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DESIGN AND CONSTRUCTION OF GROUND SUPPORT EQUIPMENT FOR THE APOLLO/SATURN V LUNAR LANDING MISSION

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DESIGN AND CONSTRUCTION OF GROUND SUPPORT EQUIPMENT FOR THE APOLLO/SATURN V LUNAR LANDING MISSION

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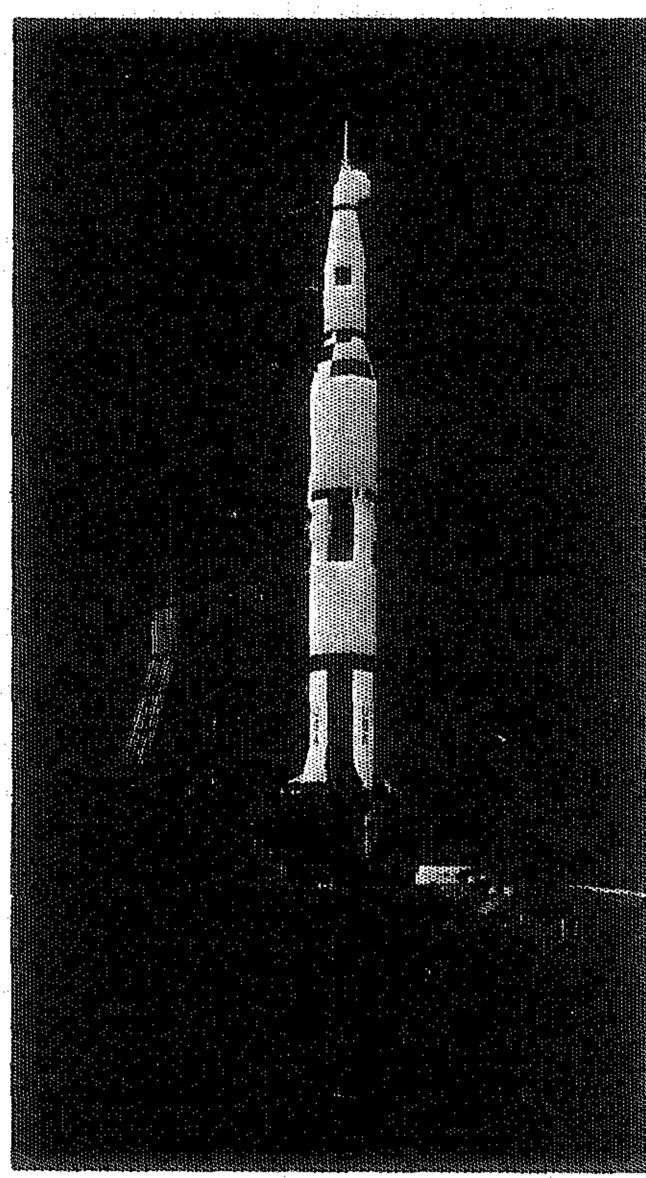
Abstract

Any doubts concerning the feasibility of the mobile launch concept have been removed. Facilities check-out tests using the 500-F version of the Apollo/Saturn V space vehicle testify to the spaceport's readiness to launch the lunar mission. The first Apollo/Saturn V, an unmanned effort, will be launched early this year. Since this is the Nation's first operational spaceport, and since launch of the Apollo/Saturn V will culminate the first research and development effort to build an interplanetary spaceport, much can be learned from a detailed, after-the-fact analysis of the approach, planning, and actual construction of these facilities and ground support equipment. Although design of the spaceport had to be accomplished using existing capabilities, considerable effort was required in terms of expanding the state-of-the-arts. As a result, ground support equipment has taken on new dimensions, new size and proportion, and must be viewed from an entirely new perspective. Ground support equipment now includes the world's largest portable structure, the world's largerst structure of space frame analysis, and many additional major accomplishments in the fields of design and construction. The project is not yet completed, but the majority of remaining work consists of completing additional capabilities to match those already proven successful. The United States has its spaceport.

