Mar 7th, 8:00 AM

Positioning and Aligning the 250 Ton Solid Rocket Motors for Titan IIIC

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In the Integrate-Transfer-Launch concept of Titan IIIC, each 120-inch solid rocket motor is first assembled on a support frame and then lifted at the base and moved about 70 feet to a precise position adjacent to the core vehicle. The positioning of the completed motor presented several unique problems because this was the first attempt in any space program to transfer a vertical solid motor weighing 500,000 pounds, measuring 10 feet in diameter and 85 feet high, and having an eccentric center of gravity.

The physical size of the positioning sling components and the magnitude of their stresses presented a series of special problems involving fabrication, shipment, installation and proof-load testing. Even the apparently simple function of disconnecting the sling from the crane hook became a problem because it involved removing a 10-inch diameter pin weighing 380 pounds, and performing this operation 180 feet above the floor.

After the solid motors have been placed on the mobile launch platform they cannot be mated to the core vehicle until they have been moved both horizontally and vertically to within .020 inch of the correct location. The difficulty in obtaining such precision was compounded because parts of the core vehicle and its supports completely obstructed a direct line of sight between the interface points and left only a 4-inch vertical space in which to install and operate the alignment tools.

Introduction

ITL Concept

The requirements for high launch-rate capability in the more recent space systems pointed out that time limitations inherent in on-pad assembly of space vehicles would result in the need for additional launch facilities; therefore, a more economical method had to be found for working on several vehicles simultaneously and launching them in rapid sequence. The separation of the assembly and checkout functions from the countdown and launch operations permits several vehicles to be worked concurrently which is the heart of the Integrate-Transfer-Launch (ITL) concept.

Titan IIIC Program

In the ITL approach of the Titan IIIC program, the three stages of the core vehicle are erected on a mobile launch platform and checked out in the Vertical Integration Building (VIB) while both solid rocket motors are being assembled and checked out in the Solid Motor Assembly Building (SMAB). After checkout operations have been completed in the VIB, the assembled core vehicle is then transported to the SMAB where the solid motors are positioned, aligned and mated with the core to complete the familiar trident configuration of the Titan IIIC. Finally, the mobile launch platform is transported with the fully-assembled space vehicle to the launch complex, for the remaining countdown and launch operations.

This paper discusses the positioning and aligning operations which are performed in the SMAB.

The Positioning Problem

Inherent in the basic concept (ITL) of Titan IIIC is the requirement to lift and move the fully-assembled solid rocket motor to the mobile launch platform until adjacent points on the skin line of the solid rocket motor (SRM) and the core are only about 6 inches apart (see Figure 1). The positioning of the completed SRM presented several unique design problems not only because this was the first attempt in any space program to transfer a vertical solid rocket of such enormous size but also because the solid motor contractor required that the motors be kept in compression during all lifting operations. This meant that the problem was not only that of lifting the huge mass but also of preventing the motor from tipping over when it was picked up at its base support frame by the crane.

The scope of the problem can best be presented by summarizing some of the statistics of the solid motor, the Solid Motor Assembly Building and the positioning sling.

Solid Rocket Motors

Statistics - The solid rocket motors are assembled at Cape Kennedy by the motor manufacturer from segments weighing approximately 50 tons each. After they are fully assembled, each motor weighs 250 tons, measures 10 feet in diameter and stands approximately 85 feet high from the lowest point of the nozzle to the tip of the fairing (see Figure 2). The SRM is supported by three adjustable support heads which rest on a structural base frame, shaped much like a hollow square to allow the nozzle to extend down into the opening.

Lifting at the Base - After the individual motor segments are assembled together, the motor manufacturer required that the solid motors be kept in compression to avoid applying any loads that tended to separate the splice joints. This meant not only that the motor had to be lifted at its base support frame but also that it must be prevented from tipping over as a result of the eccentric location and height of the center of gravity (see Figure 2 and 4).

