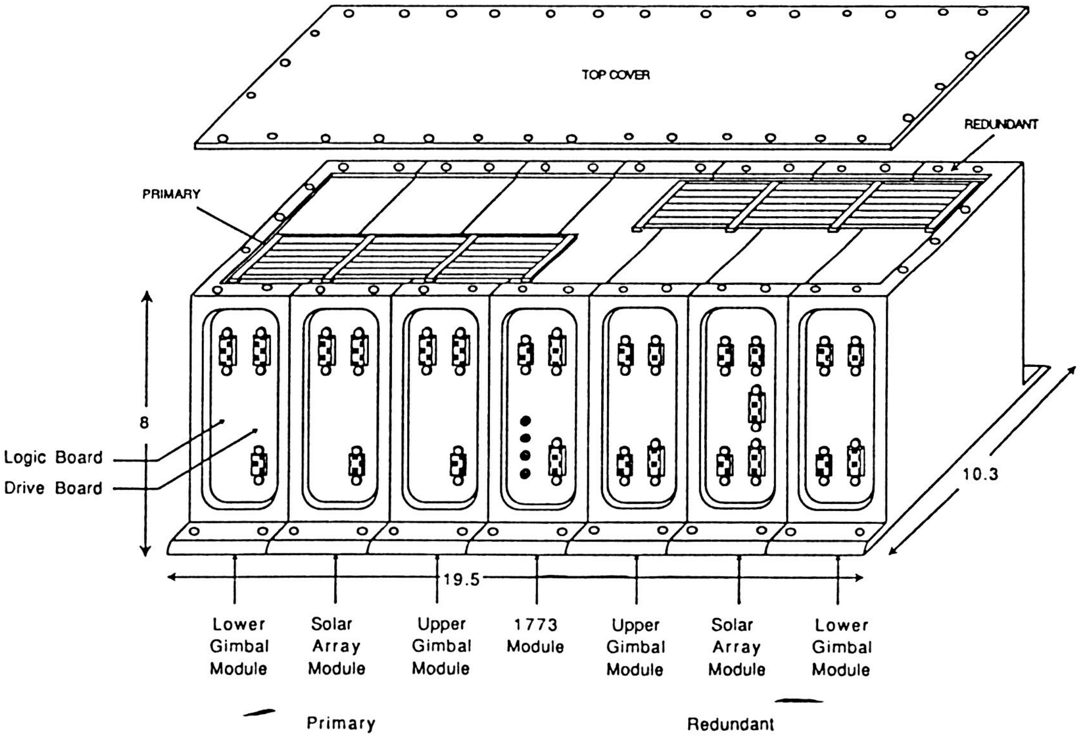
