24. CRAWLER TRANSPORTER

STEERING AND JEL SYSTEMS

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SUMMARY

A vital element to Launch Complex 39 and the Kennedy Space Center (KSC) mobile transfer operation is a culmination of many unique engineering mechanisms known as the Crawler Transporter. The Transporter is a mighty tortoise weighing 2.8 million kilograms (6.3 million pounds) used to lift a 5.7-million -kilogram (12.6-million-pound) combination of Mobile Launcher and space vehicle, transfer this load approximately 5.6 kilometers (3.5 miles) from its point of assembly, negotiate curves of 152-meter (500-foot) mean radius, climb a 5-percent grade while maintaining the 122-meter (400-foot) structure in a vertical position within 10 minutes of arc, and smoothly position this huge structure to within ±5.1 centimeters (± 2 inches) on support pedestals at the launch pad.

INTRODUCTION

There are some unique mechanisms in the hydraulic jacking, equalization, leveling (JEL), and steering systems required by the Crawler to perform its mission. Numerous problems associated with these mechanisms have been overcome in a program requiring fabrication of operational equipment while proceeding with a developmental process. This was necessary since complete data did not exist in some phases of the design prior to construction. Besides, such an independent transporter system had never been built, and today only two such systems are in existence.

PRELIMINARY DESIGN CONSIDERATIONS

The primary impetus behind the selection of the Crawler Transporter as the prime mover during the development of facilities for the Saturn V space vehicle in 1962 was the fabrication of a similar device--a 76.2-meter (250-foot) high, 8.16-million-kilogram (18-million-pound) stripping shovel. Crawler excavators were tried and proven methods of handling large loads, some similar in magnitude to those required for the Apollo-Saturn V Program. After studying various transfer modes in detail, it was concluded that a crawler-mounted transporter would be the most advantageous method of turning the mobile concept into workable hardware.

The feasibility study of the crawler transfer concept basically proposed a crawler-mounted transporter and launcher pad in one unit. It was suggested that after the transporter and launcher pad were placed on fixed mounts, the leveling cylinder pistons could be raised, the steering cylinders and struts could be removed, and the trucks could be walked out under power. Such an undertaking involved problems associated with heavy equipment movement, as well as problems in repositioning the crawlers under the transporter platform. Early in the analysis it became evident that there were considerable advantages to removing the crawlers from the launch platform and providing an independent crawler transporter structure.

This arrangement (see Figure 1) allowed the trucks, together with self-contained power-generating, hydraulic-leveling, and steering equipment mounted in a transporter structure, to act as an independent unit that could easily be removed from the blast area during launch. An independent crawler transporter could also be favorably positioned under the center of gravity of the Mobile Launcher platform to enable more even load distribution on the crawler trucks. Additionally, fewer transporter units were needed since one could be on the move to another area while its deposited load was undergoing testing or check-out.

To enable the Crawler Transporter to function in its unique role at Kennedy Space Center, there were many changes required to evolve from a stripping shovel prime mover concept to an independent transporter mode. Large stripping shovels were constructed on site in an excavated hole; they removed the overburden (earth) in front of them and moved over terrain smoothened by bulldozers. Behind them were power cables plugged into extended substations. If a support cylinder leaked, the hydraulic fluid was collected (in a saucer surrounding the cylinder) and pumped back into its own reservoir. If a shoe broke or some similar problem occurred, the shovels kept going until they were forced into a repair mode. This operational philosophy was not amenable to reliable fulfillment of strict launch schedules. Besides, the leveling capability of stripping shovels was designed primarily to prevent the machine from turning over and was not adaptable for the critical tolerance level required to transport a 36-story rocket while its topmost part remains within ± 5 minutes of arc, or within the dimensions of a basketball. It was essential to maintain the transported load in a level plane and to reduce acceleration, torque, and jarring forces to a minimum. Reliability of the hydraulic system and operational integrity of the equipment were absolute requirements and major design challenges. With these considerations in mind, KSC adopted the transporter configuration depicted in Figure 2. If a critical control component should fail, there would be a backup system immediately available. In the event of a serious malfunction, such as a hydraulic line rupture, the load would be kept from becoming unbalanced by automatically locking (or securing) the corner cylinders. These cylinders, in groups of four, were designed such that if one should fail, the 5.7-million-kilogram (12.6-million-pound) load could still be safely transported.

A contract for two transporters was awarded in March 1963. The procurement plan called for assembly of the first Crawler Transporter by late 1964, followed by operational testing with resultant changes or modifications to be complete by March 1965. Both Transporters became operational early in 1966. (Their final configuration is shown in Figure 3.)

Let us briefly look at a few of those unique mechanisms and discuss the design evolution in relationship to stripping shovels used in the early 1960's as well as problems that were associated with the fabrication/development process.

JEL SUSPENSION SYSTEM

Previously, chassis support of large crawler excavators was dependent upon the utilization of a single, large diameter, hydraulic cylinder (see Figure 1). In order to preclude damage to transported loads in the event of a single cylinder failure, a clustering of cylinders was designed for the transporter suspension system. A single cylinder would not only have to provide proper leveling, but it would have to resist side loads introduced by wind as well as propel and steering conditions. Horizontal forces acting on a fixed vertical cylinder produce bending, and, if forces are of significant magnitude, they will cause hydraulic oil leakage, galling, and possible failure.