Four lugs are provided on the base frame for lifting the frame and motor with the overhead crane, and these are centered about the combined center of gravity of the frame and the motor (see Figure 4). The center of gravity of the motor itself is not located on the motor's geometric center-lines but rather is eccentrically located because of the Thrust Vector Control (TVC) tank.

Orientation - The solid rocket motors are identical except for orientation, with the south motor having its TVC tank in the northwest quadrant as compared to the southeast quadrant for the TVC tank on the north solid motor.

Solid Motor Assembly Building

The Solid Motor Assembly Building consists essentially of a high-bay area flanked on two sides by low-bay areas for receiving and processing the solid motor segments. Material flow for the solid motors is from the side receiving areas toward the center assembly area.

Assembly Area - The center of the high-bay assembly area is reserved for the mobile launch platform and it is to here that the solid rocket motors are moved for positioning and aligning. When the core vehicle arrives from the VIB, the mobile launch platform is first centered in the building, and then lowered until it rests on 12 concrete piers. The special undercarriage assemblies are removed from the area until needed for final transport to the launch complex.

The core vehicle itself is kept in a raised position until the support members extending from the solid motor have been aligned and leveled and the mating surfaces are directly below those of the core. Then the core is lowered approximately 6 inches until the core can be structurally mated with the solid motors.

Build-Up Cells - Four build-up cells are located in the high-bay area, two along the east edge and two along the west. The north cell of the east pair and north cell of the west pair are designed to match the orientation of the north solid rocket motor and a similar plan is followed for the south motor.

Cranes - Three cranes provide overhead handling capability in the SMAB. Each of the low-bay areas are serviced by a 50-ton capacity topriding crane with cab control. These cranes are also used to assemble the segments in the build-up cells. The high-bay area is provided with a 300-ton capacity topriding crane with two control consoles located on the ground floor. The travel of the 300-ton bridge crane overlaps that of the east 50-ton crane to the extent that the hooks of either can be positioned over the two east cells; the arrangement is identical over the west cells. Of course, the lower (50-ton) cranes must be drawn back away from the cells while the 300-ton crane is operating in the area.

Hoist Travel - The main hook of the 300-ton bridge crane can travel a maximum of 20 feet vertically, from a minimum hook height of 160 feet above the floor to 180 feet. The hook itself is shaped like a ship's anchor and has a 10-inch diameter hole for a connecting pin. The hoist controls are designed to provide smooth accelerations and deceleration (0.1g maximum) for all loads and to lower the loads in vertical increments of less than 1/32 inch. The bridge and trolley are capable of being positioned horizontally to within 1/8 inch.

Access - The doors on the east cells permit a handling sling attached to the main hook of the 300-ton crane to enter the cell from the west. Those on the west cells permit access from the east. When the solid motor has been placed to within 6 inches of the core, the handling sling can be removed only by moving away from the core, to the south in the case of the south motor and to the north for the other. This meant that if the hook was not rotated, the bottom portion of the sling had to be kept open (i.e., without cross-bracing) on all four sides to allow the sling to approach the SRM from all four directions. Even if the hook was rotated, a minimum of three sides had to be kept open.

Maintenance Platforms - Two maintenance platforms are located 167 feet above the first floor, one over the northeast cell and one over the northwest. The platforms provide access to disconnect the sling from the crane and allow repairs to be made and maintenance performed on the crane hook while it is disconnected from the handling sling. However, probably the most important purpose of the platforms is to provide a place where the sling can be supported while it is disconnected, so that the crane can be freed to perform other functions in the assembly area. Two platforms are required in order that the lifting cables can hang down into whichever cell is empty, rather than interfere with build-up operations that might be going on in the other cell.

Positioning Sling

Design Criteria - The criteria which governed the design of the components parts of the positioning sling (see Figure 3) can be divided into the following groups:

1. Functional considerations
2. Stress considerations
3. Fabricating and Shipping problems
4. Assembly of the Positioning Sling

Functional Considerations - The function of the positioning sling may be simply stated as follows: The Positioning Sling is used with the SMAB crane to raise the SRM and its support frame and to position them on the mobile launch platform. Many of the specific problem areas have been mentioned in the preceding sections and need only be summarized here:

1. The positioning of a mass of such size and weight.
2. The maintaining of stability during positioning operations.
3. The compatibility of the sling and the crane.
4. The maintaining of adequate sling clearances.

