LIGO Beam Tube Module Design, Fabrication & Installation
Chicago Bridge & Iron Co. and the LIGO Project
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Cover Page and Synopsis

Synopsis

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LIGO Project Document Number LIGO-P990007-00-B

LIGO (Laser Interferometer Gravitational-wave Observatory) is an instrument for sensing the dynamics of matter in the distant reaches of the cosmos using laser interferometry. LIGO does this by detecting gravitational waves - ripples in the fabric of time and space - created by violent events such as the collisions of stars and the vibrations of black holes. LIGO's interferometers will be the world's largest precision optical instruments. As such, they are housed in two of the world's largest vacuum systems. The observatory is made up of two separate facilities with L shaped vacuum beam tubes which are each composed of (4) 2-kilometer long, 1245 mm diameter beam tube modules. The unprecedented sensitivity of the LIGO detector requires an unobstructed path for the laser between the suspended mirrors. The beam tubes must be essentially leak free, clean, and composed of material with very low outgassing characteristics. Under the direction of the LIGO Project, Chicago Bridge and Iron Company (CB&I) designed, fabricated, erected and tested the beam tube modules at two separate facilities. Important developments were made in the areas of material processing, mobile fabrication, spiral welded tube fabrication, leak detection, field clean room construction, and alignment. This paper describes the developmental and installation process and the resulting configuration, procedures and equipment used by CB&I to successfully build the LIGO beam tube modules.

B. Materials and Manufacturing of Components

4. Factory and on-site manufacturing techniques

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Abstract

The Laser Interferometer Gravitational-wave Observatory (LIGO) is designed to measure the gravitational waves emitted by astrophysical sources. Gravitational waves are ripples in the fabric of space and time caused by motions of objects in the universe. At the Earth, the ripples are sensed by measuring a small expansion of space in one direction and a contraction of space in an orthogonal direction. The observation is carried out by measuring the difference in the time it takes laser light to travel along two orthogonal directions. The difference in the time compared to the average time, the gravitational strain, is expected to be 1×10^{-21} or smaller. The paths along which the laser beams travel are enclosed within 4 kilometer long, 1.2 meter diameter, high vacuum beam tubes. The design, qualification testing, and installation of the LIGO beam tube modules took approximately 5½ years from the initial design effort to the final testing and acceptance which was completed in January of 1999. The development consisted of a series of prototype tests including the full scale testing of a representative section of the proposed configuration. After successful testing, another year was spent developing and implementing the equipment and fabrication facilities necessary to fabricate the components in the vicinity of the two separate installation sites. Once the procedures, plans, and equipment were in place, the actual component fabrication and installation was accomplished in approximately one year at each site. This paper describes the design, fabrication, and installation of 8 kilometers of high vacuum beam tube at each of two separate locations.

Requirements and Configuration Discussion

Beam Tube Requirements and Selected Configuration

In 1993, a contract was awarded for the Design and Qualification Test of the LIGO Beam Tubes. The beam tubes are the connecting pathways between the corner station, mid-stations, and end-stations of the LIGO facility. The essential function of the beam tube is to provide a vibration free, high vacuum environment to maintain the coherence of the laser between the corner and end stations. Maintenance of a high vacuum environment is primarily dependent on the following items:

- Leak tightness of the pressure boundary.
- Outgassing of contaminants from within the pressure boundary material (predominately hydrogen).
- Outgassing of contaminants on the pressure boundary.

The LIGO facility at each site includes four Beam Tube Modules with the following physical requirements:

- Provide a 2 kilometer straight stainless steel pressure boundary with a clear aperture of 1 meter.
- Limit the pressure boundary thickness to a maximum of 3.3 mm.
- Process the material to limit the hydrogen outgassing and measure the H_2 outgassing rate prior to fabrication.
- Provide adjustable supports to allow for the initial tube alignment and future alignments of +/- 75 mm horizontally and vertically.

- Support the beam tube in a manner which prevents "stick-slip" vibrations and allows vacuum bake-out of the module at temperatures up to 170°C.