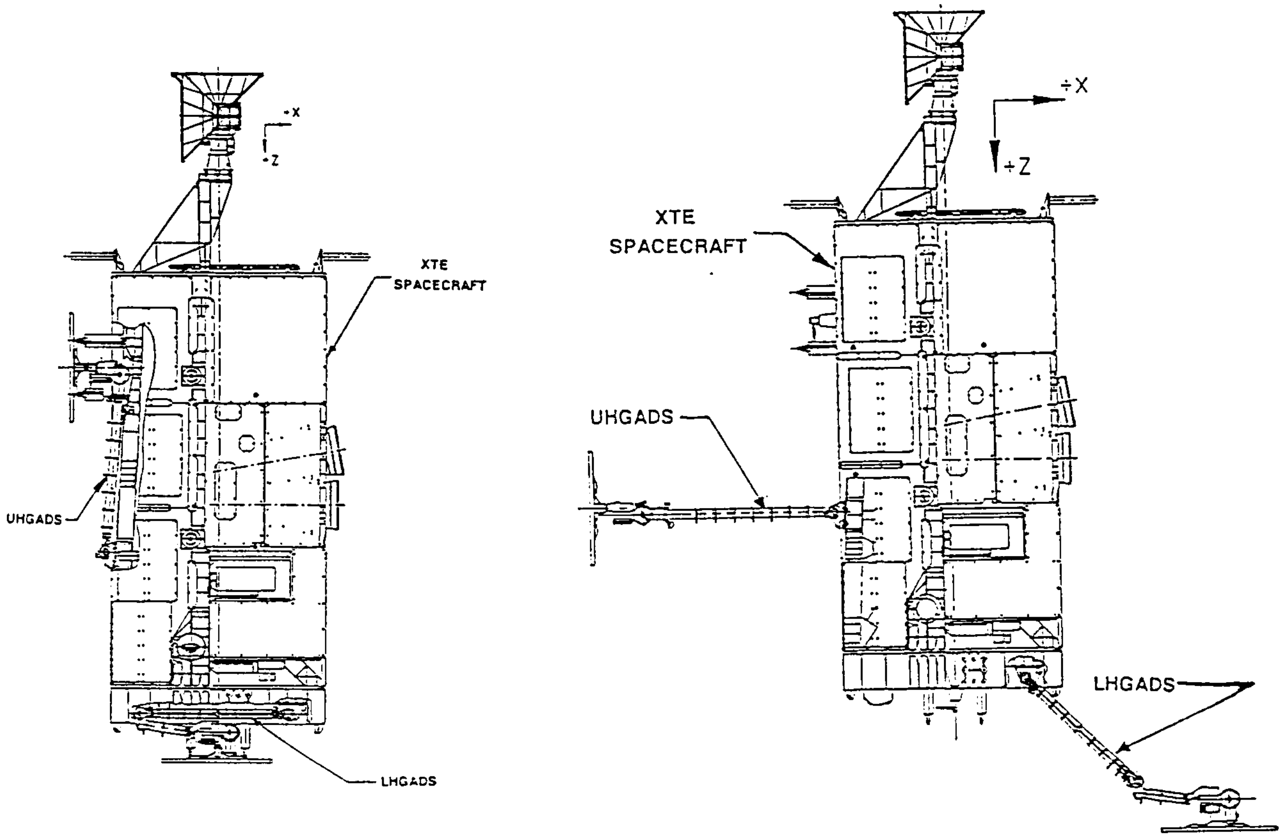