Stress Considerations - Stress considerations include three important design parameters: design loads, safety factors and proof-load testing. The design loads of the positioning sling include the dead load weight of the sling (34,000 lbs), the live load weights of the support frame (25,000 lbs) and the solid rocket motor (500,000 lbs), and an impact load (25% of the live load). The design loads of the stabilizing cross-brace cables were based upon the cables preventing the base and motor from tipping if hoisting was attempted with the lifting cables differing in length by 1/2 inch and with the crane hook 2 inches off-center.

All steel components were designed with a safety factor of 3 on yield strength; for the cable assemblies, yield strength was assumed to be one-half of breaking strength. All cable assemblies were individually static proof-load tested to 2.0 times their design load.

Fabricating and Shipping Problem - The main problem in fabrication was that of accommodating the large size of the major components. The apex cable support measured 17 feet by 18 feet and stood 13 feet high. A special enclosure was built to shield personnel from the X-rays emitted during radiographic inspection of the welds of this assembly.

The apex cable support and the stabilizer were shipped by barge to Cape Kennedy because they were too wide for rail or road shipment.

Although the lifting cables were about 140 feet long, the cables presented no special problems during fabrication. However, each cable was "prestretched" by using a tension load of 537,000 lbs to eliminate most of the construction looseness and draw the individual wires tightly together to form a compact strand. This process resulted in a higher modulus of elasticity of the finished cable and caused the different cable assemblies to elongate uniformly over their entire operating range.

In order to retain these advantages resulting from prestretching, the cable assemblies were shipped laid out flat along three flatcars rather than winding them into coils or around wooden reels.

Assembling the Sling - The maintenance platform above the northeast cell in the SMAB was selected for the assembly of the positioning sling. The first step was hanging the lifting cables from four temporary hooks welded to the underside of the maintenance platform. To keep from getting a sharp bend in the cable and thus losing the advantages of prestretching the 20-ton auxiliary hook of the 300-ton crane was attached to one end of the cable assembly and, as the hook was raised, the flatcars were gradually moved toward the hook. This made it possible to keep the radius of the bend in the cable larger than the recommended minimum of 20 feet.

The apex cable support was then hoisted up and positioned over the opening in the maintenance platform, and when this was completed, the four lifting cables were attached.

The stabilizer was hoisted to the correct elevation and the cables were inserted into the open ends of the stabilizer so that it rested on the support clamps which had previously been attached at the correct height. The clamps above the stabilizer were tightened to hold the stabilizer firmly in position before installing the cross-brace cables.

After the upper ends of the cross-brace cables were fastened to the apex cable support, the lower ends were attached but the turnbuckles were kept loose until the next step was completed. To keep the cross-brace cables from becoming overloaded when the sling was used to pick up the solid rocket motor, the turnbuckles were not tightened until the sling was under load. A stack of concrete weights weighing 500,000 lbs was placed on the support frame and stabilized laterally by tying the top of the weights to the four lifting cables. After the crane was connected to the sling and the weights were lifted up, the support frame was leveled and then the turnbuckles were tightened to put a tension load of 8,000 lbs in each cross-brace cable.

Major Components - The Positioning Sling (Figure 3) has four major components:

1. The apex cable support
2. The lifting cables
3. The stabilizer
4. The cross-brace cables

Apex Cable Support - The apex cable support is fabricated from T-1 steel and resembles a hollow pyramid with two sides of the base kept open; these openings permit the sling to approach close to a large diameter payload (located on top of the core vehicle) while positioning the solid motors.

The connecting pin is 10 inches in diameter and weighs 380 pounds. Inserting the pin connecting the apex support to the hook was simplified by storing the pin on a projecting bracket and limiting the handling to simply moving the pin straight in along a guided path. One technician stands on the ladder and exercises visual control while another stands on the access platform and operates the hand chain which causes a jackscrew mechanism to insert or extract the pin.

