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Saturn V

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FABRICATING THE SATURN S-IC BOOSTER

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INTRODUCTION

The Saturn S-IC booster is the first stage of the Saturn V/Apollo launch vehicle scheduled to place a man on the moon in this decade. It is the largest and most powerful vehicle ever built by the free world. The Boeing Company is under contract to NASA'S George C. Marshall Space Flight Center for the design, development and manufacture of the S-IC. The tremendous size of this vehicle, coupled with its design complexities, have created many unique and challenging problems for the Aerospace materials engineer. Existing fabrication methods and facilities have been stretched to their maximum capacity, and in many instances it has been necessary to develop new techniques and new facilities. A brief description of the S-IC will provide a basis for appreciation of the fabrication problems associated with this booster.

The Saturn booster is 33 feet in diameter and 138 feet tall. Depending upon the payload attached to the upper stages, the overall height of the Saturn V vehicle will be about 350 feet or the equivalent of a 42 story building. The overall weight will approximate seven million pounds. The propulsion system of the Saturn Booster consists of five F-1 engines supplied by the Rocketdyne division of North American Aviation which develop a total thrust of 7.5 million pounds.

The following table summarizes S-IC stage Characteristics.

Overall Height	138 ft.
Diameter	33 ft.
Weight:	
Empty	287,000 lbs.
Fueled	4,711,000 lbs.
Burn Time	150 sec.
Distance Above Earth at Burn Out	38.5 miles
Propellant	LOX (oxygen)& RP-1 (Kerosene)

The Booster, as illustrated in figure 1, structurally consists of a thrust structure to which the engines are attached; two welded aluminum liquid propellant containers (a LOX tank and an RP-1 fuel tank); an intertank structure connecting the two tanks and a forward skirt structure which provides an attachment point for the upper stages. The selection of materials for a booster such as the S-IC is a complex process at best, but in general begins with a consideration of the types and characteristics of the loads to be carried by the structure under consideration. The forward skirt, intertank, and thrust structures are designed as ring stiffened cylinders and are primarily loaded in compression from the weight of the upper stages and the thrust loads generated by the engines. Compressive yield strength, modulus and density of the materials under consideration are the criteria for selection. These considerations result in the use of 7075 aluminum for compression strength critical applications; 7079 aluminum for compression stability critical structures and 7178 aluminum in certain applications which are critical in combined shear and compression.

The LOX and fuel tanks, in addition to carrying thrust and upper stage compression loads in their cylindrical sections, must also carry hydrostatic pressure loads. This situation places the tank domes in bi-axial tension and the tank cylindrical sections in axial compression and hoop tension. The combination of hydrostatic tension and axial compression resulted in an integrally stiffened design utilizing welded aluminum fabrication techniques.

Three aluminum alloys were considered for the tankage applications, including alloys 2014, 2219, and 5456. Aluminum alloy 2219 was selected as the prime structural alloy for both the liquid oxygen and the fuel tanks. Several factors were considered in making the alloy selection, including: strength and ductility at room and cryogenic temperatures; weldability; fracture toughness; available sizes and tempers; stress corrosion resistance and previous experience with the alloys under consideration. Several of these factors are compared in figure 2

MANUFACTURING SEQUENCE

Each of the Lox and Fuel Tank domes or bulkheads are elliptically shaped and are made of eight pie-shaped gores. A gore is made up of a triangularly shaped apex segment and a trapezoidally shaped base segment. Each segment is made from a single piece of material approximately 12 feet by 12 feet up to an inch thick. These segments, shown in figure 3, are sculptured to provide integral stiffening and beefed-up weld lands. The thicker weld lands compensate for lower strength weld joints. At the present time most of the gore segments are machine sculptured in the flat then hydraulically bulge formed to contour. The remainder are hydraulically formed to contour and then sculptured by chem milling. Machine sculpturing in the flat and then forming is the more economical of the two processes and the chem milling is currently being phased out.

Hydraulic bulge forming has been used previously, however, the application usually required the use of complex hydraulic presses. Since Saturn gore segments are larger than existing press capacities this method had to be ruled out. A technique has been worked out which utilizes die halves to restrain the part blank with a peripheral seal to withstand the pressure of the fluid (in this case water). Typical forming tooling for an apex segment is shown in figure 4. Forming pressures vary from about 500 psi for thin parts (sections as thin as 0.10 inch) to about 1100 psi for thicker parts (sections as thick as 0.835 inch). Contours are held to ± 1/8 inch and thinout is held to less than 0.008."

The initial assembly step in the manufacture of a bulkhead is the welding of fittings into the apex and base segments. These fitting joints are made using hard tooling and fitting size and configuration varies widely. Fitting weld tooling is shown in figure 5 with a base segment in place. High residual stress in these circular welds sometimes causes "oil canning" deformation. This is usually corrected by age forming in a fixture or in extreme cases by the use of roll planishing. An alternate technique for correcting "oil canning" utilizes a magnetic hammer which was developed by the George C. Marshall Space Flight Center. The "hammer", shown in figure 6, is a large coil through which a high voltage, short duration impulse is passed. While current is passing through the coil a field is created about the coil which in turn creates an opposing field in the part. The opposing fields tend to move apart and since the mass of the coil is greater than the mass of the part, the part actually moves. There is no physical impact and a piece of tissue paper placed between the coil and the part will be undamaged.

The second assembly step is the joining of apex and base segments to form gores. Each gore contains 3 inches of excess material around the edges to compensate for movement during trimming and provides integral runout tabs for welding. Apex to base weld tooling is shown in figure 7.

Next, eight gores are joined to form a bulkhead. During welding the gores are held in place by an ellipsoidal vacuum chuck. Figure 8 shows the gore to gore weld station with a final bulkhead meridian weld in progress.

The bulkhead is joined to cylindrical tank sections through a transition piece called a Y-Ring. Figure 9 shows the weld station for joining these two parts. This seam is welded from two sides using a modified v-type edge preparation on the inside.

The Y-Ring configuration is illustrated in the cross section schematic in figure 10. This ring was specifically designed to eliminate lap joints in joining the bulkhead, intertank, and tank cylinder walls. The Y-Ring begins as three, five-inch thick flat plates, 27 inches wide by 40 feet long. Each plate is roll formed to a 16.5 foot radius. Three of the curve plates are welded to form a ring 33 feet in diameter. Figure 11 shows the Y-Ring weld station. The edge preparation for this joint is a double J. About 160 passes using oscillating torches from both sides are required to make each joint. After welding each joint is stress relieved using large induction heaters. The 5" thick ring is then placed on a boring mill and approximately 14,500 pounds of material is removed leaving the finished 3,500 pound Y-Ring. The boring mill (Figure 12) was built in 1914 with an original capacity of 27' dia. It was enlarged to a capacity of up to 42' diameter, the largest in this country and has a maximum turning speed of six rpm.