Introduction

Two points of reference are necessary to comprehensively understand the mission objectives for Launch Complex 39 and related ground support equipment. The first is the Vehicle Assembly Building (VAB) facility. Here personnel of the John F. Kennedy Space Center assemble, check out, test and prepare for launch the Apollo/Saturn V lunar landing space vehicle. Details of the VAB construction have been amply covered by most technical journals, providing a thorough familiarization with aspects of the facility. For a review of major ground support equipment elements, it is sufficient to know that in the VAB the various individual components are processed and mated into an end product that requires only transportation to the launch site, fueling, and a few last minute preparations prior to launch.

Adjoining the VAB is the Launch Control Center. This building houses four firing rooms equipped for monitoring all phases of launch preparations conducted in the VAB, monitoring transport activities necessary to position the space vehicle on the launch pad, and, finally, launch.



That the spaceport is ready is evidenced by the 500-F facilities checkout vehicle standing on Pad A.

The second point of reference is the launch pads. There are two launch pads at Complex 39 with space provided for a third should future launch requirements increase. Launch Pad "A" is complete and Pad "B" is 99 percent complete. Each launch pad offers an interesting story in itself. Far more than steel and concrete, they contain elaborate support equipment and represent advanced states-of-the-art over their historical counterparts which were designed as research and development facilities. The VAB and the launch pads are over three miles apart. The story of Apollo ground support equipment is the story of equipment needed to bridge this gap and support the launch of the Apollo lunar landing mission.

The scope of this requirement has given new depth to the term ground support equipment. In fact, it is becoming increasingly difficult to differentiate between what constitutes ground support equipment and what constitutes facilities. At best, today's definition of ground support equipment must serve as a common ground of understanding rather than a simple label. Ground support equipment is now best defined in terms of what it does rather than what it is.

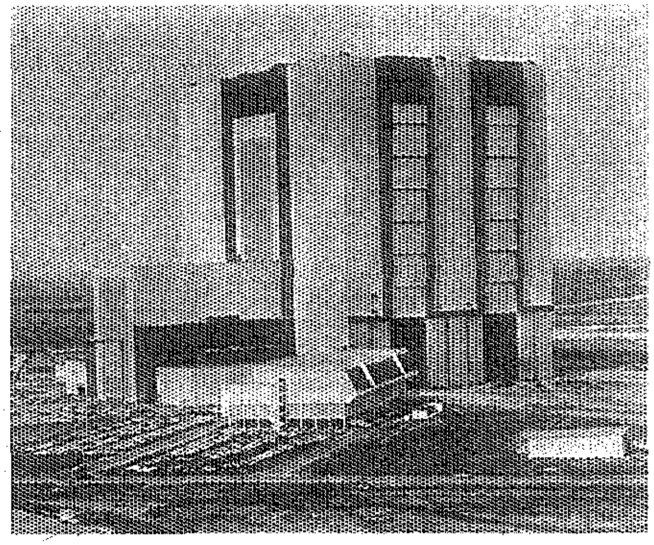
Ground Support Equipment

Ground support equipment, in terms of Launch Complex 39, means any and all equipment necessary to transport the space vehicle from the Vehicle Assembly Building to the launch pad, complete the final prelaunch preparations, and support the actual launch.