Lifting Cables - In order to minimize cable size and elongation under load, 3-inch diameter galvanized bridge strand was selected in preference to bridge rope because of its modulus of elasticity (25,700,000 psi actual) vs (20,000,000 rated) and its superior breaking strength (612 tons actual vs 412 rated). Standard open-socket clevises were attached to each end of the cable by pouring molten zinc into the socket. Each cable assembly was first prestretched as described above and then all lengths were measured while the cable was under a tension load of 179,000 lbs.

A special bracket for supporting and locating the stabilizer was clamped to each cable tightly enough to resist a downward force of 4,000 lbs.

Each cable assembly has a device that can be used to level the support base. This is done by turning a handwheel on the leveling turnbuckle to make adjustments in length while the cable is not under load.

The four cable assemblies were individually proof-load tested to 358,000 lbs before shipment.

Stabilizer - Stability studies indicated that the solid rocket motor could be picked up at the base and held stable if the base was kept reasonably level and if the sling could be prevented from distorting into an oblique parallepiped thereby tipping the base and the SRM with it. A scale model of a positioning sling was used to study the stability of different designs.

To achieve the desired stability, it was decided to use four cross-brace cables between the apex cable support and the stabilizer. Placing the cross-braces in the planes of the diagonals provided the maximum clearances and stabilized the sling at the same time.

It was recognized that a final measure of safety was needed -- a structure to prevent the SRM from tipping over by restricting how much it could lean in any direction. A continuous ring stabilizer was considered but the clearance needed for a structure of this type was not available when the SRM was positioned next to the core. Therefore, the stabilizer was divided into two halves resembling opposing cresents but joined structurally by an overhead steel frame. Also, since the positioning sling was centered over the center of gravity and since the center of gravity was oriented differently for the two motors, each motor was located differently with respect to the sling; therefore, the stabilizer was designed with a surrounding clearance, rather than touching the motor. The concave surfaces were lined with rubber to prevent damaging the SRM and four resilient pads were provided to act as spacers and helped insure that the sling was centered over the motor.

The stabilizer is supported by brackets clamped to the four lifting cables and is itself clamped to the cables so that it can act as a lower anchor for the cross-brace cables.

Cross-Brace Cables - The cross-brace cables were fabricated from 1-inch diameter galvanized bridge strand and included turnbuckles assemblies for adjusting the cables to the correct length. The cables were anchored to the apex cable support at one end and to the diagonally opposite point, on the stabilizer at the other. The lower half of the positioning sling was not braced but instead was kept open to allow the sling to be positioned over the motor from any of the four directions.

Positioning Procedure

To position the solid rocket motors, a crew of 10 men was needed including a crew chief, a crane operator, and observers to watch that critical clearances were maintained. The positioning of both motors was completed in approximately eight (8) hours.

Procedure - When the south solid rocket motor was ready to be moved to its position next to the core vehicle, the positioning sling was first stationed outside the assembly cell with the crane hook raised to its highest position. With taglines being used to guide the ends of the lifting cables away from the SRM, the sling was moved directly over the solid motor. The hook was lowered slowly until the stabilizer approached the lower end of the nose fairing. The hook was stopped and the location of the bridge and trolley was adjusted until the clearance at the four resilient pads on the stabilizer indicated that the positioning sling was within two inches of being centered over the SRM. The hook was lowered until the lifting cables could be attached to the four lifting lugs and when this was completed, the motor was lifted up approximately 1 inch. When the base frame was not level, the motor was seen to lean slightly against one of the stabilizer pads. The levelness of the frame can be determined by comparing the measurements taken between the bearing plates on the bottom of the frame and the base plate at each of the four supports in the cell. The hook was lowered back down until the motor and frame rested on the supports and then the leveling turnbuckles were used to adjust the cable lengths. This was repeated until the base frame could be lifted up and held level to within .06 inch which meant the top of the solid motor was not leaning toward the core vehicle more than .5 inch from true vertical and thus was ready to be moved.