The cylindrical tank walls are made of integrally t-stiffened skins. This part begins as a $2\frac{1}{4}$ inch thick by 11 foot wide x 26 foot long plate. A numerically controlled skin mill sculptures the integrally stiffened skin from the plate. After machining the parts are clamped in a fixture having a 148 inch radius as shown in figure 13. The clamped part is then aged in a furnance at 325° for 24 hours. While at temperature the part takes a permanent set to contour, is age hardened to the T87 condition and reaches its maximum strength. When removed from the fixture, the panel springs back to the desired 198 inch radius. Four of these skin panels are welded together to form a cylindrical skin ring 10 foot high and 33 foot in diameter as shown in figure 14. LOX tanks are assembled in the station at the left while fuel tanks are assembled at the right. The left hand station shows a skin ring in place prepatory to lowering a bulkhead. A completed fuel tank is in the right hand station. The lower bulkhead is in a pit and is not visible. The circumferential welds made at this station are made with a fixed torch and the part is rotated past LOX tunnels.

Liquid oxygen is transmitted from the Lox Tank through the Fuel Tank to the engines by means of Lox suction lines. These are straight tubular assemblies consisting of two concentric ducts forty feet long. The inside duct, or lox suction line, is 321 steel and has an inside diameter of 20 inches and a wall thickness of 0.085 inches. The lox tunnel, which encases the suction line, is a one-piece seamless tube shear spun from 2219 aluminum to an inside diameter of 25 inches and a 0.098 inch wall thickness.

When applying shear forming or flow turning to thin-wall tubes 40 feet long squeezed from a one-inch thick cylindrical blank only 62 inches long, conventional methods must be modified to insure distortion free and properly sized parts. The Parsons Corporation, the manufacturer, accomplishes this in a series of passes which first reduces the annealed workpiece 75 percent of its wall thickness. It is then solution heat treated to the -T42 condition and further reduced 50 percent of the remaining wall thickness. After the part is aged to the -T8 condition, it exhibits an ultimate strength of 65KSI, a yield strength of 55KSI, and an average elongation of 9 percent, in 2 inch gage length. A completed lox tunnel with attached bonded stiffeners is shown in figure 16.

HELIUM BOTTLES

The ullage pressure in the fuel tank is controlled by helium stored under 3000 psi pressure in four bottles located inside the LOX tank, see figure 17. These storage bottles are fabricated by the Martin Company from the largest 2014 aluminum extrusions ever made. These extrusions are approximately 22 inches in diameter, 20 feet long and have a one inch wall

thickness. The fabrication sequence is as follows:

a. Procure 2014 -T6511 extrusion.
b. Machine to .90 wall thickness.
c. Full anneal
d. Forge end closure and machine.
e. Solution heat treat and age to T6 temper.
f. Finish cut end threads.
g. Shot peen inside of bottle
h. Anodize outer surface and chemical finish inner surface per MIL-C-5541.
i. LOX clean final assembly.

Extremely tight inspection controls are maintained in procuring the material and in the production processing.

THRUST STRUCTURE

Figure 18 is a photograph of a completed thrust structure. This assembly is fabricated of 7000 series alloy and the skins are stiffened by fastening hat-shaped stiffeners. The intertank and forward skirt are similar 7000 series alloy non-welded structures. Engine thrust is transmitted to the tank walls through the thrust structure skins. The center engine support which fits in the center of the thrust structure is shown in figure 19. This support transmits the center engine thrust to the thrust structure skins.

Some of the largest forgings ever produced in this country are also part of the thrust structure. These forgings are used as anchors or hold down posts to hold the vehicle in place during countdown. The forgings, made by Wyman Gordon are 14 feet long and weigh 1800 pounds. Figure 20 shows two of these forgings. These forgings are produced on one of the two presses in this country capable of 50,000 tons of pressure. The finished hold down post, weighing 670 pounds is milled from the forging using punched tape controlled machines. Shot peening is used to compress and seal the surface structure of the metal, to help prevent stress corrosion.

Figure 21 shows the initial step in the build up of the booster. It shows a fuel tank being lowered onto a thrust structure.

Since the S-IC is designed to boost man into space the reliability demanded of it is exceedingly high, on the order of 99.9 +. In order that this reliability might be assured

Quality Control in each step of fabrication is highly stressed. Concurrent with the fabrication steps described above an extensive program of nondestructive testing is also carried out. The various applications of nondestructive testing begins with the raw material suppliers. For example, each plate which is subsequently machined either into a skin segment, a gore segment or ultimately the Y-Ring is ultrasonically inspected to assure that the material is of class "A" quality. In addition to plate material forgings, rod and bar stock and extrusions are also ultrasonically inspected.

Subsequent to machining, all parts are pentrant inspected to assure that no discontinuities have been initiated or exposed by the machining process. Figure 22 is a photograph of the penetrant inspection facility in use at Michoud. The tanks are 26 foot long x 11 feet deep by [illegible] foot wide. They are capable of accepting the largest of the Saturn detailed parts which are the 26 foot by 10 foot skin segments. Water washable fluorescent pentrant ZL-[illegible]B is used.

There are over 5,000 feet of weld in each booster, most of which are made in the tank fabrication sequence described above. 20,000 feet of weld wire is added during weld operations. To insure higher quality in welds each weld is inspected radiographically in at least two angles and sometimes three depending upon the thickness of the weld. 20,000 feet of 70 mm radiographic film is used for the x-ray inspection of welds on each booster. The radiographic inspection is accomplished with a minimum of interference and delay in the manufacturing sequence. This is accomplished by use of semi-automatic x-ray inspection tooling which was devised by NDT engineers at Michoud. Each weld is radiographed, penetrant inspected and accepted before the next weld in the manufacturing sequence is made.

Under NASA specification all radiographs have to exhibit a sensitivity of at least 2 percent and resolution cabple of allowing identification of defects as small as 0.020 of an inch in a .1 inch thick weld and 0.010 inch diameter defects in 5 inch welds. In addition, cracks, lack of penetration and lack of fusion have to be detected. Repairable defects have to be located for depth in addition to the usual coordinate locations, therefore all of the x-ray tooling was designed for taking angular shots up to 30 degrees each side of normal.

The unique radiographic system utilizes a method where approximately 200 feet of 70 mm film is placed in a lead covered magazine which includes necessary motorized controls and switches to advance the film approximately 16 inches at one time. 12 inches of this film is exposed leaving a margin of 2 inches on each end to guard against the changes of overexposure or double exposure. The film reel unit is mounted on a track which allows for movement of the unit along the weld bead and by means of limit switches can be stopped at preselected positions. At the same time the x-ray machine is mounted on the opposite side of the part to be inspected and is advanced along the contour of the part and stopped to align its position with the film reel unit on the opposite side.