Figure 3. GSACE Electronics Box



HGAS at Stowed Configuration

HGAS at Deployed Configuration

Figure 4. XTE Spacecraft

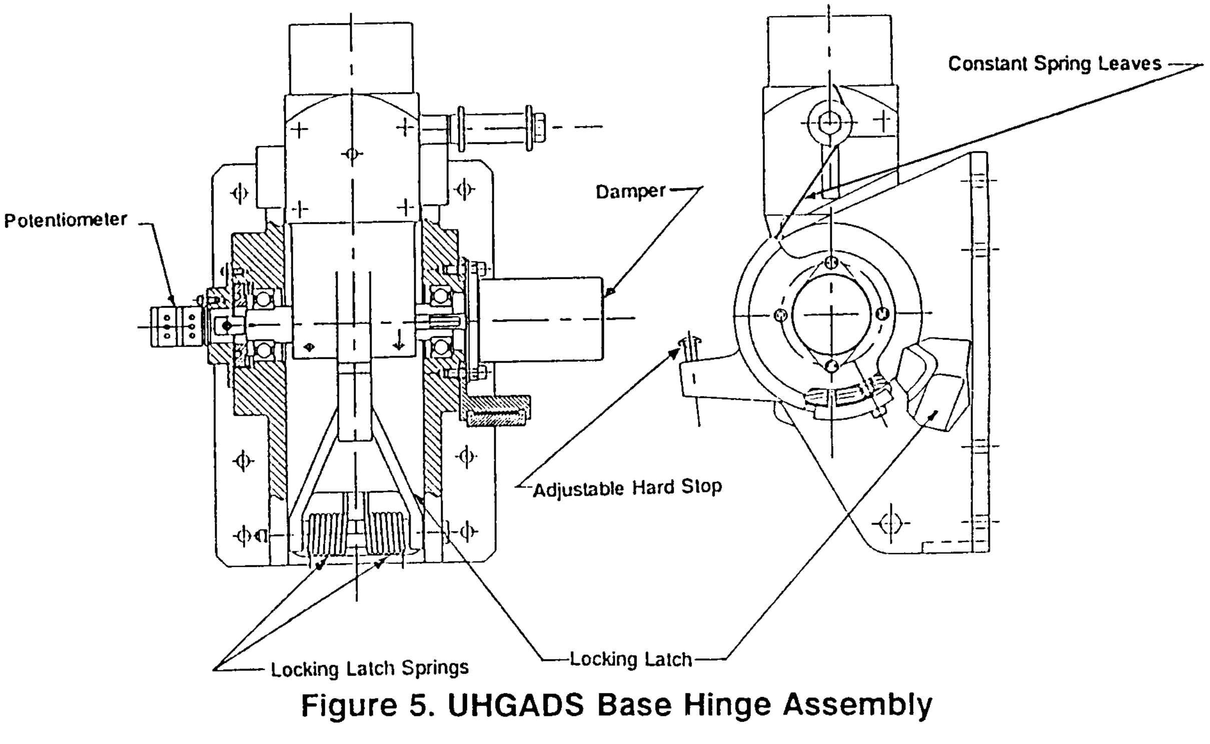


Figure 5. UHGADS Base Hinge Assembly

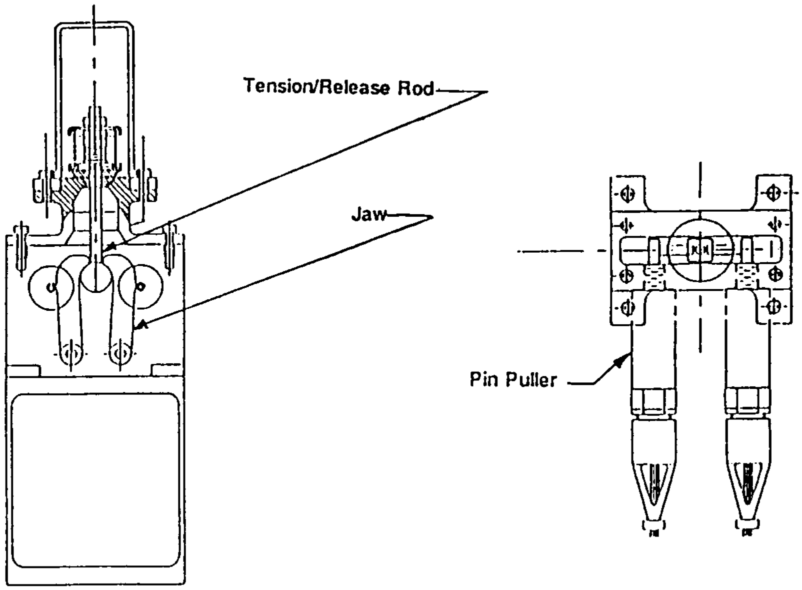


Figure 6. Release Mechanism Assembly