To prevent introducing shearing forces into the hydraulic actuators, a unique arrangement was designed for the four double-track truck suspension system. In the center of each truck is a 1.22-meter (4-foot) diameter guide tube that slides in a spherical bearing (see Figure 4). Clustered around this guide tube are four linear single-acting hydraulic cylinders with a 508-millimeter (20-inch) bore and an extensible stroke of 2006 millimeters (79 inches). The cylinder assembly on which the weight of the transported load rests is designed to operate at a normal pressure of 20.7 million newtons/meter^2 (3000 psig), an emergency pressure of 33.1 million newtons/meter^2 (4800 psig), and to withstand 41.2 million newtons/meter^2 (6000 psig) proof pressure and 62.3 million newtons/meter^2 (9000 psig) burst pressure. The support cylinders are attached to the chassis and trucks with spherical ball bushings to assure that only vertical loads are transmitted.

Shear forces from propel, steering, or wind loads are transmitted through the guide tube and into the chassis through a spherical bearing housed on the trucks. This not only removes horizontal loads from the cylinders but provides a pivot for the truck and permits vertical movement of the chassis in relation to the crawler truck. The guide tube fits into the cylindrical inside surface of a bronze ball bushing (see Figure 5). The outside surface of the bushing is a spherical section that mates with the inside surface of a concentric bushing container. This assembly enables limited tilt of the trucks in any combination of lateral or longitudinal motion. Changes in the vertical position of the chassis and rotational positions of the crawlers are supplied to the steering and JEL servo systems by transducers mounted at the bottom of the guide tube assembly.

The extremely low vertical friction allowed by this mechanism has provided for smooth leveling and jacking operations. This unique grouping has resisted large wind loads, having carried a Saturn V test vehicle on board a mobile launcher 5.63 kilometers (3.5 miles) at 0.04 meter/second (1 mile/hour) in winds as high as 30.1 meters/second (68 miles/hour) without incident. After more than eight years of operation, there has been no hydraulic leakage from these cylinders, and none have even had to be removed or partially disassembled.

STEERING THE TRANSPORTERS

Positioning the Mobile Launcher on its support pedestals requires precise maneuverability since alignment must be within $\pm$50.8 millimeters ($\pm$2 inches). Not only is this no easy task, but special considerations had to be taken just to enable the negotiation of a 152-meter (500-foot) radius curve. Since the crawler trucks are located on 27.4-meter (90-foot) centers, there is an angular position error between the inside and outside crawler trucks during great circle steering. Experience with large shovels propelling over surfaces other than coal, upon which they are usually operated, revealed that large horizontal loads were applied to their trucks. This lead to a reevaluation of the preliminary concept (depicted in Figure 1) of using a single-acting cylinder to pivot each truck about its center. The front and rear end trucks were connected by a large tie rod that pulled one truck while the opposite truck was being pushed by one single-acting steering cylinder. Since an independent transporter chassis would be much less rigid than that required for a permanently attached platform, scuffing loads introduced in skidding a crawler truck through a one-degree steering error could introduce stress levels high enough to cause severe chassis distortion. A mechanical linkage could have been designed to give the desired correction, but due to maintenance, cost, and weight considerations, it was decided to provide an Ackermann correction in the electronic servo system. Independent push-pull action was incorporated into each corner by using large double-acting hydraulic cylinders. For redundancy, these cylinders were mounted in pairs at each end of a crawler truck. These two mechanisms (electronic Ackermann correction and double-acting cylinders) allow the four trucks to be steered independently around corners in a great circle mode as well as diagonally in a crab mode.

The possible consequences of stresses introduced by the truck/road contact surface (46.5 meters^2) (500 feet^2) were areas of major concern and consequently were thoroughly investigated and analyzed. The chassis structure was designed to resist scuffing loads of 2.3-million kilograms (500,000-pounds) over those expected. A scale (1/8) model of the Crawler Transporter chassis was constructed to determine and analyze projected loads. A scale (3/8) model of the steering arm assembly (see Figure 4) was assembled and tested. A scale (3/8) model of the Crawler shoes was tested to destruction. Results of the model analyses were used to formulate design modifications to improve the load carrying capability of these structures. Since stresses are at a maximum during steering (sliding the trucks across the road surface), many tests were performed in an effort to determine a suitable, low friction, resilient roadbed. Model tests were not easy to simulate; therefore, verification was accomplished after construction. Tests on a prepared surface, sand, macadam, crushed granite, and river rock led to the selection of river rock as the minimum frictional surface for utilization on the Crawlerway.

Operational experience with the transporter disclosed that, even with a reduced frictional surface, large pressures were exerted in the hydraulic steering system. Since both corner cylinders were needed for proper steering, the required redundancy was marginal at best under full load. The loss of a cylinder under these conditions could possibly result in a launch scrub. In order to adequately provide redundancy and to increase the capabilities of the system, two steering cylinders were added to each truck. The new cylinders work perpendicular to and are identical to the original ones. They are used in pairs extending from steering brackets mounted below the Crawler Transporter chassis to an auxiliary steering arm (see Figure 4) welded to the inside frame of each truck.

The uprated steering system was not implemented until 1969. Before proceeding with the modification, a sound engineering basis was developed through a detailed control servo system analysis, through mathematical stress analysis, and through a model evaluation program. The scale (1/8) model originally used for chassis design verification was modified and used to evaluate structural response to loads introduced by the uprated steering system. An analysis showed that the proposed hydraulically activated electro-mechanical steering network was inherently stable; testing and operations have verified this many times.

In addition to structural changes, the modification included 16 four-way two-position pilot-operated valves. In the disabled condition, these isolate selected cylinders from the hydraulic pumps. They also allow the double-acting cylinder to "float" by permitting trapped hydraulic fluid to flow back and forth from a compressed chamber into an expanded chamber. The system now has the capability of operating with one or both pump sets and with two, three, or four operating steering cylinders per corner--thus providing complete redundancy with only a small sacrifice in steering rate.