The overriding concern during the design effort was to develop a configuration and the required fabrication and installation procedures to efficiently produce the beam tube modules with the highest degree of reliability. In total, 16 kilometers of beam tube needed to be installed in a clean room environment with essentially no measurable leakage. The design effort consisted of a series of tests and tube prototypes to select the configuration weld procedures and equipment. The following configuration was selected and eventually installed:

- Each 2 kilometer beam tube module is composed of 100 beam tube sections.
- Each beam tube section is 1250 mm in diameter, 19.81 meters long, and composed of ASTM A240 Type 304L stainless steel with a thickness range of 3.05 mm to 3.3 mm thick.
- The beam tube ends were expanded to a uniform circumference. All circumferencial seams are butt-welded.
- The beam tube sections were fabricated by spiral welding and are stiffened every 760 mm with circumferential bar stiffeners composed of a single rolled bar with lap welded ends.
- Alternating fixed and guided supports are located near the beam tube section ends every 19.81 meters along the beam tube module. The guided supports consist of a steel frame with horizontal and vertical cables to suspend and support the beam tube.
- An expansion joint is located at the guided support to allow for thermal movements due to seasonal and daily temperature changes and to allow a high temperature bake out of the completed beam tube for removal of water molecules, the primary outgassing load.

The design culminated in a qualification test of a 39.62 meter long, full diameter prototype tube to qualify as many features as possible. The qualification test identified critical elements of the process and contributed greatly to the ultimate success of the project.

Fabrication Discussion

The beam tube sections were fabricated in the vicinity of each installation site. A 2500 square meter warehouse was converted into a tube section fabrication facility in less than 6 months. Stations were developed for major fabrication activities and a system of carts and overhead cranes was installed for tube section handling. Once the fabrication of 400 tube sections was completed for the first site, the entire fabrication facility was moved approximately 4000 kilometers to the vicinity of the second site. Again, a warehouse was converted into a fabrication facility where another 400 beam tube sections were fabricated.

Spiral welded tube station

A customized spiral tube mill was developed for the LIGO project. The key elements of the customized mill were the ability to control the spiral seam fit up to an alignment tolerance of within 0.25 mm with a gap less than 0.25 mm. The mill was designed to use coil material ranging in width between 610 mm and 1220 mm with a maximum coil weight of 18,000 kg. Coil material was hydrogen de-gassed by air baking at 444°C for 36 hours to greatly reduce vacuum pumping loads during observatory operation. Careful attention to shield gas and purge gas maintenance during welding helped to preserve the de-gassed condition of the material. Fit up was facilitated by stretcher leveling and slitting the coil material to one half ASTM tolerances. During the developmental stage of the project, a series of welding tests revealed that it was difficult to control the depth of weld penetration achieved. After a series of tests including production of the full sized tube sections, specialized high power gas tungsten arc welding (GTAW) equipment was selected for the spiral tube mill. The special welding equipment included the following components:

1. High amperage welding power supply with the following special characteristics:
   a) Capacity for 900 amps at 100% duty cycle.
   b) True Square Wave power output characteristics.
   c) High frequency pulsing capability (10,000 Hz).
2. Gas Shielding composed of 75% Helium and 25% Argon.
3. Mounting of an Arc Voltage Control Device (AVC) to allow the voltage to be maintained within a fairly narrow range.
4. An arc stabilizer was useful in promoting a stable arc.
5. A computer controlled Laser Tracking System (camera) measured the joint conditions at the inside and outside welder. The laser tracking system followed the weld joint and kept the arc centered by activating a motorized slide assembly. The laser tracker also controlled the weld joint gap spacing by continuously measuring the weld gap. When the measured gap reached the limit of a preset gap range, the computer activated equipment made appropriate adjustments.

The inside pass was made first in down position without filler wire. The second pass was made on top of the tube with filler wire and ensured the 100% penetration, which was confirmed by etching and polishing the weld ends on all tubes. After initial development, the weld speeds ranged between 760 and 1015 mm per minute. A total of 800 beam tube sections were fabricated with a total spiral weld length of approximately 72 kilometers. The spiral tube mill is shown in operation in Figure 1.