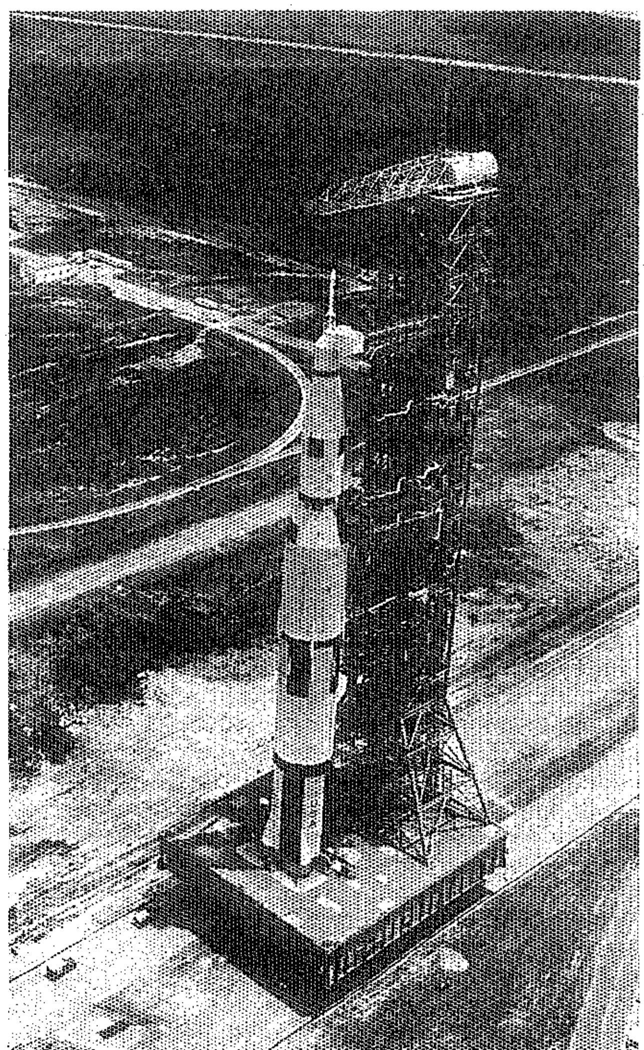
This paper is concerned with major elements of ground support equipment. The problem with categorizing any selection of ground support equipment as major is that, by inference, those items not included are categorized as minor or incidental. This is not the case. Samples of major ground support equipment selected for this paper were chosen only because they dramatize new dimensions in this engineering discipline. They are discussed in terms of mission objectives, letting those objectives provide a brief physical description indicating equipment complexity.

Mobile Launcher

The Mobile Launcher used for the Apollo/Saturn V is the largest gantry in the world. Standing 445 feet high and weighing 10.2 million pounds, its most singular characteristic is that it is portable. The Apollo/Saturn V space vehicle is assembled and prepared for launch while standing on the platform of the Mobile Launcher. The S-IC booster stage is positioned on the launcher immediately upon arrival at the Kennedy Space Center; the Apollo/Saturn V is literally assembled from the ground up. The space vehicle and the Mobile Launcher therefore become an integral unit from the off-set and remain inseparable until the actual launch. Because of this, the Mobile Launcher is really much more than a gantry. It provides internal access to the space vehicle and access for the astronauts, and furnishes fueling links between transfer equipment at the



The Vehicle Assembly Building - assembly facility for the Apollo space vehicle.



The Apollo/Saturn V, Mobile Launcher and Transporter represent nearly 18 million pounds.

pad and fuel receptacles on board the space vehicle. The lower platform is a two-story base containing electronic equipment for relaying to the firing rooms pertinent data needed to maintain an up-to-date log of prelaunch information. A significant fact is that the Mobile Launcher and its electronic equipment were designed and constructed to withstand an Apollo/Saturn V liftoff thrust of 7-1/2 million pounds.

Mobile Service Structure

There are less than 200 buildings in the entire country taller than the 402-foot-high Mobile Service Structure. But, of all 200, only the Mobile Service Structure weighs 9.6 million pounds and is portable. Although the structure contains all the characteristics of a building, it is carried over one mile and positioned at the pad to support prelaunch operations. Of all Apollo program ground support equipment, the Mobile Service Structure best illustrates the difficulty that now exists in differentiating between today's ground support equipment and what five years ago would have been clearly a facilities item. For this reason the Mobile Service Structure will be discussed in detail later.