JEL SYSTEM STABILITY

Conventional leveling of large stripping shovels was accomplished by adjusting the relative height of diagonally opposite corners by sensing the height variation with crude mercury-level switches or by using large heavy pendulums to sense level changes. These mechanisms were centrally located and mounted on rigid structures. They were not considered feasible for use on an independent, flexible structure due to tighter level requirements and possible chassis deflection. A manometer-type leveling system extending across diagonal corners was proposed, and a 39.6-meter (130-foot) full-scale experimental mockup was made to determine the dynamic characteristics of acceleration forces inherent in such a system. Theoretical analyses confirmed by test results demonstrated that a closed manometer system equipped with differential pressure transducers was a feasible level sensor for Crawler Transporter applications.

Although diagonal axes may be level, they may also lie in separate planes. Design specifications required that no support point be more than 50.8 millimeters (2 inches) out of plane. Large shovels, when propelling, would connect two adjacent corners together so that the loads would be equal on one end. An off-centered load with such a three-point equalization system could set up large twisting or warping moments in the chassis. Therefore, it was proposed to use a hydraulic-equalizing system, causing the sum of corner loads on one diagonal to be equal to the corner load sum of the other diagonal.

Initial test runs during 1965 resulted in over-reaction and instability in the hydraulic servo system. A stability study and computer analysis revealed that the original pressure loop criteria had not taken into account (1) varying oil compressibility constants caused by cylinder extension nor (2) differences in the spring constant incurred by mass changes between loaded and unloaded configurations.

The problem was corrected by augmenting two additional manometers across the front and rear corners perpendicular to the travel direction. Unloaded moves are performed using only the manometer system for leveling and equalization control. During loaded moves, hydraulic-pressure transducers located at each corner are used to control platform equalization. With the Mobile Launcher on board, the manometer equalization system provides only out-of-limit warnings and shutdowns. Leveling is accomplished at all times by the mercury manometer mechanism.

CONCLUDING REMARKS

In order to meet schedule requirements of a facility of such complexity and unprecedented size, it was necessary for ground equipment design to proceed in parallel with vehicular design. The evolution from concept to operational hardware of such unique equipment was not strictly based on a theoretical approach but on reasonable criteria developed through actual experience with past design and a periodic update resulting from actual and model test results. The Crawler Transporter is an exemplification of this methodology. The end result (see Figure 6) speaks for itself. Theoretical evaluations were supplemented by model tests and these in turn by actual tests of the physical hardware--each stage of the development leading to an improved design.

Although the Crawler Transporter was designed specifically for the Apollo Program, it has supported the Skylab Program without modification, even though the Mobile Launcher pedestal addition for the Skylab 1B configuration caused a weight increase. The adapatability of the independent Crawler Transporter is evident as it has supported various platform configurations for the Apollo and Skylab Programs as well as the giant steel Mobile Service Structure (see Figure 7). The Crawler Transporters will not require modification to transport the Space Shuttle on its Mobile Launcher Platform (see Figure 8). Once again, our Space Program's success will be highly dependent on a tried and proven "mighty tortoise"!