Stiffener Attachment Station

Two types of circumferential stiffeners were used. The entire project required 1,200 support stiffeners and 20,000 vacuum stiffeners. Due to the exacting tolerance requirements at support locations, 102 mm deep X 12.7 mm thick circumferential stiffeners were located at all support attachment points. The support stiffeners were machined on the inside and outside diameter to locate the centerline of the tube, provide a close fit up between the tube and the stiffener, and to provide a concentric outer surface of the stiffener for alignment of the beam tube at the support locations. The vacuum stiffeners were composed of a single rolled bar 32 mm X 4.76 mm with overlapping ends. Due to the maximum tube thickness limitation of 3.30 mm, vacuum stiffeners were required every 762 mm along the length of the tube. All beam tube sections were capped and purged with nitrogen prior to any welding on the tube exterior surface. The stiffener attachment station consisted of a roller to support and rotate the tube section during fit up and welding. After fit up on one side of the stiffener, stiffeners were welded continuously on the opposite side with a gas metal arc welding (GMAW) machine. The welding equipment traveled on a rack and pinion track with automatic positioning equipment to locate the weld head. The stiffener fit up is shown in Figure 2.

End expansion and Machining

After stiffening, the tube ends were expanded to a uniform diameter with a circumferencial length tolerance of +/- 1.27 mm. Once expanded and while securely held, the tube ends were cut to length with a tolerance of +/- 6.3 mm. Flatness and perpendicularity of the cut ends were within a tolerance of 0.25 mm TIR to provide a tight weld fit up and to maintain the straightness of the tube through the circumferential seam. The end expansion and cut off station consisted of two expander units and end mills. This equipment allowed both ends to be cut while held in the same fixture thus ensuring that both ends would be flat and parallel. The end preparation operation is shown in Figure 3.

Tube Dimensional Control Station

To maintain the clear aperture of the tube module, each beam tube section was subjected to a dimensional inspection. The allowable range in beam tube outside diameters was 1245 mm to 1252mm. The longitudinal straightness of each tube section was verified to be within +/- 3.2 mm over the 19.81 meter length.

Expansion Joint Attachment

Due to the configuration selected, an expansion joint was located between every other beam tube section. The expansion joint was attached to one end of the beam tube at the fabrication facility. The expansion joint thickness of 2.54 mm was selected to provide the required flexibility while at the same time allowing the expansion joint to be butt welded directly to the end of the beam tubes. This wall thickness at the convolutions also provided robustness that ensured high reliability against damage during fabrication, installation, and operation. The expansion joints are 635 mm long and contain six convolutions 86 mm deep. After fit up, the expansion joint was welded to the beam tube from the outside with a machine GTAW process. The first pass was made without filler wire and the second pass was made with filler wire. Both passes were made from the outside with a stationary weld torch as the tube was rotated.

Section Leak Testing

Each beam tube section was leak tested to a helium sensitivity of 1×10^{-10} atm cc per second. An area in the fabrication facility was built with a separate HVAC system to limit back streaming of helium to the helium mass spectrometer. Three leak test stations were built to allow three beam tube sections to be prepared and tested simultaneously. Each station consisted of a test head with a roughing pump, diffusion pump, and cold trap to protect the tube section from contamination by diffusion pump oil. Diffusion pumps were selected for high pumping speed and durability. Heads were supported on rolling frames to allow the tube section to be dropped in place with an overhead crane and capped. Each test station contained a split casket used to completely encase the beam tube section. Once the tube was evacuated, the casket was evacuated and back purged with helium to provide a near 100% helium environment around the evacuated tube section. The helium mass spectrometers were calibrated before and after each test to ensure adequate sensitivity. Once the test was completed, the helium was pumped from the casket to the atmosphere to maintain a low helium background in the test area. All 800 tube sections were tested without a single leak. The leak test stations are shown in Figure 4.

Cleaning Station

After leak testing, tube sections were stored until shipment to the installation site. The cleaning station was segregated from the remainder of the fabrication facility with controlled access. Beam tube sections were inclined and then steam cleaned with a surfactant solution. Following this cleaning, the tube sections were rinsed with hot de-ionized water. The cleaning solution and rinse were applied with a rotating spray head traveling the length of the tube. Following cleaning, the tube section was allowed to dry in the cleaning area and capped with covers for shipment to the field. The covers contained a filter element to allow the sealed tube sections to breathe without contaminating the tube interior while in transit to the installation site. The cleaning facility is shown in figure 5.