Figure 23 shows the x-ray tooling used in the gore to gore assembly fixture. The x-ray film reel unit follows the external contour of the gore weld by riding on a gear rack supported on a large curved beam. The x-ray machine is driven in a similar manner on a contour rack arrangement which permits the x-ray tube to follow the inside contour of the bulkhead. The x-ray unit is always placed tight against the bulkhead during exposure to prevent scattered radiation. All of the x-ray equipment has appropriate interlock switches so that no exposures are made unless the tube and the x-ray film unit are properly aligned and are in position against the bulkhead. The design of the shielding as evidenced by the lead rubber bellows in the figures is so efficient that a cperator could if necessary stand within a few feet while exposure is being made. The tight shielding is necessary and allows manufacturing organizations to continue welding on other gore to gore segments while a finished weld is being inspected radiographically.

At the left in Figure 23 is an x-ray console which controls the speed of movement of all the drive motors in the film reel unit and the x-ray tube drive motor, as well as the necessary controls for angular positioning of the x-ray tube, and the incremental movements of both the x-ray tube and the film reel unit. It also has controls for movement of the film between shots, for adjusting tube KV and MA and all other necessary controls for one operator to perform the entire radiographic inspection of the weld at the station at which the equipment is located.

The mere handling of 20,000 feet of x-ray film per booster, both before and after exposure and again after processing and interpretation has introduced problems which necessitated design of specialized equipment. 70 mm is purchased in 2,000 foot rolls and it is necessary to remove the film from the larger rolls to the 200 foot reels which are utilized in the magazines in a manner which is not only efficient but is least likely to cause damage to the film during handling. The film used is commercially available, 70 mm, type M with the lightproof paper covering produced by the Kodak Company. The film is dereeled from the 2000 foot roll and placed on the 200 foot reel just prior to use in the film reel unit.

Figure 24 is a close-up view of the film reel unit. The reel at right contains the unexposed film while the reel at left is the take-up reel. The reels are fitted behind a heavy lead plate to prevent fogging during exposure. The unit also contains motors for advancing the film as well as film tension devices and automatic marking and coding devices. A small reel of tape with punched numbers automatically indexes to provide sequential numbering of the x-ray frames each time the film advances and an exposure is made. Complete traceability with all other records is maintained and films are stored in environmentally controlled vaults for a period of not less than 5 years.

Figure 25 is a close up of the x-ray tube angular manipulation track and tube positioning track.

Figure 26, is a schematic of the mechanized x-ray tooling used to inspect the base to apex weld. The weld joining the base to the apex is approximately 10 feet long and using the mechanized concept it is possible to complete ten straight through shots and 10 angular shots across this weld in approximately 30 minutes or an average of about 1½ minutes per shot.

Similar mechanized x-ray tooling is used at all other tank weld stations. These include the Y-Ring weld station, the Y-Ring to bulkhead station, the skin segment to skin segment station, The Y-Ring to skin ring and skin ring to skin ring stations in the vertical assembly building as have been described previously.

Figure 27 shows a device known as the film stripper. It is designed primarily to remove the paper from the film and at the same time roll the exposed film on a special reel which is later used in feeding the film through automatic film processors. At the same time that the film is rolled up the two separate sections of the paper are also rolled on spools whose ends may be quickly removed so that the scrap paper can be disposed of in roll form. This machine was designed so that film would be undamaged in any way that might affect the emulsion in the exposed condition prior to its being processed. The film is then processed in automatic processors which take not only the rolled film but also sheet film which is used in other applications. After the film is processed it is moved into the interpretation room where special consoles provide maximum efficiency for interpreting results. The consoles as shown in figure 28 are designed to take 200 foot reels of film and pass them over a viewing area. The operator of this machine can control film stop and start, forward and reverse, feed-through speed, light intensity for viewing, light spot size and other factors which are necessary to insure accurate interpretation. The console also provides for an overlay feature which permits the operator to drop over the film a previously printed, clear plastic sheet which is marked with certain coordination lines which permit the operator to mark the position of defects.

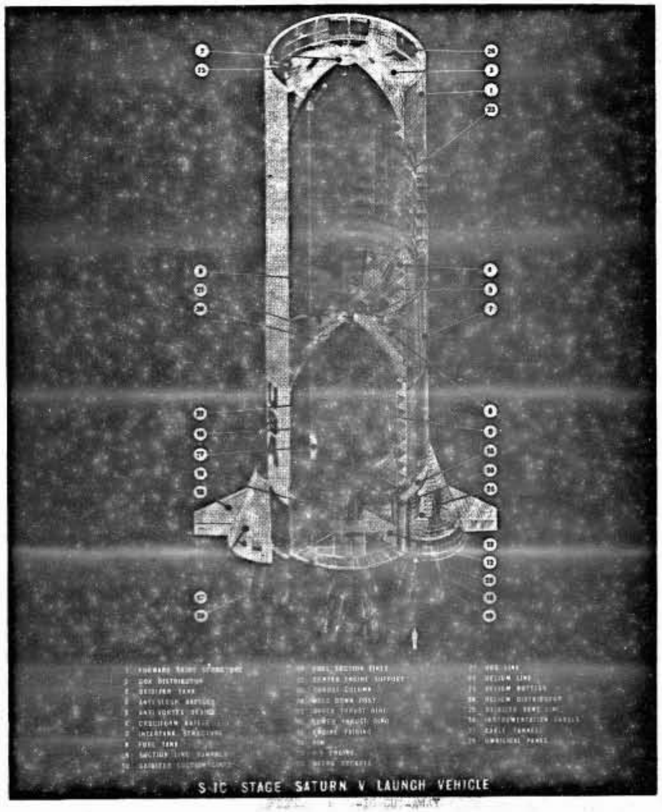


FIGURE 1 - S-IC CUTAWAY

COMPARISON OF CANDIDATE CONTAINER MATERIALS

Candidate Alloy & Temper	Base Metal Room Temp. Properties		Weldment R. T. Ultimate Strength in K.S.I.	Weldment Critical Flaw Depth in. (1)	Weldability	Comments
	Ultimate Strength in K.S.I.	Yield Strength in K.S.I.			(2)	
2219 -T87	63	50	37.6	.18	Excellent	(a) Parts may be fabricated in soft -T37 temper then aged to -T87 (b) Available in all mill widths & thicknesses (c) Immune to stress corrosion
2014 -T6	67	59	37.6	.07	Fair	(a) Parts may be fabricated in soft -T4 temper then aged to -T6 temper (b) Available in all mill widths & thicknesses (c) Susceptible to stress corrosion
5456 -H321	53	41	37.6	.18	Excellent	(a) Parts must be fabricated in end temper complicating forming (b) Available widths & thicknesses are limited (c) Immune to stress corrosion

(1) Critical flaw depth at operating stress based on results of recommended A.S.T.M. fracture toughness tests

(2) Includes evaluation of automatic and manual MIG, TIG original and repair welds