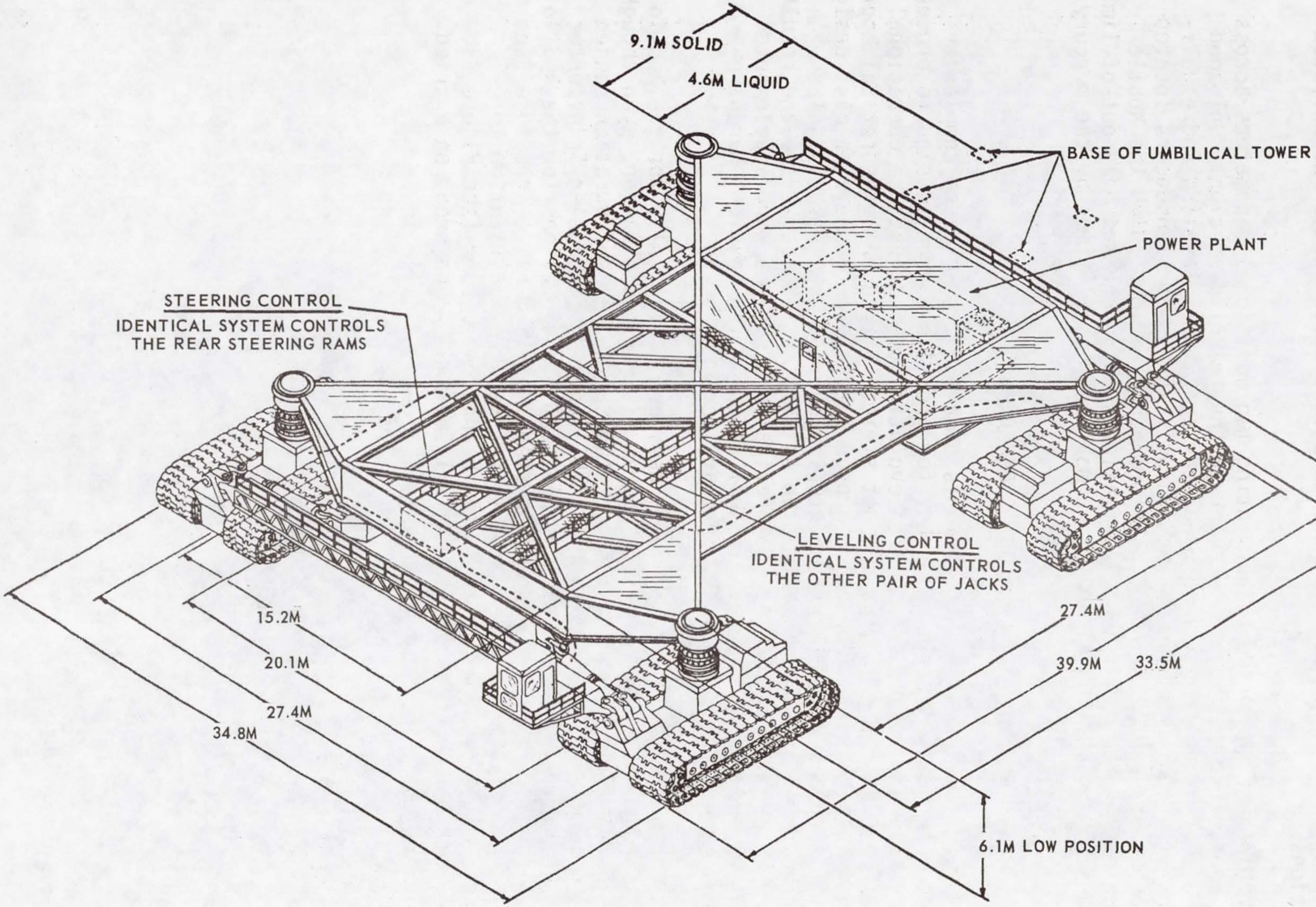

Figure 1. Preliminary Concept: Independent Crawler Transporter

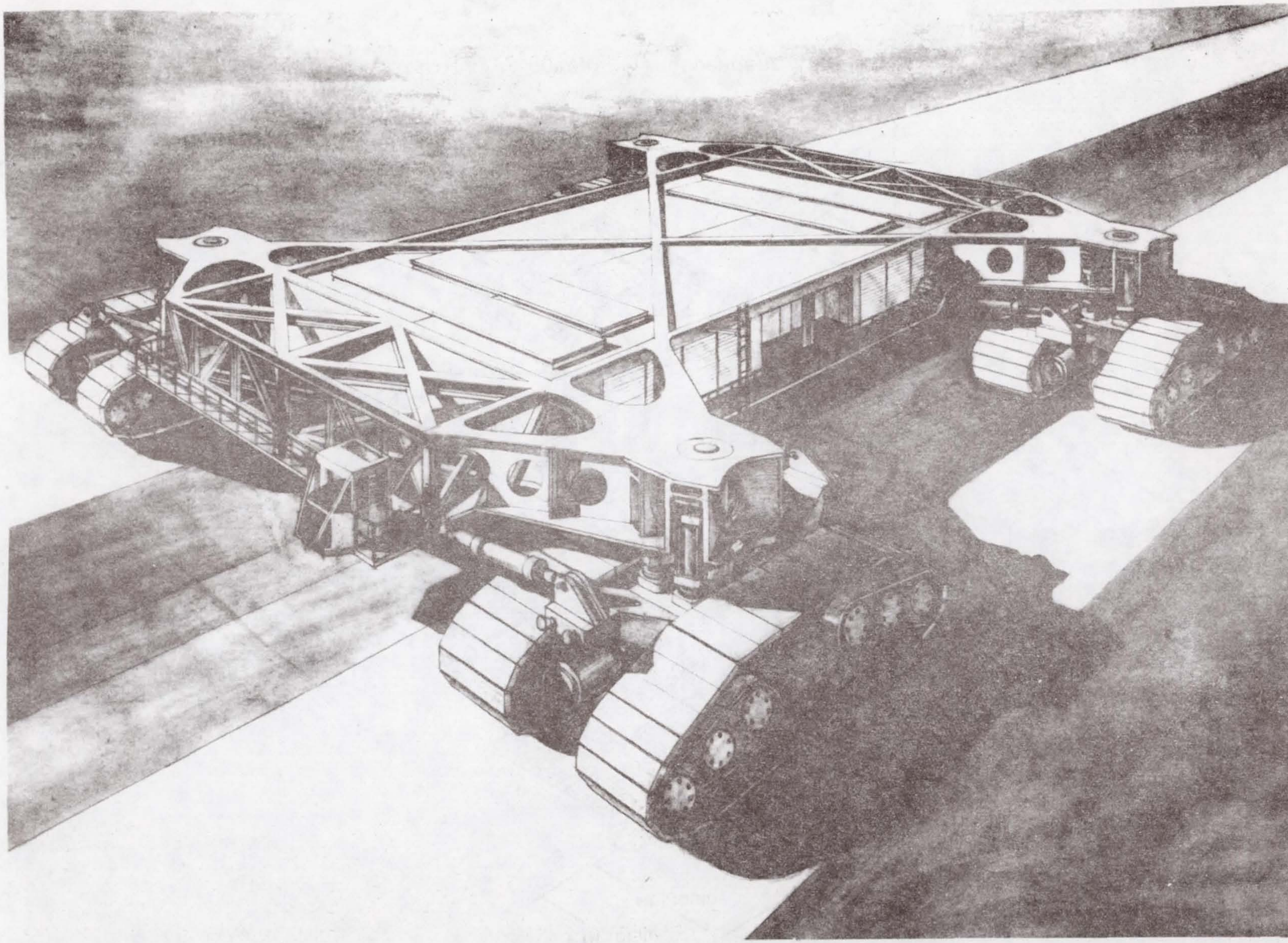