Transportation to Site

The fabrication facility at both sites was between 30 and 50 kilometers from the installation site. Beam tube sections were shipped two per truck to the installation site. Each tube section was completely wrapped in white tarps to maintain the cleanliness of the beam tube and to minimize breathing of the tube section due to temperature changes. The tube sections are shown leaving the fabrication facility in Figure 6.

Beam Tube Installation

The critical requirements of the installation were to maintain the cleanliness of the beam tube sections during the placement, welding for leak tightness, and alignment to provide the clear aperture. The first site is located in a relatively arid area and is subjected to high winds, dust, and temperature extremes. The second site is located near a warm gulf and is subjected to temperature extremes, periods of high winds and heavy precipitation, and numerous insects.

The cleanliness requirements were met by maintaining the cleanliness of the raw materials and fabrication process and then cleaning the completed tube sections at the fabrication facility and maintaining the cleanliness in the field. Access to the interior of the beam tube was controlled through a mobile clean room at the working end of the beam tube module. Each arm of the LIGO facility consists of two beam tube modules with one connecting the corner station to a mid-station and one connecting the mid-station to the end-station. A traveling clean room, weld shelter, and leak test shelter were used to maintain the cleanliness of the beam tube sections when they were exposed for work activities. The clean room, weld shelter, and cleaning shelter are shown in Figure 7.

Initial Tube and Valve Installation

Valves were installed at the ends of each beam tube module. Temporary enclosures were built at the valve locations to provide a clean environment. A rough layout was made of the entire beam tube to establish the position of the beam tube for installation. Once the valve position had been established, the first beam tube section was positioned with the valve and temporary enclosure at one end and the traveling clean room at the other end. After welding the valve to the beam tube end, a flow of clean dry air was established from the valve end of the beam tube to the traveling clean room. Once the airflow was established, the only access to the beam tube was through the clean room at the working end of the module.

Clean Room

Access to the beam tube was required to install the internal gas purge ring at the circumferential weld, to visually inspect the weld seam, and to install circumferential baffles inside the beam tube at various locations for the control of scattered light. The clean room provided access and consisted of a change room, anteroom, and clean room working area. All personnel entering the clean room were required to wear clean room overalls, booties, headgear, and gloves. All equipment inside the clean room was inventoried to prevent items from being left inside the beam tube. The clean rooms contained their own clean air supply system which was balanced with the flow of air coming into the clean room from the beam tube to maintain a positive pressure inside the beam tube and clean room and to maintain a flow through the beam tube module. Diaphragms with 100 X 100 mesh screens were installed inside the beam tube when not occupied by personnel to keep insects from entering the beam tube. Prior to removing the clean room for installation of another beam tube section, the beam tube was closed with a cap and filter to close the end of the beam tube and allow the continuous flow of clean dry air through the beam tube. The interior of the clean room is shown in Figure 8.

Weld Shelters

Weld shelters were placed over the circumferential seams for fit up and welding. Each weld shelter contained a central weld room with anterooms at each end. Plastic bags over the capped beam tube sections were removed from the beam tube ends in the anterooms and the ends of the beam tube exterior were wiped with a solvent to maintain the cleanliness of the clean room and weld shelter. The beam tube end and beam tube section end were then brought together in the central portion of the weld shelter. At the same time, the clean room was moved onto the end of the installed beam tube section. Just prior to fit up, end caps were removed from the beam tube section and from the working end of the beam tube and the tube sections were pulled together. From inside the clean room, a purge ring was placed inside the beam tube at the circumferential joint. The purge ring provided an inert gas environment on the inside of the weld seam to prevent oxidation during fit up and welding. In addition, the purge ring later was used to contain a helium environment for the leak test of the circumferential seam as described later. Like the circumferential weld seam made in the shop, the field circumferential seam was made with a machine GTAW process. However, for this weld, the weld head rotated around the tube section on a track. The first pass was made without filler wire and the second pass was made with filler wire. The weld procedure produced a full fusion weld with reinforcement. The circumferential welding is shown in Figure 9.