FIGURE 2

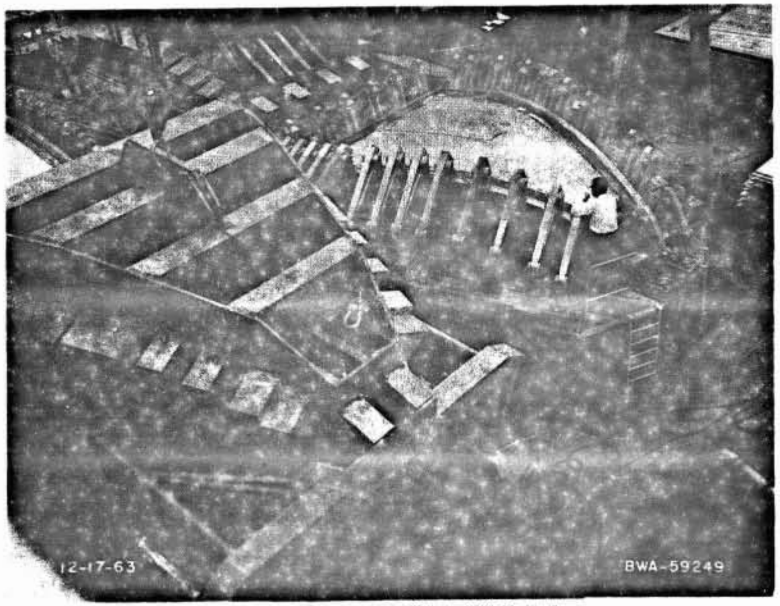
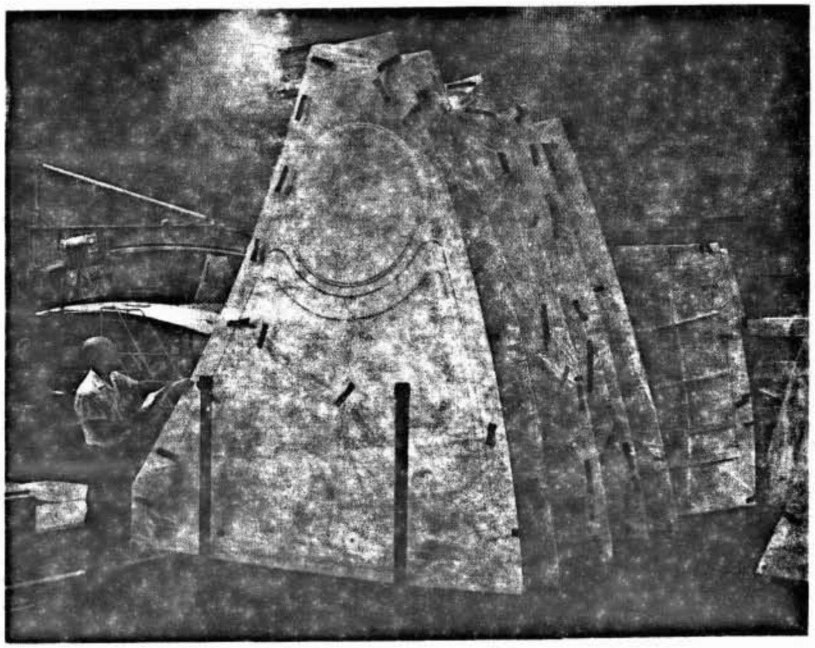
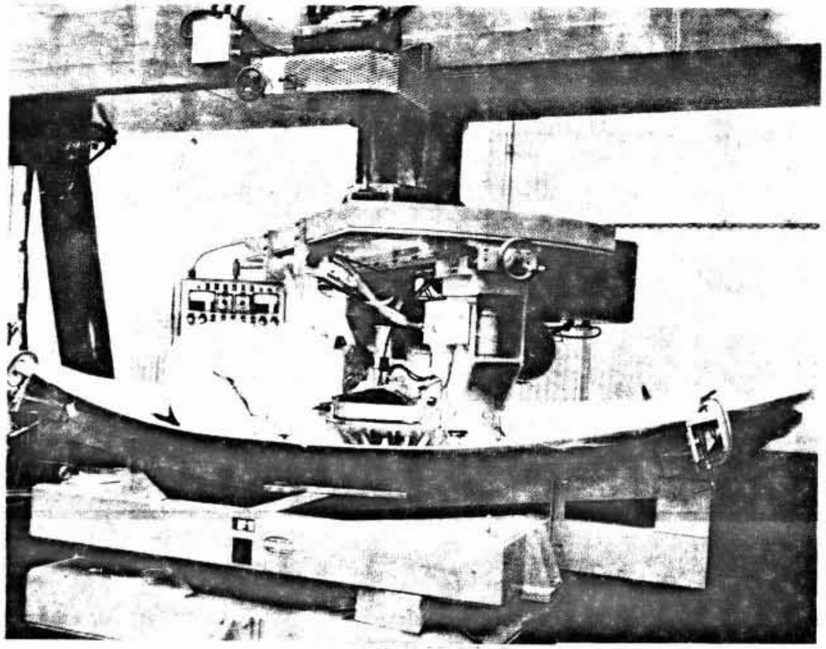
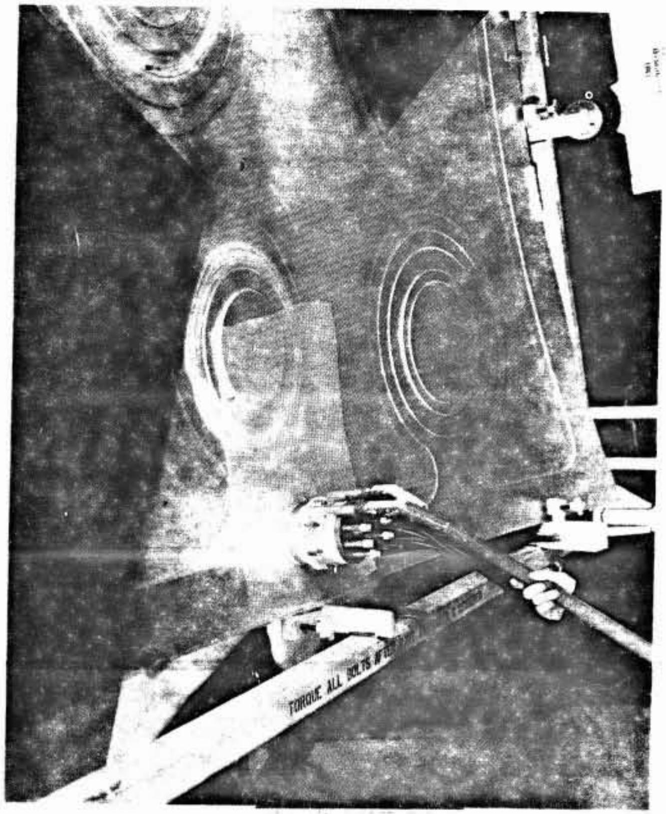