Transporter

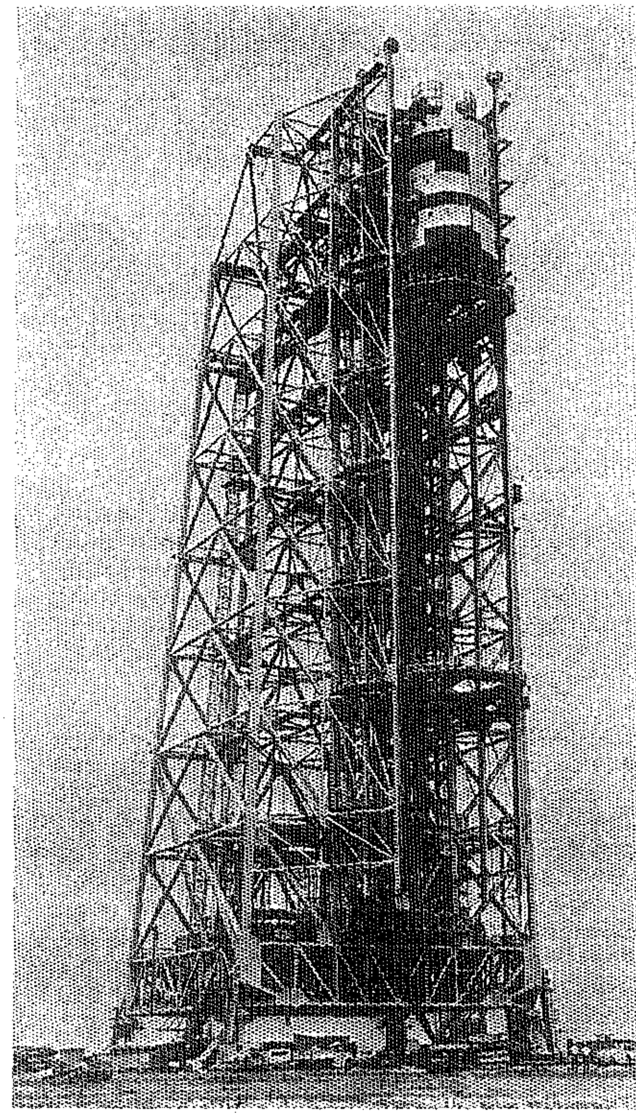
The Transporter is the third element of ground support equipment used in Launch Complex 39 operations, and it is the key to the now well known mobile launch concept. The importance of this piece of equipment cannot be minimized. Obviously, the most singular requirement of any mobile launch concept is mobility. And, as such, the Transporter might be called the pachyderm for NASA's spaceport.

Oversimplified, the Transporter is a 5-1/2 million pound tractor. The spaceport has two, and their basic mission is to transport the Assembled/Saturn V, vertically positioned on the Mobile Launcher, from the VAB to the launch pad. The Transporter will then travel to the Mobile Service Structure parking area and move the structure to the launch pad, positioning it so the clam shell work platforms can encompass the space vehicle.

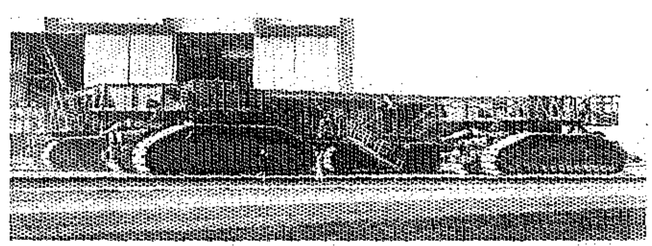
Prior to launch, the Transporter will return to the launch pad, remove the Mobile Service Structure, and return it to the parking area.

To do this, the Transporter must be much more than a tractor. There are three separate on-board power systems, each performing specific functions. Transport power is provided by a power system consisting of two diesel engines with 2750 horsepower each, driving four 1000 KW dc generators (two for each diesel). There are 16 dc traction motors, four on each truck, with a rating of 375 horsepower each.

A second power system, producing a 750 vdc output from each of two generators, powers the Transporter's leveling, jacking, steering, lighting, ventilating, and electronic equipment. Third is a power system that provides alternating current for emergency use and for use during transport. This system provides air conditioning for the spacecraft, provides power for lighting, and runs one of the Mobile Launcher's two elevators. It also activates instrumentation systems needed to monitor critical space vehicle measurements and provides radio frequency communications between the Mobile Launcher and the firing room.



The 402-foot high Mobile Service Structure is the world's largest portable structure.



The Transporter is the 5.5 million pound pachyderm used in the mobile launch concept.

One of the Transporter's more sophisticated assignments comes into play during transportation of the space vehicle to the launch pad. During this operation, the Transporter carries a cargo of nealy 12 million pounds, reaching a height of 445 feet. A computerized jacking system maintains the vertical alignment within 10 minutes of arc. This job is complicated by a turn in the crawlerway road that has a 500-foot radius and an approach to the launch pad that consists of a 5 percent incline plane.