Leak Test Shelters

Each circumferential seam was helium mass spectrometer leak tested inside a separate leak testing shelter. As was the case for the section leak tests in the shop, the leak test had a sensitivity of 1×10^{-10} atm cc /second. The test was made by imposing a vacuum around the complete circumference of the weld seam with an external ring chamber. The chamber was composed of two 180-degree sections that fit to the expanded ends of the beam tube on each side of the weld. The sides of the ring and the seams in the ring were sealed with putty. Once in place and sealed, the ring was evacuated to impose a vacuum on the outside of the weld seam. Helium was then injected into the purge ring inside the beam tube to provide a near 100% helium environment on the inside of the weld with a vacuum on the outside of the tube. The helium mass spectrometer was calibrated before and after each circumferential leak test to confirm the sensitivity of the test. All 808 field weld seams were tested without a single leak. The circumferential leak testing is shown in Figure 10.

Once the welding and leak testing were completed, the purge ring was removed from the tube interior. Areas subjected to worker activity were wiped down with solvents as the workers exited the completed tube for the last time. Shelters were then moved in preparation of the next tube section to be installed.

Support Placement and Alignment

The beam tube was supported on temporary rolling supports during installation, welding and testing. Once the welding and testing of two adjacent sections were completed, the beam tube was aligned with Global Positioning System (GPS) measurements. Final supports were then installed on the completed beam tube. To account for temperature variations during the beam tube installation, the longitudinal position of the expansion joint was established based on the tube temperature. A guided support is shown in Figure 11 and the alignment is shown in Figure 12.

Results

The beam tube modules have been completed, leak tested, and aligned. A leak test of the completed modules prior to bake out of the beam tube was performed and confirmed no leakage to a sensitivity of 2×10^{-7} torr liters per second. Following the bake out of the first four beam tube modules by the LIGO Project, the leak rates were confirmed to be less than 2×10^{-10} torr liters per second. Outgassing rates from the material and interior of the wall surface are lower than expected as is the resulting beam tube pressures.

Conclusions

LIGO's interferometers will be the world's largest precision optical instruments. As such, they are housed in two of the world's largest vacuum systems. The success of the LIGO Beam Tube Module Project was the result of the following factors:

- Development of literally hundreds of plans and procedures to control the fabrication and installation activities.
- The development and testing of weld procedures and automatic and semiautomatic equipment to provide reliability and economies of scale.
- Careful execution and control of the welding, leak testing, cleaning and installation enabled a clean, low outgassing, essentially leak free pressure boundary to be installed in a harsh, outside environment.

Acknowledgements

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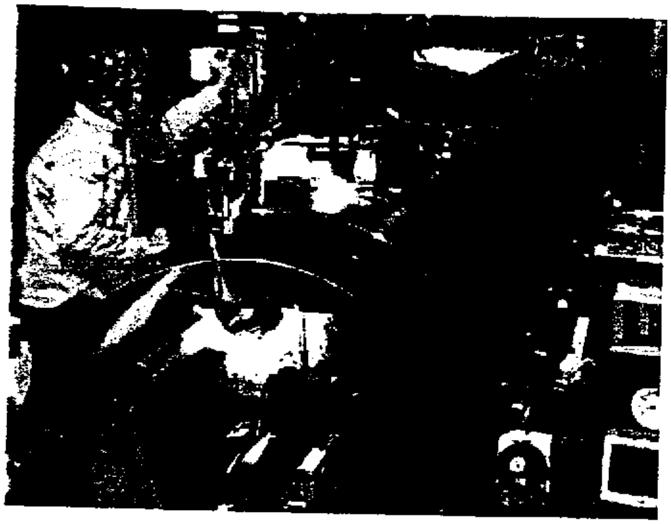