Figure 2. Approved Concept: Crawler Transporter

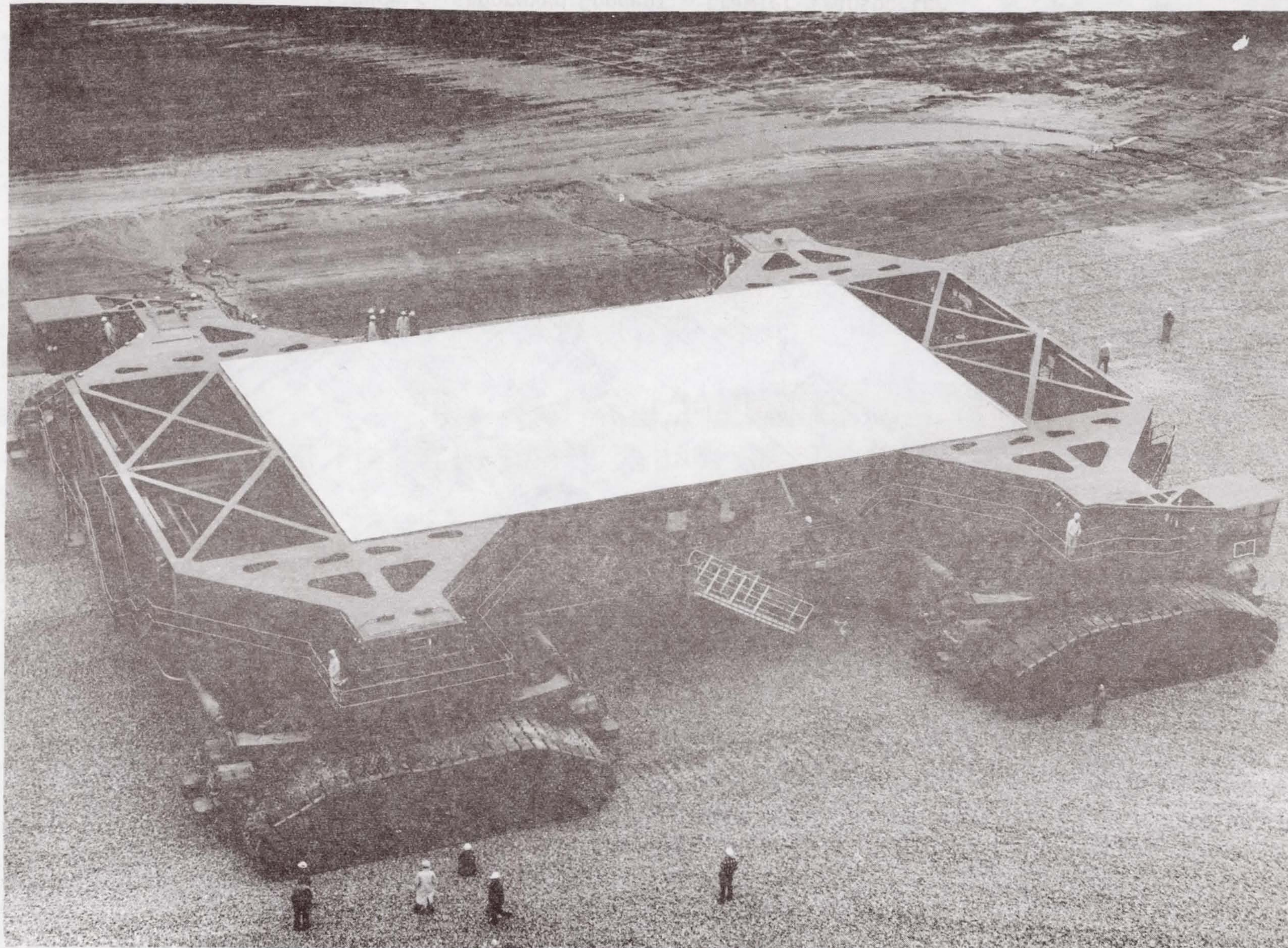

Figure 3. Crawler Transporter

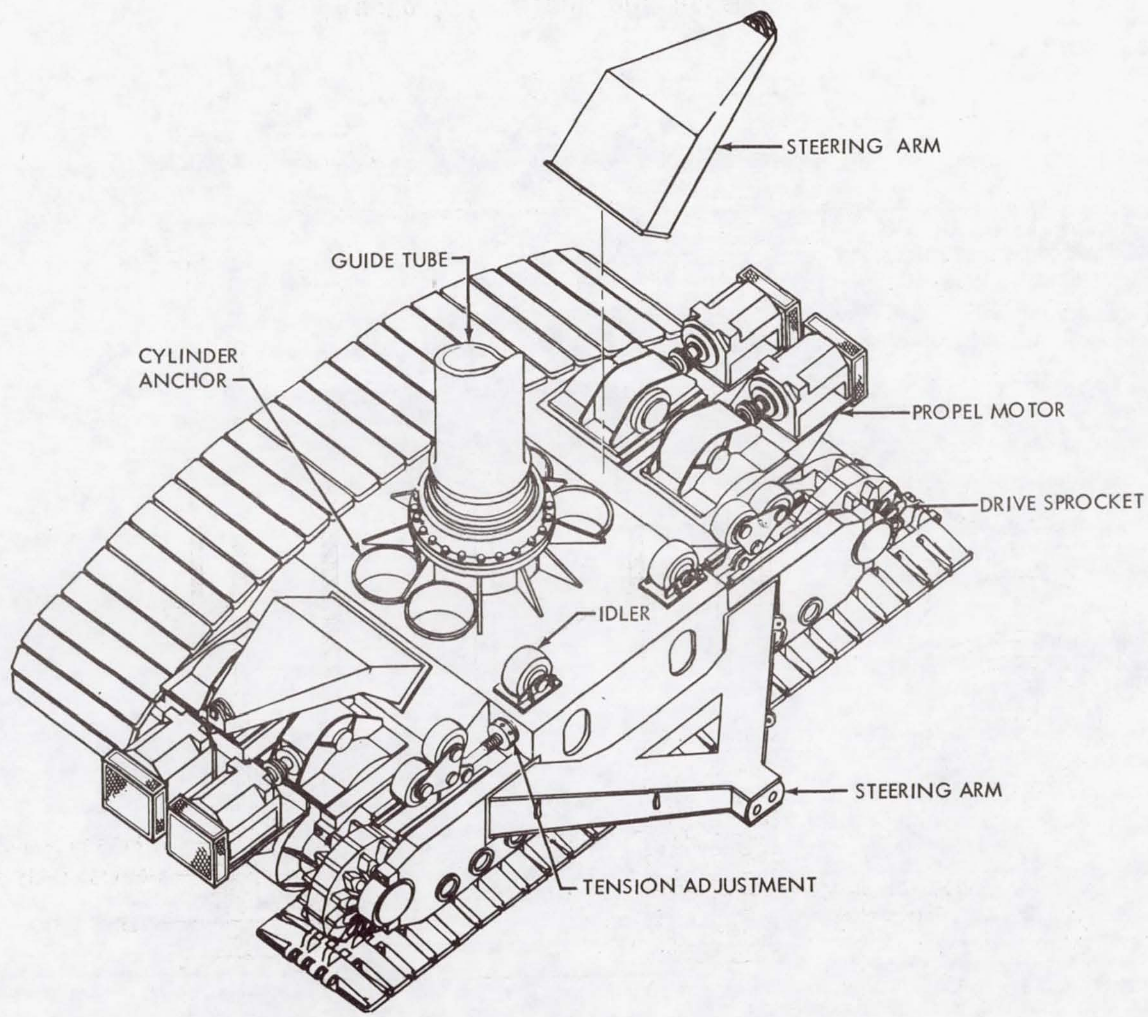