In summary, the Transporter has a big job to do. But, sufficient redundant systems have been built-in to assure continuous, reliable operation, and repeated tests and checkouts have proven that the Transporter, in size equal to half a football field, is also equal to its task.

Crawlerway Road

The Transporter alone cannot solve all transportation problems. Including the weight of the Transporter, the mobile launch concept will require transporting cumulative weights up to 17.5 million pounds. Loads such as these cannot be transferred on Florida's sandy soil; nor, for that matter, could they be supported by modern super highways.

To meet this challenge NASA built a dual roadway designed to support 65 psi. Special preparation for the Crawlerway road bed runs nearly seven feet in depth. The bottom layer of the road consists of two and one half feet of hydraulic fill. On top of that comes one foot of selected fill compressed to maximum density. Three feet of graded lime rock is next and this is then topped off with a sealer coat and four to eight inches of river rock. Each lane of the crawlerway is 40 feet wide and layed out on a 90-foot center line. This gives the crawlerway an overall width of 130 feet.

A Closer Look

These then are a few examples of the new dimensions in ground support equipment. But the greatest singular example of growth contributed by the Apollo program to the world of ground support equipment is one of challenge. Some of these challenges were products of size and complexity, some were products of environment, and some were products of the program itself. All, however, warrant the attention of the scientific and technical community. Lessons learned on the Apollo program will pay dividends for many years to come. A good example of this increased challenge can be obtained by a review of the technical problems that highlighted design and construction of the Mobile Service Structure.

Natural Elements

Before reviewing the detailed design criteria for the Mobile Service Structure, it is necessary to understand the basic design considerations presented by the environment of Central Florida and prevalent in the design considerations of all Apollo ground support equipment.

Choosing a site for our nation's first operational spaceport required an intense effort. After the final technical qualifying factors had been evaluated, eight locations remained for consideration. Of those locations, Central Florida was the area most capable of meeting the human factors essential to an industrial complex employing over 20,000 people. But selection of Merritt Island as the site for the Spaceport also presented some adverse conditions that would affect each of the design efforts.