Figure 1 - Spiral Tube Mill

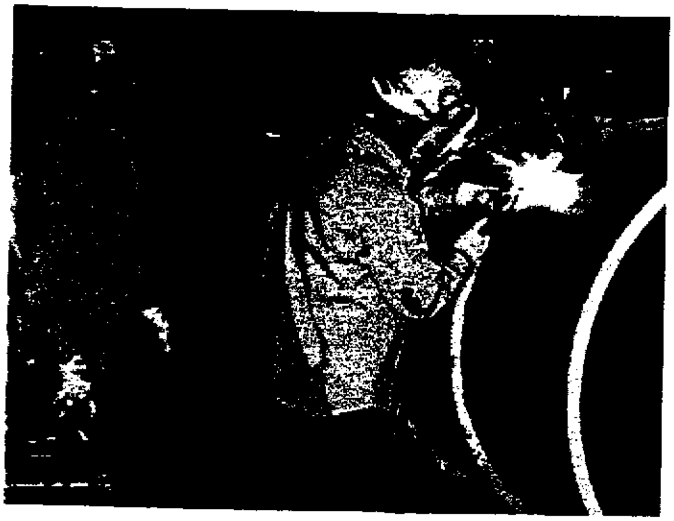

Figure 2 - Stiffener Welding

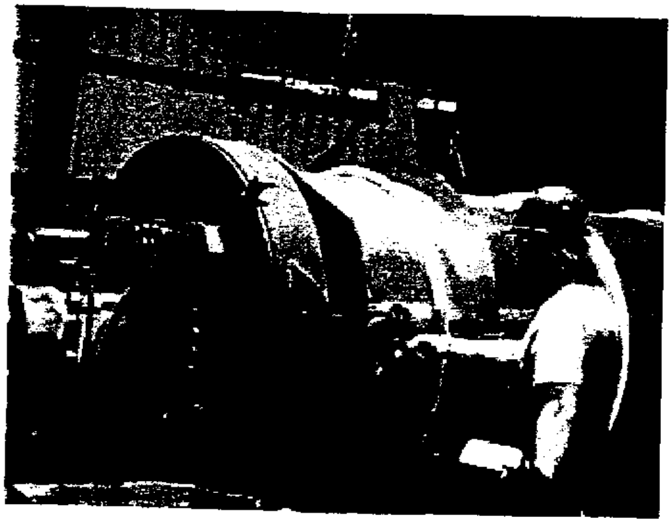

Figure 3 - Machining Tube Ends

Figure 4 - Section Leak Testing

Figure 5 - Section Cleaning

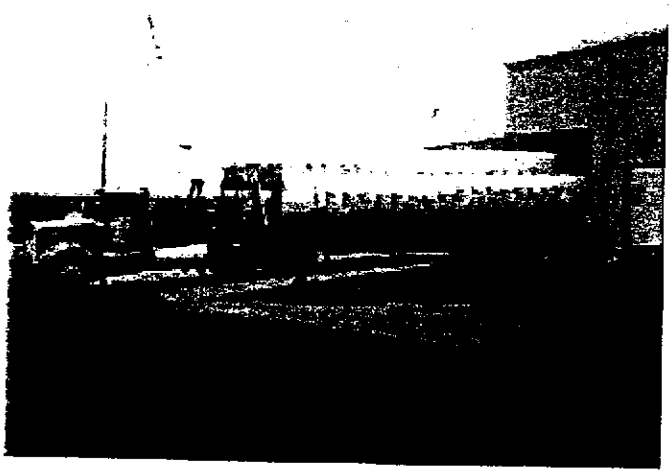

Figure 6 - Transportation to Site