The motor was then lifted about 7 feet, moved out of the cell about 50 feet and, making a right-angle turn, was moved another 20 feet toward the core vehicle. Then it was lowered down into the opening in the mobile launch platform until the base support frame was only 1 inch above the platform. From this position, the motor was inched forward until it was about 1 inch from its position for mating, where the alignment procedure began the final adjustments.

The motor was slowly lowered until the base frame was fully supported by the launch platform and then the positioning sling was disconnected from the lifting lugs. The hook was raised until the stabilizer cleared the tip of the fairing on the solid rocket motor. Taglines were used to guide the ends of the lifting cables around the TVC tank and the sling was moved back away from the solid motor until positioning of the north SRM was ready to begin.

The Aligning Problem

When the Titan IIIC is launched, the core is supported by the two solid rocket motors until Stage I engines ignite and staging occurs. Since the core vehicle is the first to be erected on the mobile launch platform, it must be supported and held in a raised position until the support trusses on the solid motors can be positioned underneath the core longerons. This is done by bolting the sides of the four longerons to the temporary core supports that keep the core raised up about 6 inches. The aligning problem consists essentially of adjusting the position of the solid motors until their support points are level and directly below the core longerons so that when the core vehicle is lowered down, it can be structurally mated to the solid motors without excessive stresses at the support interfaces.

Requirements

Core Interface - Each of the four interface points on the core vehicle consists of a spherical socket machined into the aft frame at the base of each longeron to a radius of 2.0635 ± .0020 inches. A cylindrical hole passes vertically through the center of the socket for the bolt that joins the core to the solid motor.

The four spherical sockets are located in plan at the corners of a square measuring 90.510 ± .010 inches on a side.

SRM Interface - Each solid rocket motor has two of the matching interface points, and these consist of hemispherical extensions located at the end of motor's core support trusses, and machined to a radius of 2.0595 ± .0010 inches. These ball joints also have a hole for inserting the connecting bolt. Distance between centers of the interface points is held to 90.510 ± .010 inches.

Alignment Tolerances - Before the core vehicle can be lowered down onto the support trusses extending from the solid motors, each motor must be positioned horizontally to within .020 inch of the correct location. Also, all four support points must be adjusted vertically to within .020 inch of the correct position. Positioning the solid motors to these tolerances was necessary to insure that the build-up of excessive stresses could not occur during the mating of the core vehicle to the motors.

The difficulty in locating the solid motors to within .020 inch was increased considerably because parts of the core and its adjustable supports completely obstructed a direct line of sight between the interface support points and left only a 4-inch vertical space in which to install and operate any tools needed for alignment (see Figure 5).

In addition to the precision required for the horizontal and vertical positioning of the interface support points, the solid motors must be adjusted vertically so that they do not lean more than .38 inch either toward or away from the core. This insures that the shear-tie connections between the core and the solid motors have both adequate clearance and minimum engagement necessary to accommodate the relative movements of the two vehicles that take place during staging.

After the core vehicle has been structurally mated to the solid motors, the core must be within 0.5 inch of true vertical.

Aligning Tools

Four identical sets of aligning tools were provided so that one set could be used at each of the four interface points. Each set consisted of two alignment tools (upper and lower) and a precision plumb bob.

Upper Alignment Tool - The upper alignment tool is hemispherical in shape and machined to a radius of 2.0595 $\pm$ .0010 inches; the tool is tapped for inserting a bolt to hold the tool into the spherical socket of the core vehicle. The bottom of the tool is flat except for a small diameter boss which was located at the center of the tool and on whose surface was located the center of the spherical radius. A small vertical hole (.016 $^{+.002}_{-.001}$ inch in diameter) was provided and held concentric within .001 inch to the center of the upper alignment tool to permit the inserting of a monofilament nylon line (.015 inch in diameter) for suspending a precision plumb bob.

Precision Plumb Bob - The precision plumb bob was only 2 inches high but was relatively heavy. The radius of the point of the plumb bob was machined to .002 inch maximum and held concentric with the centerline of the plumb bob to within .001 inch. When the two aligning tools were installed, the total distance between them (in which the plumb bob must operate) was less than 3 1/2 inches.