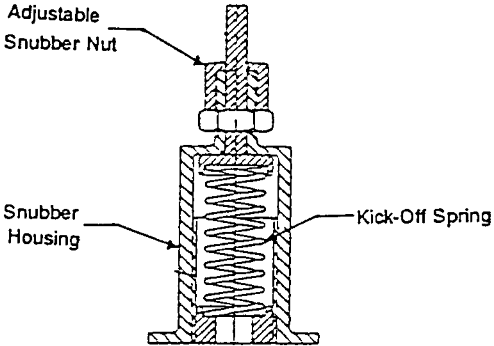


Figure 7. Snubber/Kick-off Spring Assembly

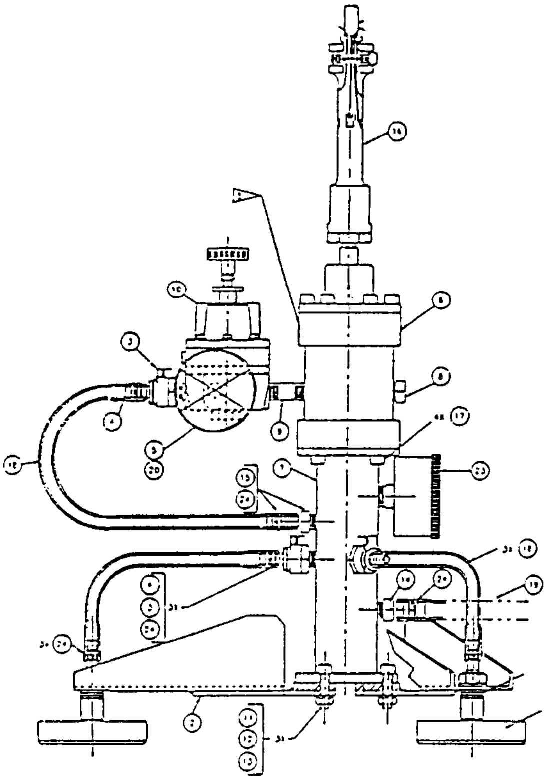


Figure 8. Typical Air Pad and Air Active Suspension Assembly

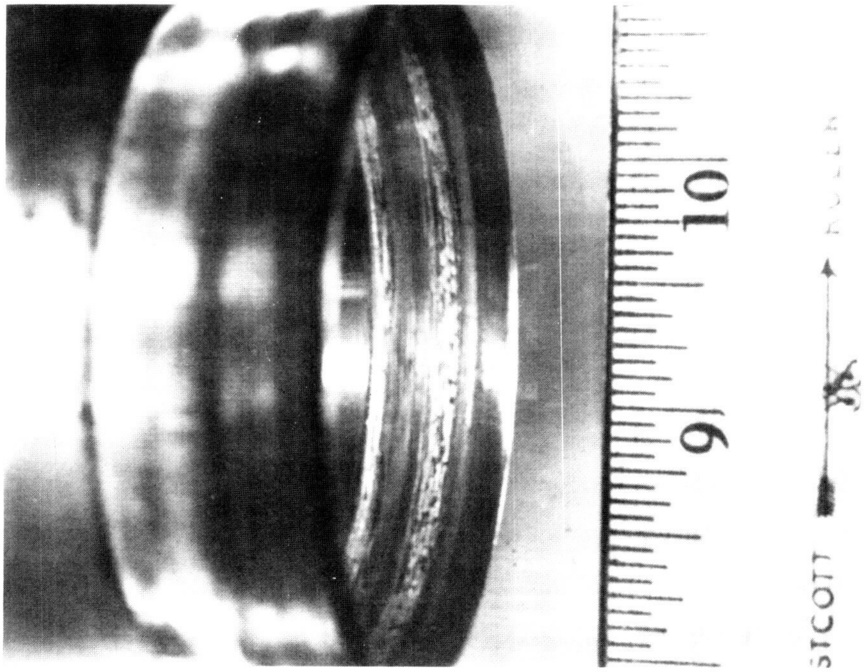


Figure 9. Harmonic Drive Flexspline After First Lifetest

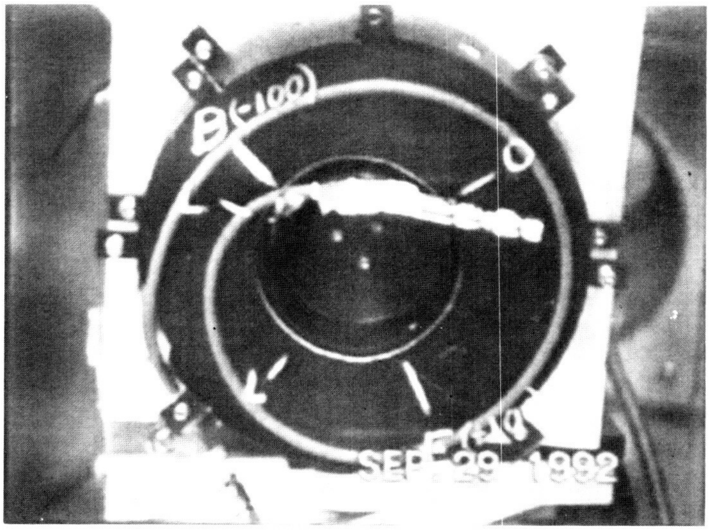