FIGURE 4: GORE BULGE FORMING FIXTURES



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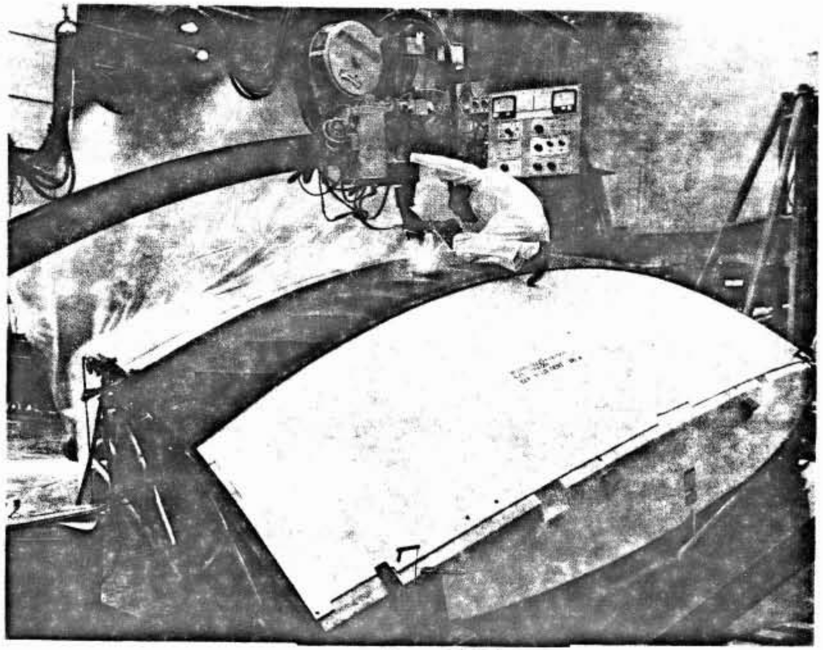
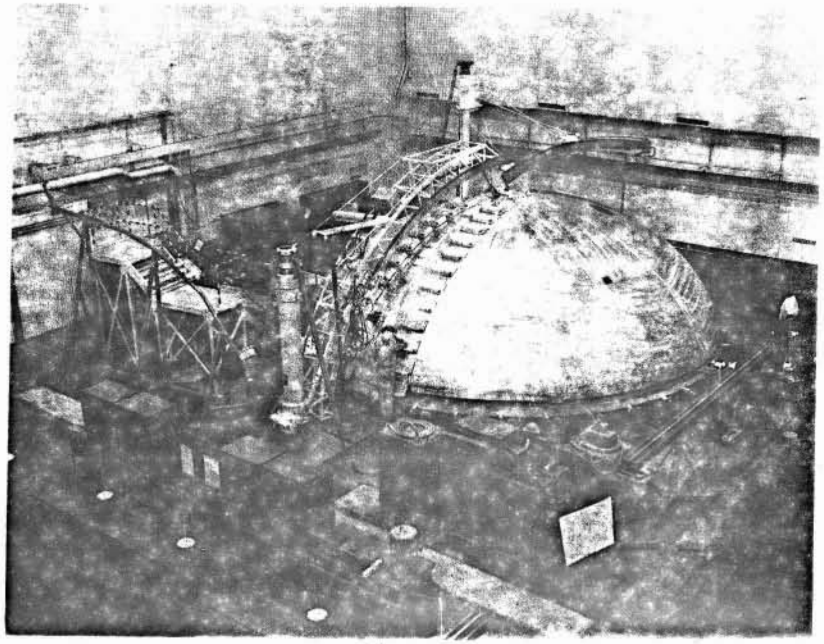