Figure 4. Crawler Truck Assembly

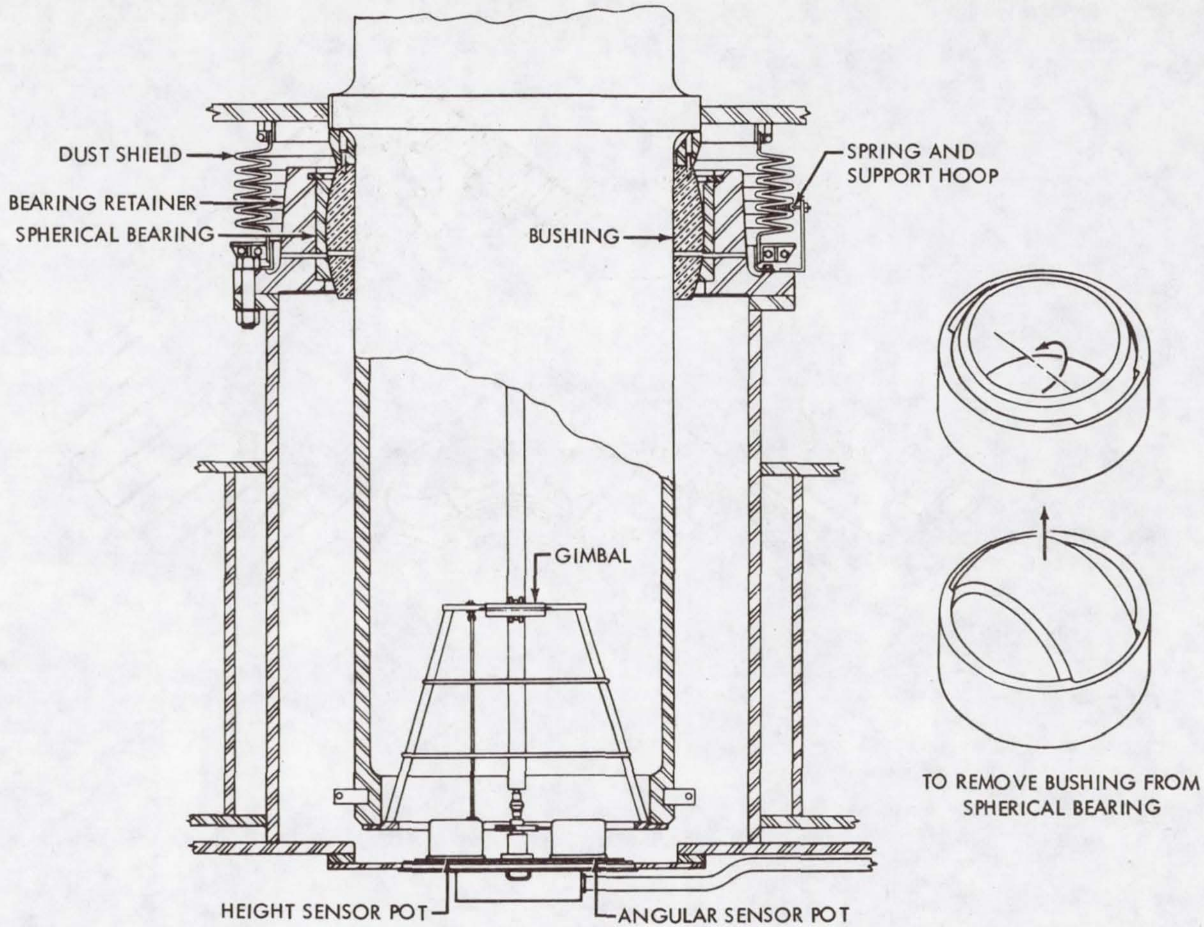

Figure 5. Guide Tube Assembly