Lower Alignment Tool - The lower alignment tool resembles a cylinder containing a spherical socket machined to a radius of 2.0635 $\pm$ 0020 inches. The distance between the center of the radius and the top of the cylindrical surface was machined to 3.010 $\pm$ .010 inches. An internal thread was provided for bolting the tool to the SRM support interface.

Two grooves, perpendicular to each other and only .007 $\pm$ .002 inch wide, were inscribed on the flat upper surface of the tool and intersected at its exact center. A third (offset) line was also inscribed parallel to and 1 inch away from one of the other pair.

Dial Indicator - A dial indicator was used to measure the distance between the tools at all four interface points. The indicator was clamped to a small base for stability and located so that the tip of the indicator touched the small boss on the upper tool.

Close Tolerances - One of the most important considerations in the design of the alignment tools was holding the build-up of manufacturing tolerances to a level that left a margin of safety for the inaccuracies inherent in visual sighting. The tolerances were established after a thorough study was made regarding the possible loss of positioning accuracy due to several different considerations - due to the core not being truly vertical, to the space left between the tools and the matching surfaces because of very small differences in radii, to the plumb bob line resting against one side of the drilled hole, to the center of gravity of the precision plumb bob being eccentrically located, to the width of the inscribed lines and to the width of the point on the plumb bob.

Aligning Procedure

Since the procedure for aligning the solid motors is based upon using the core vehicle as a reference datum, the first step in the procedure was to use a transit to verify that Stage I was still within 1/8 inch of true vertical, which is the requirement for proper installation in the VIB. Any adjustments that were required were obtained by raising or lowering the jackscrew mechanisms in the temporary core supports.

The upper alignment tool and the precision plumb bob were installed in each longeron socket; the tool was leveled by equalizing the length of the tool protruding from the socket all around the periphery.

The lower alignment tool was placed over the SRM interface point and leveled with a spirit level. The tools on the South SRM were oriented to make the grooves parallel by stretching a nylon cord from one interface point to the other (and across the offset lines) and rotating the tools until the grooves line up with the cord. The same procedure was followed for the north SRM, the bolts were tightened to hold the tools firmly in place and the length of the plumb bob was adjusted to barely clear the surface with the grooves.

The entire alignment procedure consisted essentially of a series of operations, each starting with measuring how far and in what direction the solid rocket motor had to move and each concluding with the moving of the SRM.

Torque multipliers were used to turn jackscrew mechanisms which pushed against the support frame and slid it in the direction desired until the point of each plumb bob was directly over the intersection point of the two grooves. While this was being done, measurements were taken at the shear tie fitting near the top of the SRM, to insure that it was not leaning toward or away from the core more than 1/8 inch. When corrections were necessary, a torque multiplier was used to raise or lower the center adjustable support until the solid motor was in the correct position.

The final step of setting the four interface points parallel to each other was accomplished by using the dial indicator to compare the gap between the alignment tools at all four points. After the dial indicator was clamped to the base and adjusted to touch the boss on the upper tool at one interface point, it was taken to the other three points where it measured the differences in distances between the tools at all four places. The interface points were made parallel by raising or lowering all three adjustable support heads under one solid rocket motor, until the gaps at all four interface points were equalized within .005 inch. The core vehicle and the solid rocket motors were now ready to be structurally mated by inserting bolts at the interface points and attaching the shear-tie fittings and outriggers.

After the alignment tools were removed, hand-cranks were operated in unison to turn the jack-screws in the four core supports until the core vehicle had been lowered to rest firmly on the core support trusses. Once structural mating was completed, the fully assembled Titan IIIC was ready to be transported to the launch complex.