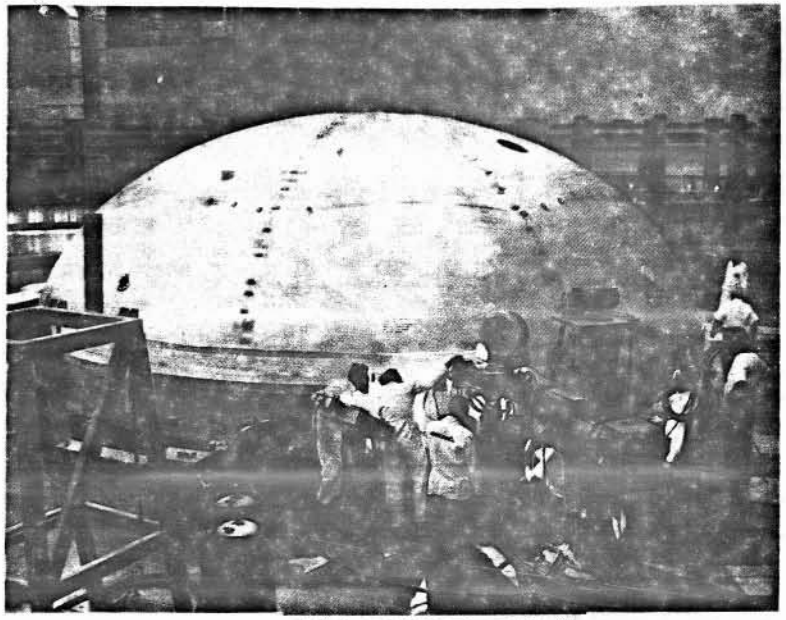


FIGURE 9: [illegible] HEAD TO Y-RING WELD STATION

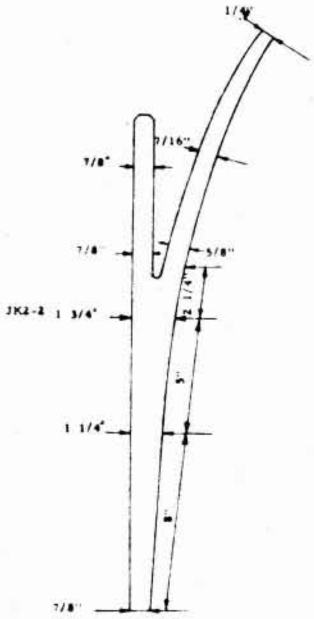


FIGURE 10: Y-RING CONFIGURATION

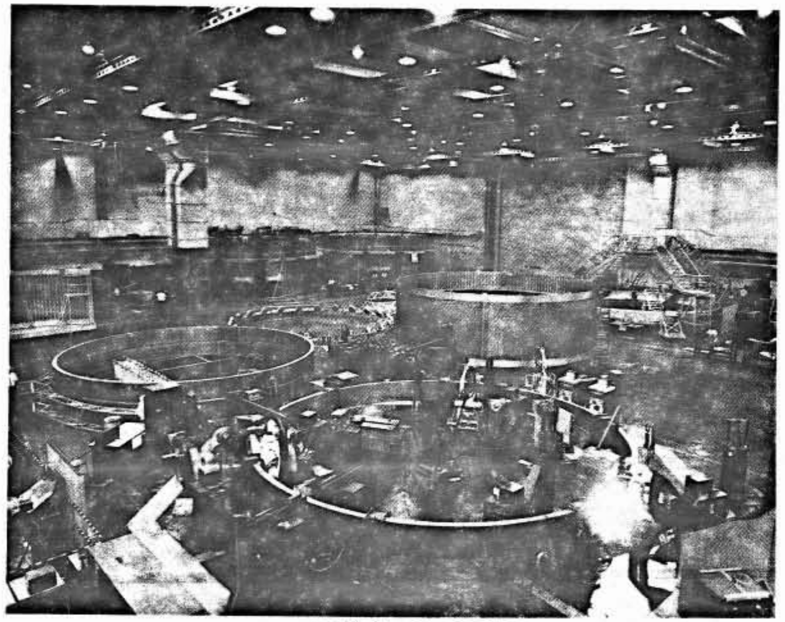


FIGURE 11: Y-RING WELD STATION

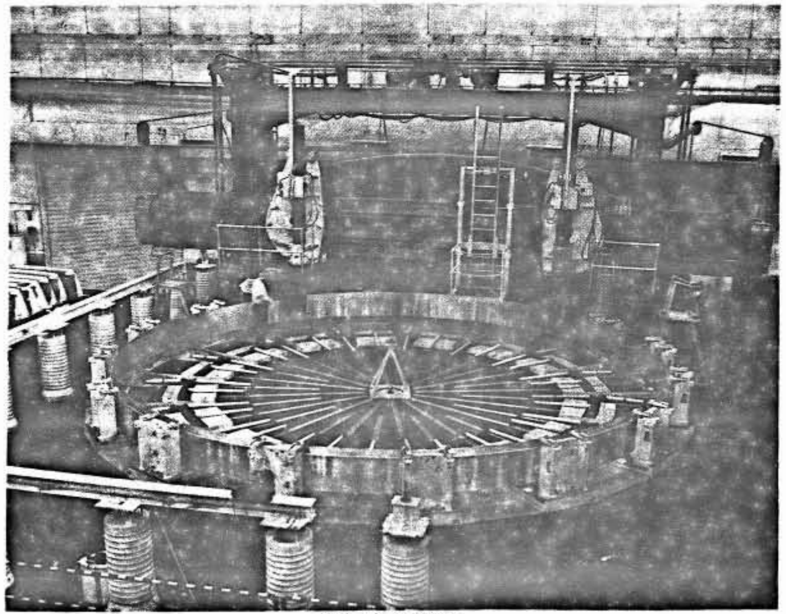


FIGURE 12: BORING MILL

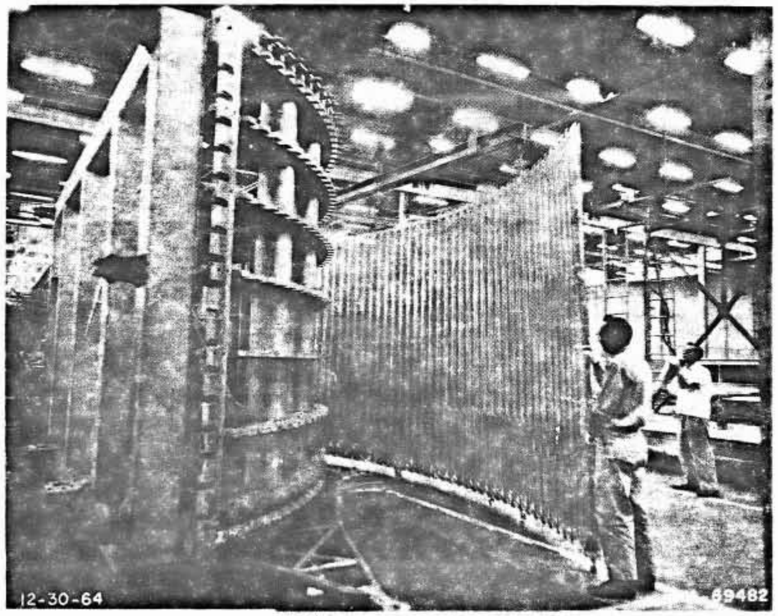


FIGURE 13: SKIN SEGMENT FORMING FIXTURE

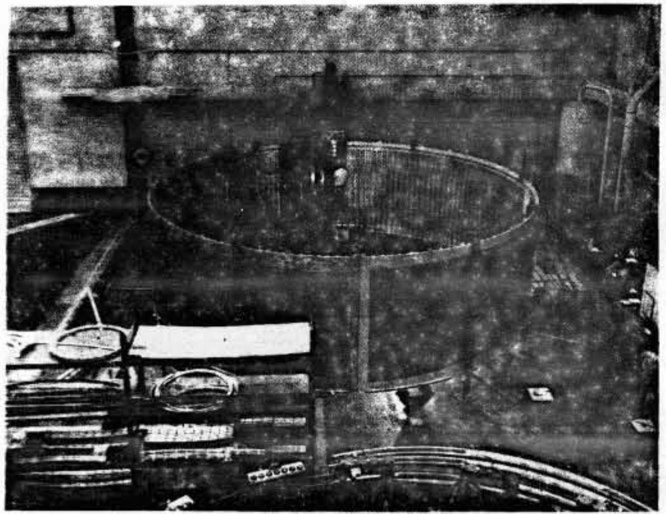


FIGURE 15: SKIN RING ASSEMBLY

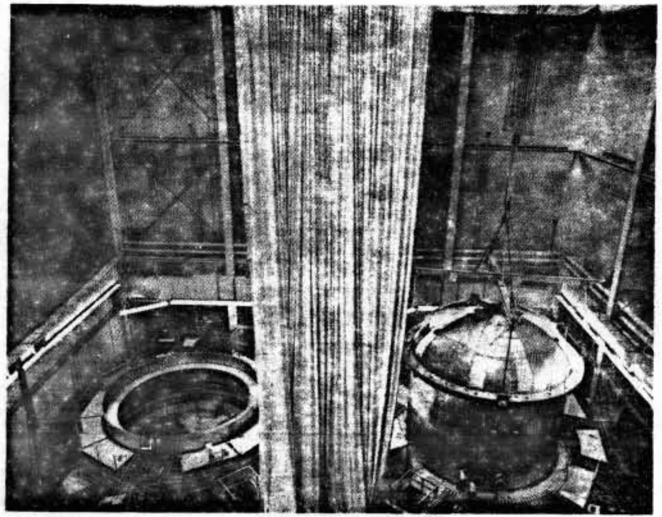


FIGURE [illegible] [illegible] ASSEMBLY [illegible]