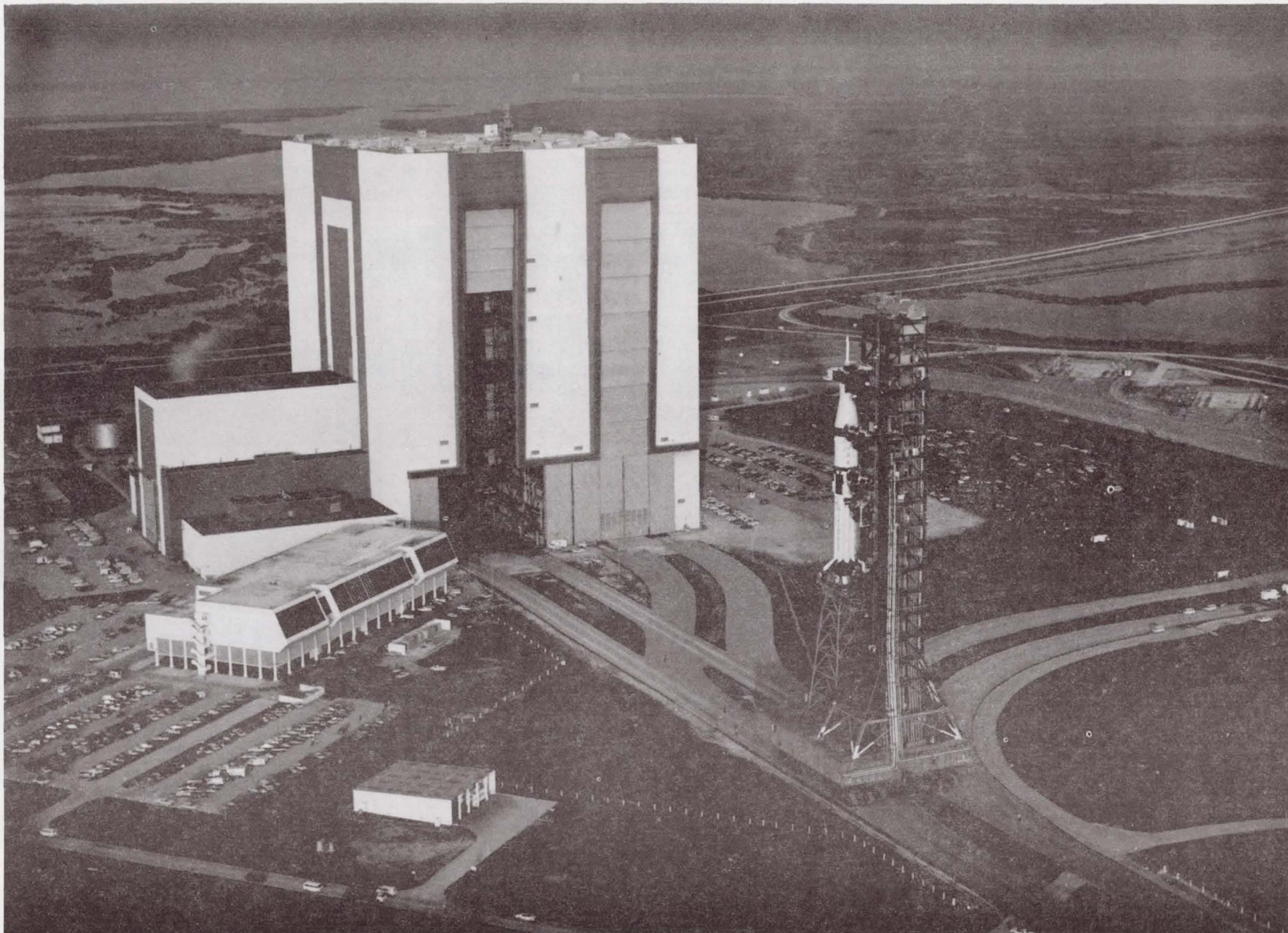

Figure 6. Crawler Transporter Moving Mobile Launcher (Adapted to Skylab II Configuration) from Vehicle Assembly Building