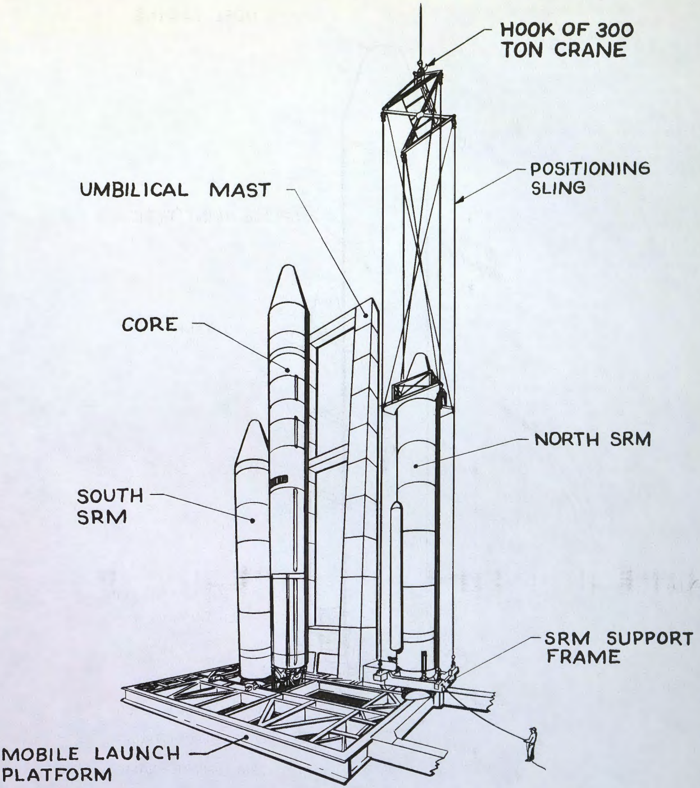

FIGURE 1
POSITIONING THE 250 TON
SOLID ROCKET MOTOR

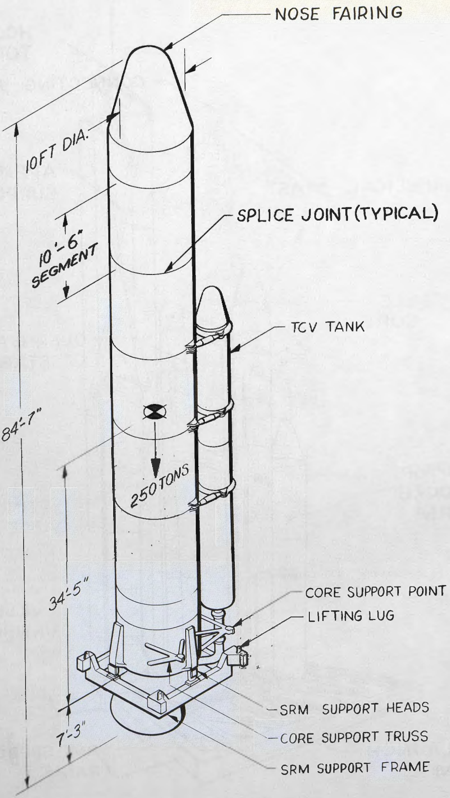

FIGURE 2
SOLID ROCKET MOTOR AND FRAME

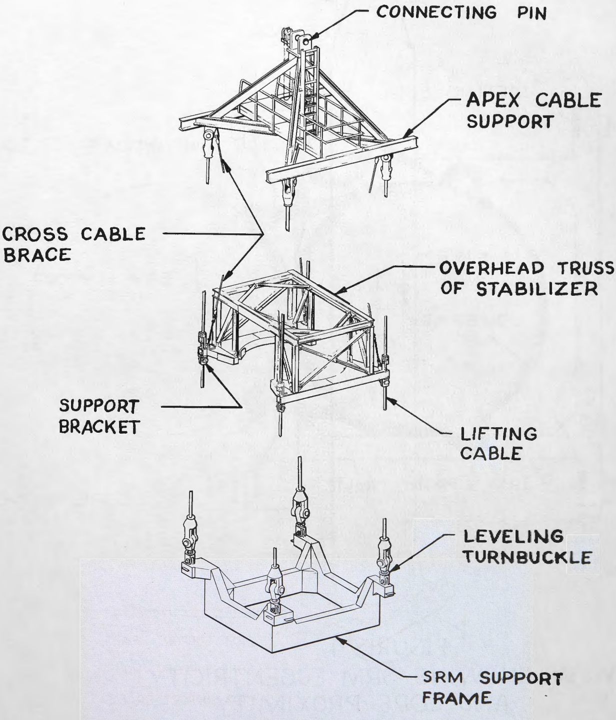

FIGURE 3