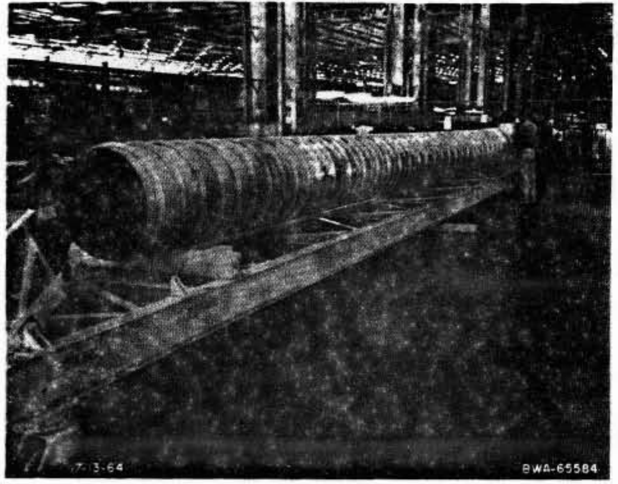
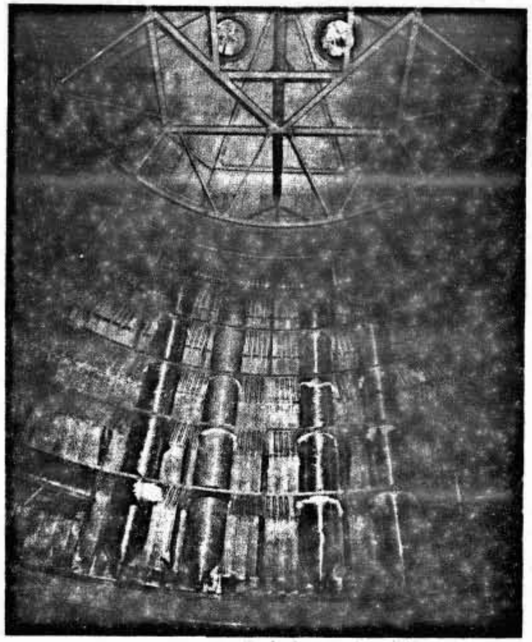


FIGURE 18: [illegible]



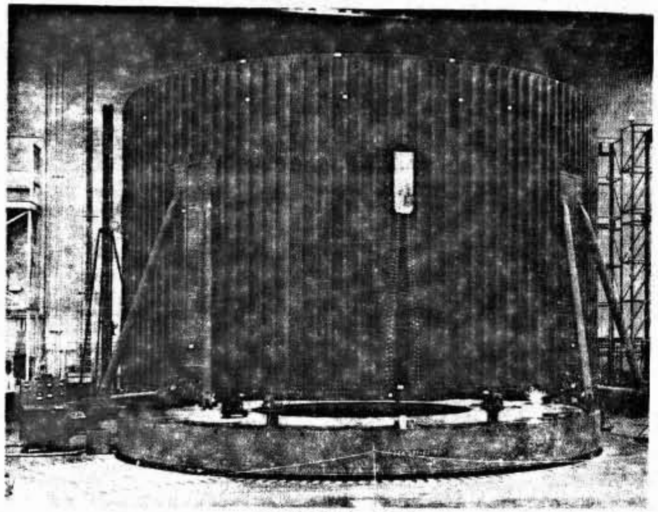


FIGURE [illegible] [illegible]

FIGURE [illegible] CENTER ENGINE [illegible]

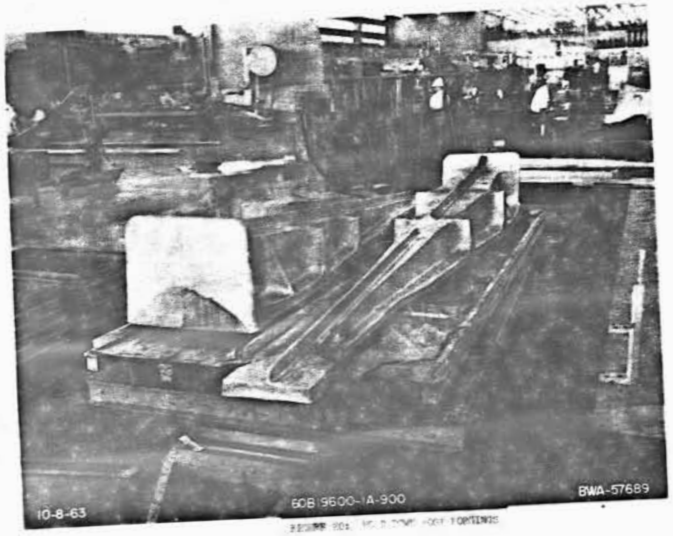
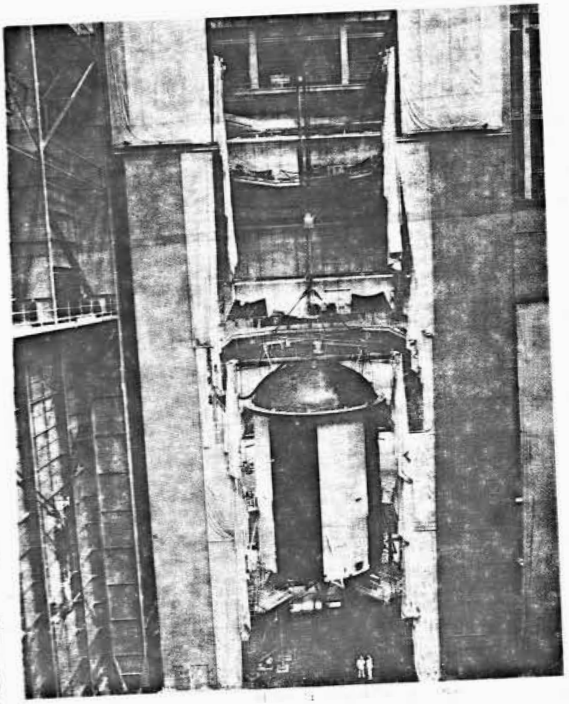


FIGURE 20: HOLD DOWN POST FORGINGS



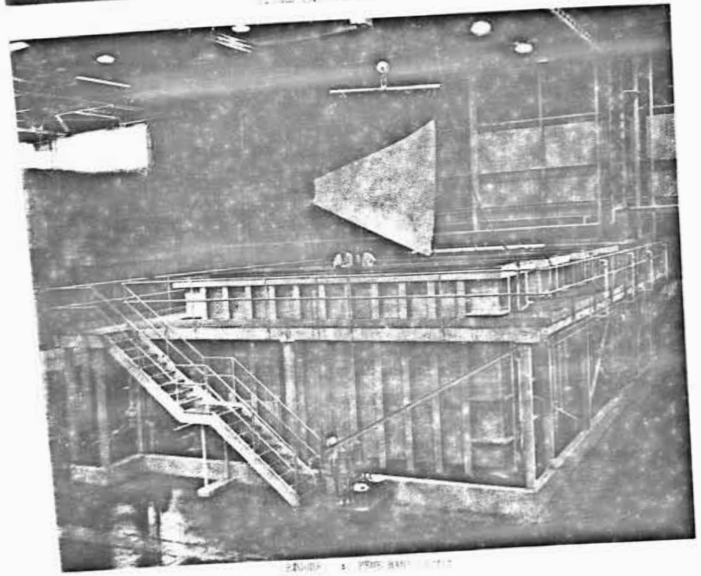


FIGURE [illegible]