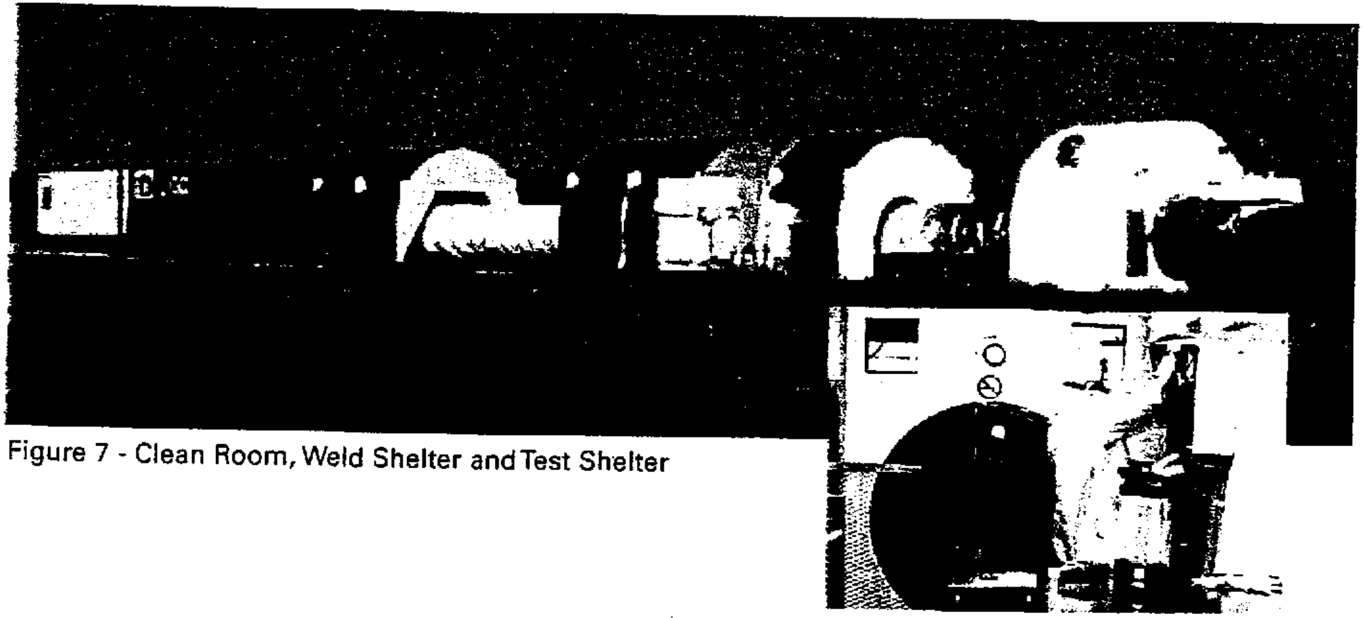

Figure 7 - Clean Room, Weld Shelter and Test Shelter

Figure 9 - Circumferential Seam Welding

Figure 10 - Circumferential Leak Testing

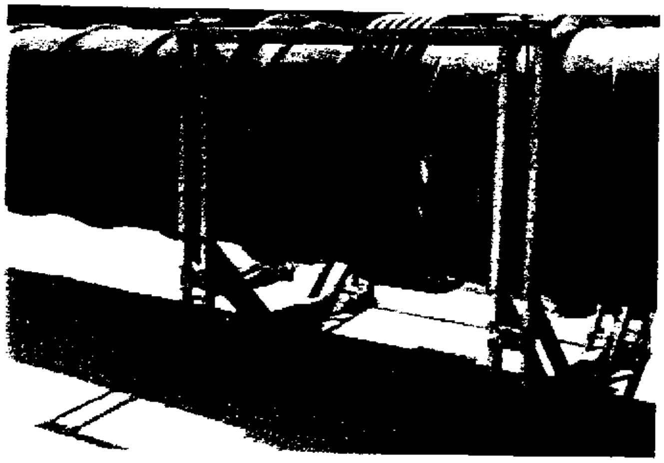

Figure 11 - Guided Support

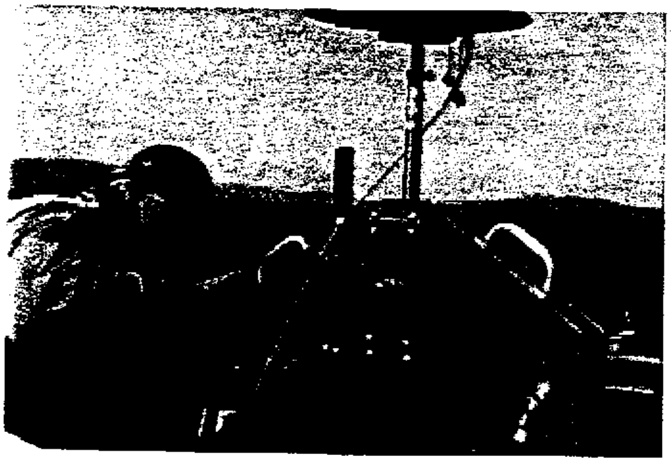

Figure 12 - GPS Alignment