SRM POSITIONING SLING AND FRAME

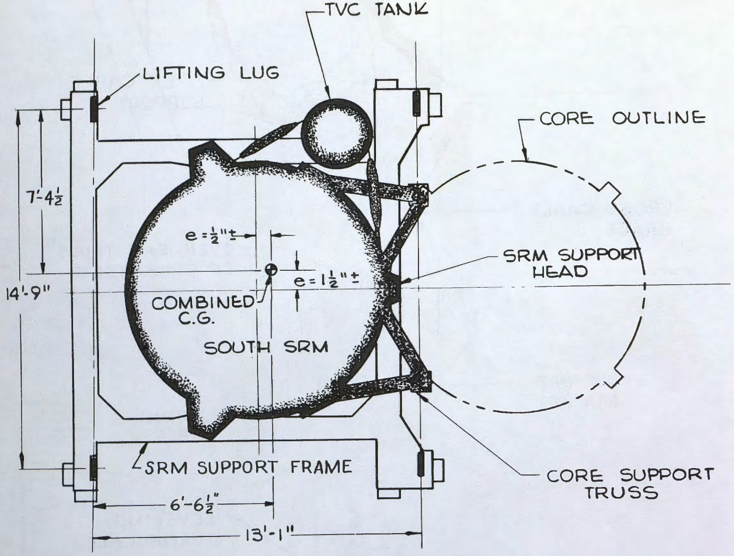

FIGURE 4
VIEW SHOWING SRM ECCENTRICITY
AND CORE PROXIMITY

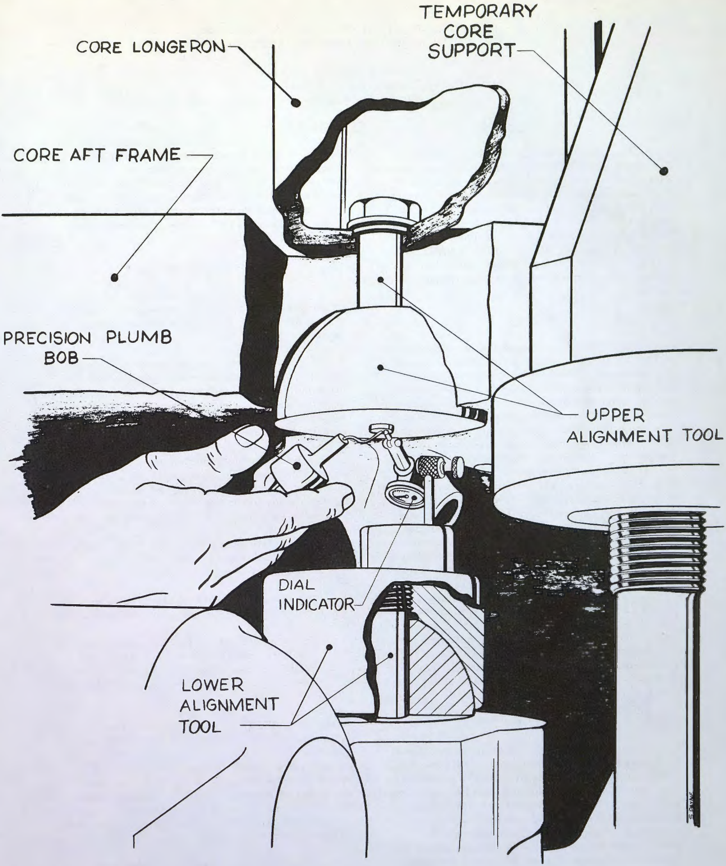

FIGURE 5
ALIGNING THE 250 TON SOLID ROCKET MOTOR