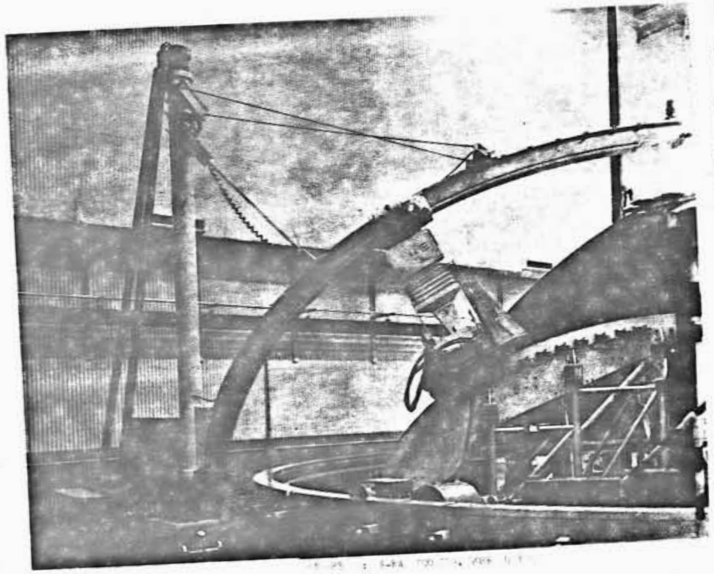
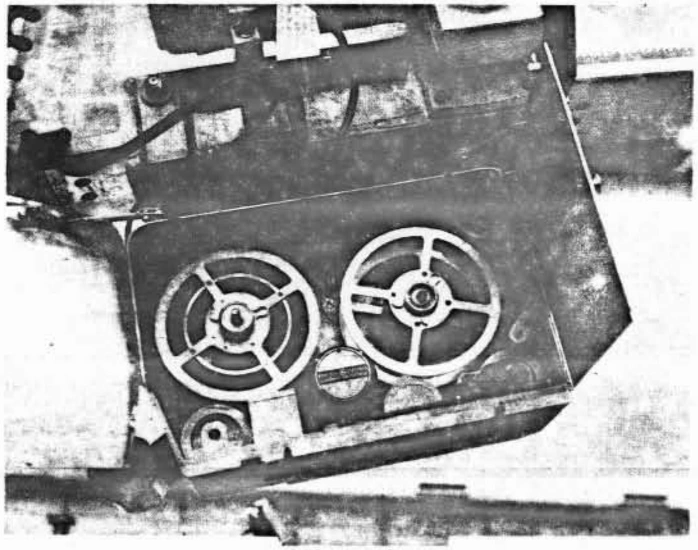
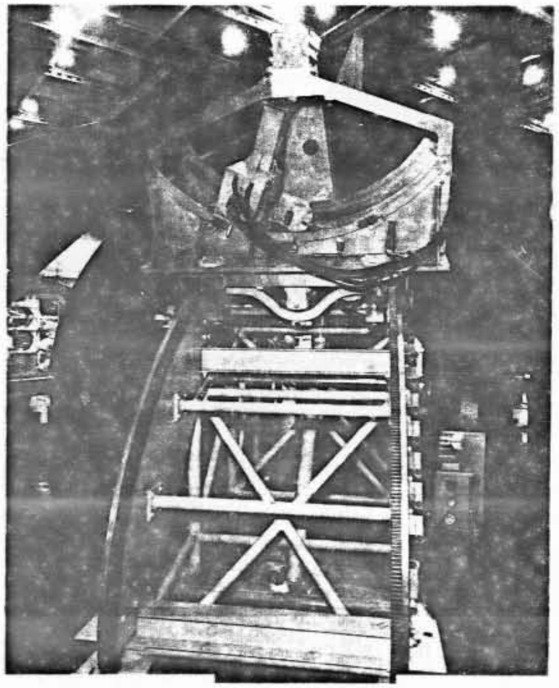
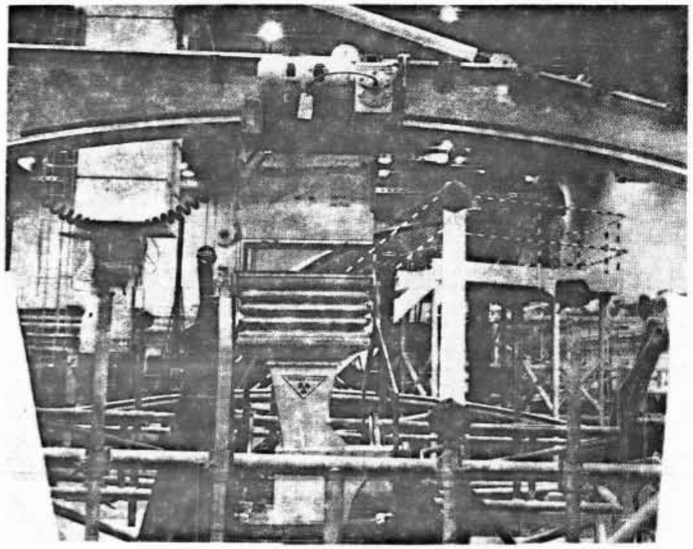
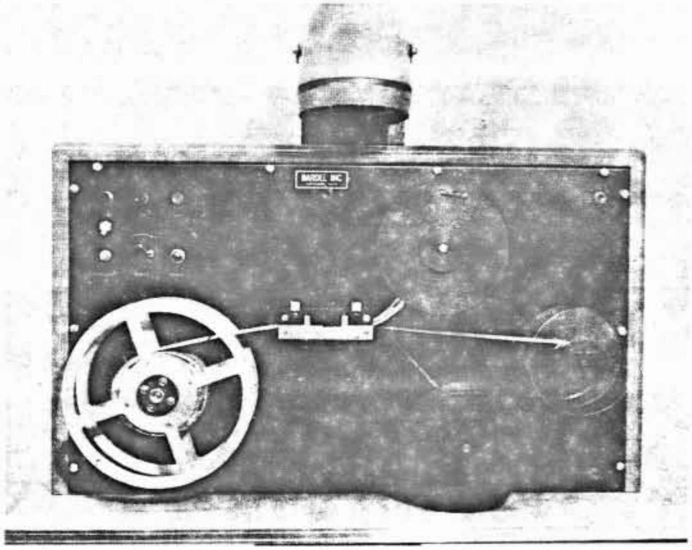


FIGURE [illegible]








BARDELL INC.