Figure 10. RF Cable Lifetest Fixture

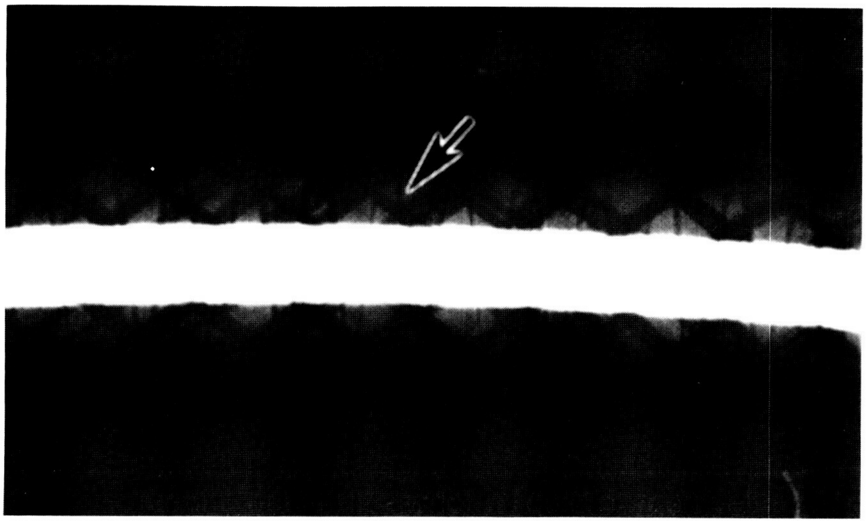


Figure 11. Pre RF Cable Lifetest X-Ray

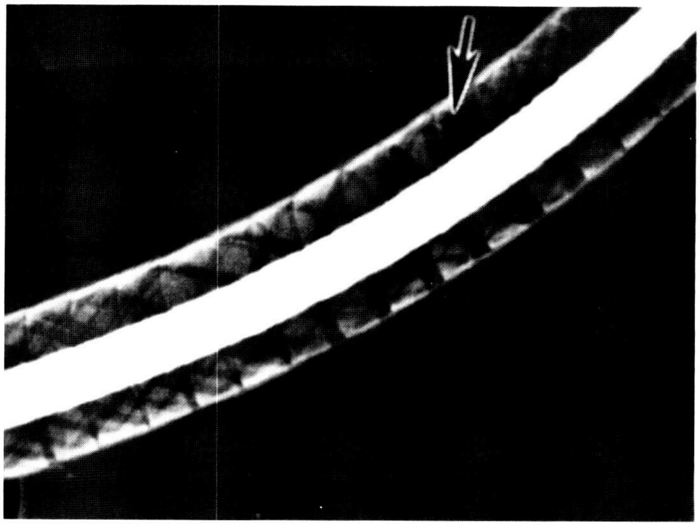


Figure 12. Post RF Cable Lifetest X-Ray

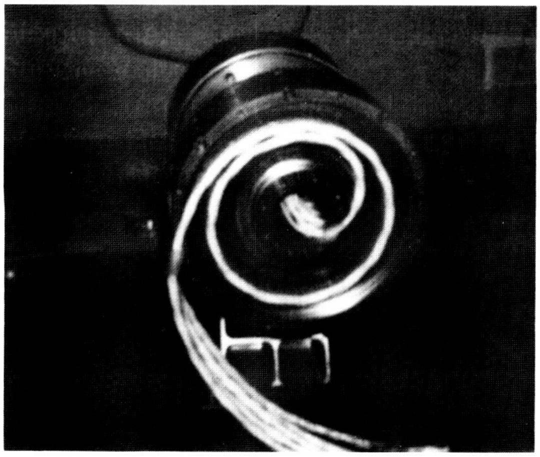


Figure 13. Final Harness Wrap Lifetest