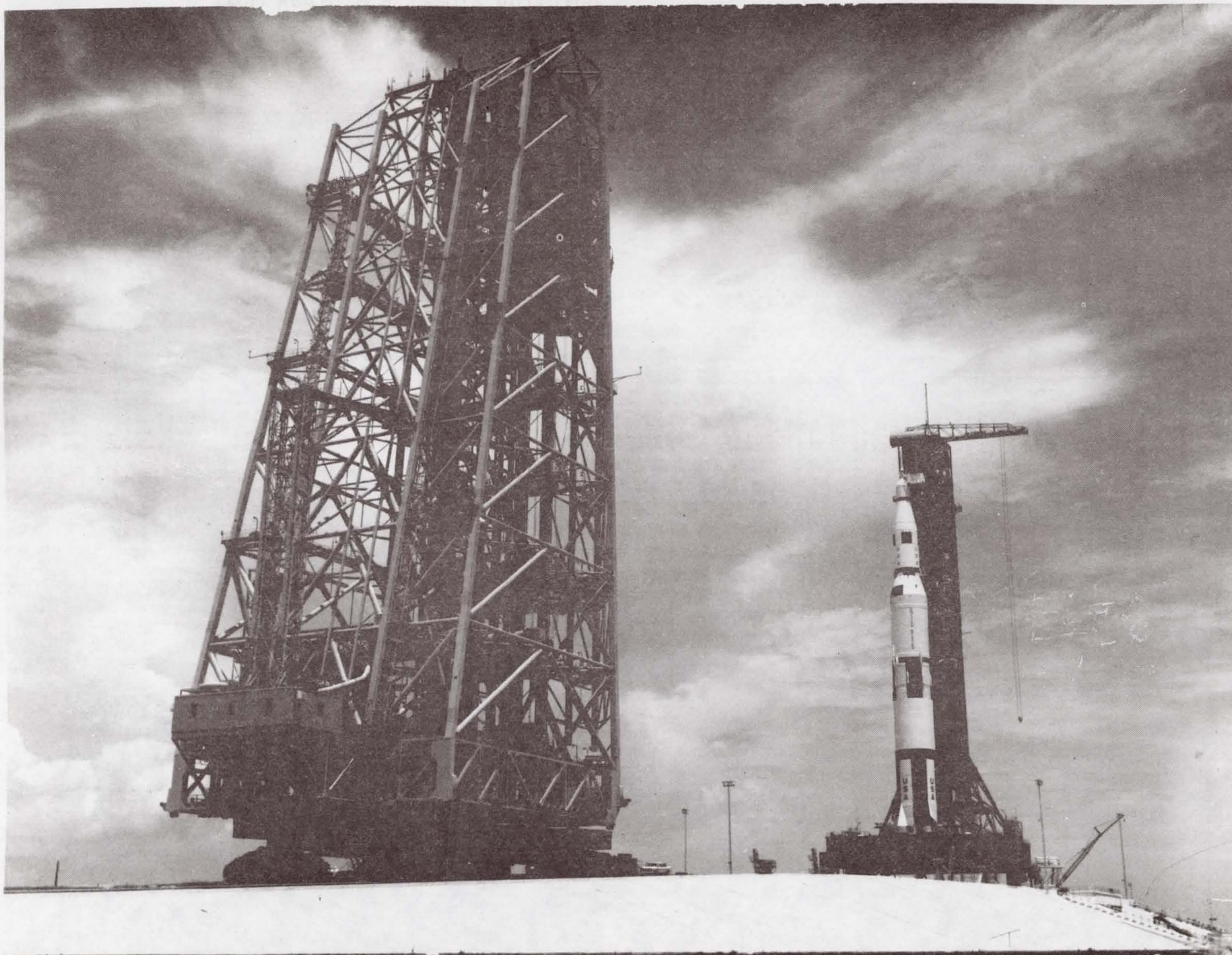

Figure 7. Crawler Transporter Carrying Mobile Service Structure Up Five Percent Slope to Saturn V Mobile Launcher

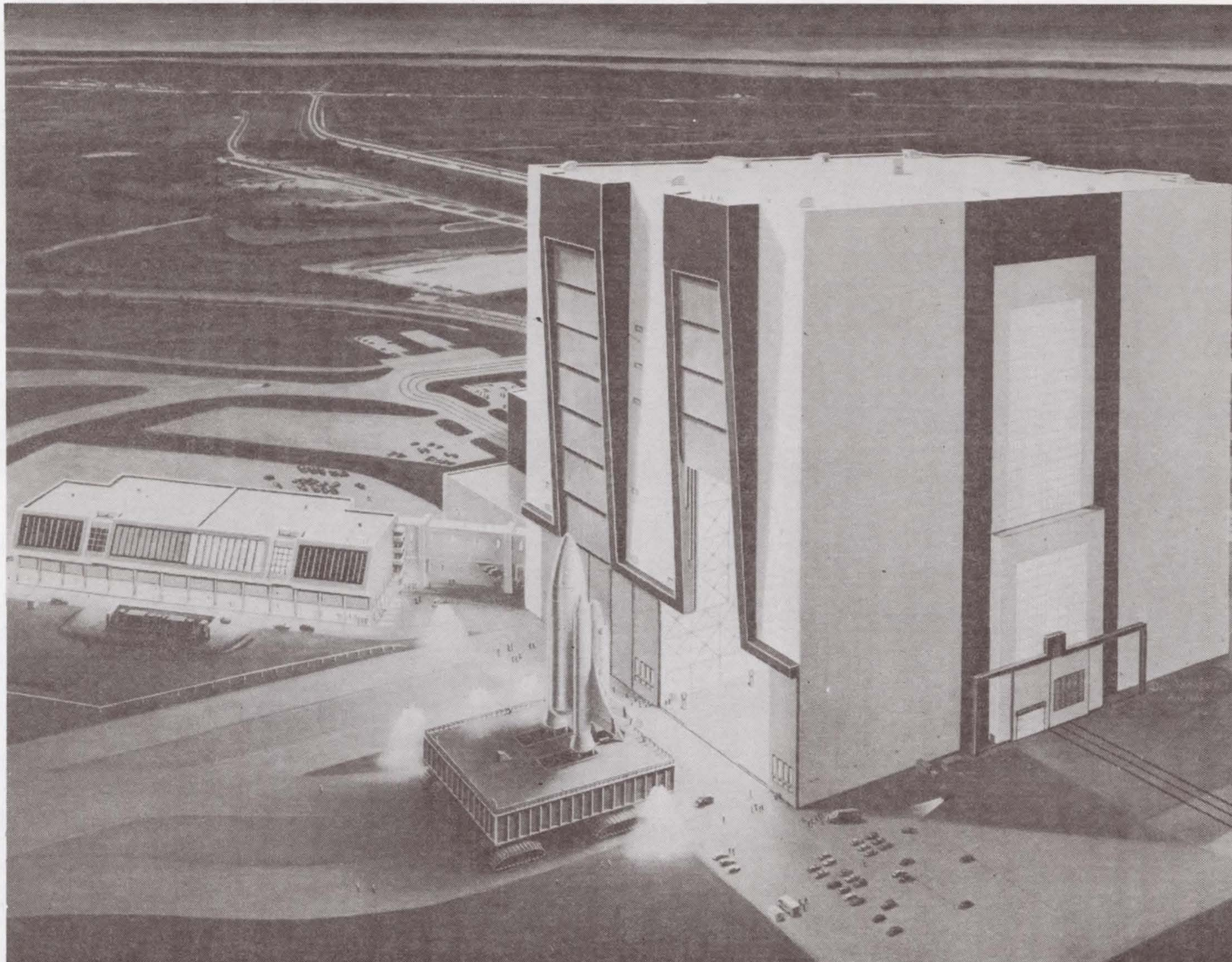

Figure 8. Sketch of Crawler Transporter Carrying ML Platform and Shuttle from VAB