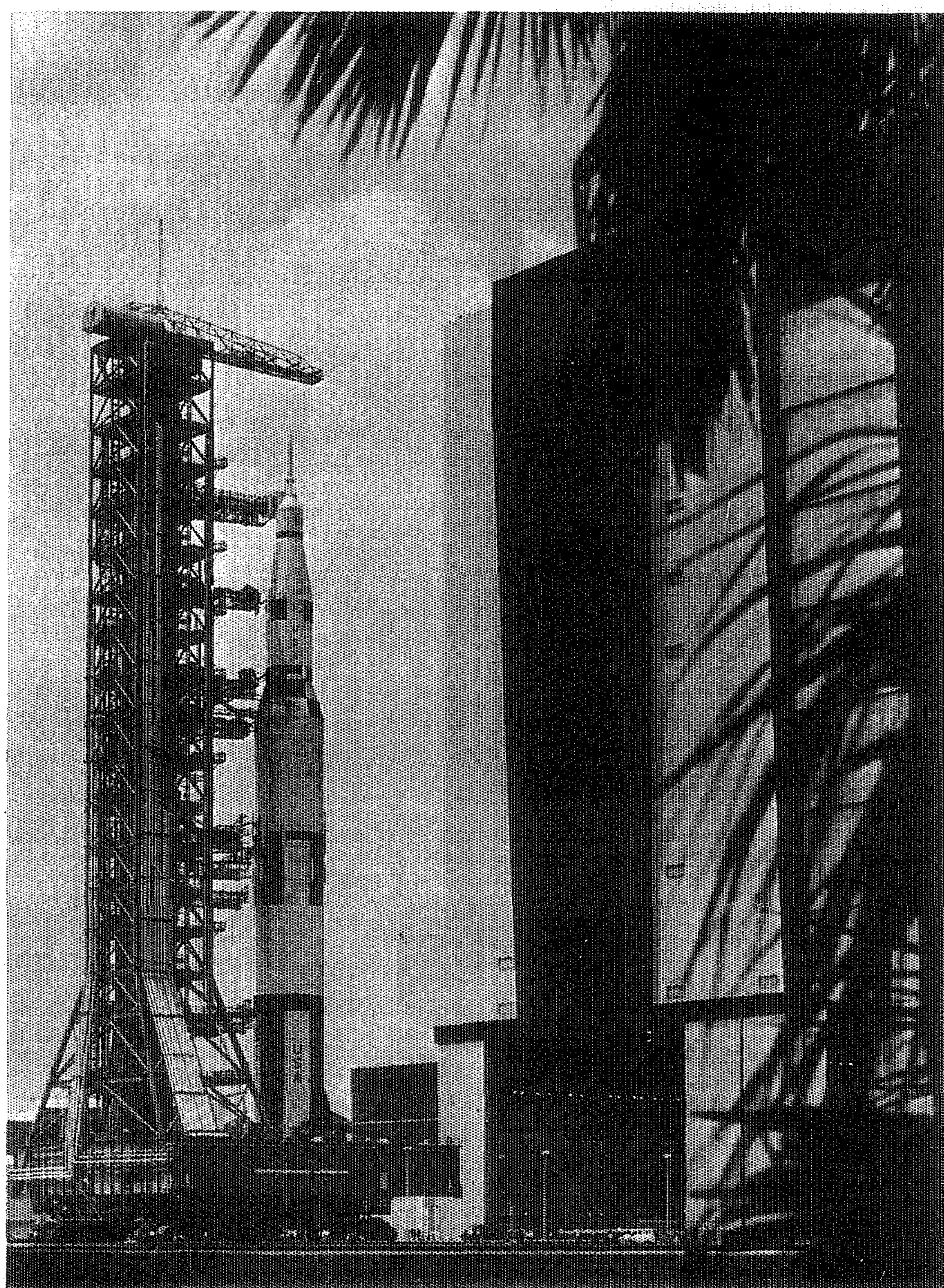
Central Florida is a semi-tropical, seaside area. This meant designing the mobile launch concept for soil conditions not consistent with the required equipment weights. The upper miocene of the Brevard County coastal region consists of a top layer of fine sand and shell 39 feet deep. Beneath this are silt and clay reaching to the 94-foot level. At that point there is a hard layer of indurated clay and then more silt and clay extending down to the 148-foot level. Below this is limestone.

The spaceport faces the ocean and is constantly exposed to extreme natural elements. Early consideration was, therefore, given to the prevention of corrosion. Much of the ground support equipment was to be built of ASTM-A36, and the structural steel would receive a daily coating of five microns of salt. Rain, which might normally be expected to furnish a natural rinse, merely compounds the problem. Rain in coastal Florida forms around grains of salt resulting in a saline deposit that, during precipitation, exceeds 100 microns.

Corrosion prevention techniques had to withstand galvanic corrosion, filiform corrosion, fungi caused by high humidity and emphasized by the presence of fuel vapors, stress corrosion, and hydrogen corrosion.

Of equal significance was design effort needed to prevent damage by high winds. In the last 20 years Florida and the surrounding two hundred mile area have felt the effects of 23 hurricanes, 16 tropical storms and five tropical depressions. These figures have dual significance. In addition to designing against wind damage, the operational aspects of the spaceport had to be designed to remain mobile in winds up to 43 mph, and functional in winds up to 63 miles per hour. Directly related to high winds, and especially hurricane force winds, was the possibility of high-water damage. Hurricane tides in Florida reach as high as 14 feet. The average ground elevation is 8 feet above sea level.

Lightning protection furnished another area of activity. Estimates for the level of lightning protection required for the spaceport were based on the



The Apollo/Saturn V is assembled on the Mobile Launcher and the two remain mated until launch.

isokeraunic system. Relating lightning probability to the frequency of thunder storm activity, Florida has one of the higher probability factors in the country with an isokeraunic rating ranging from 70 to 90 thunderstorm days per year.

A mathematical illustration of lightning probability is furnished by our three Mobile Launchers. Under maximum conditions an average of five lightning strikes per year were expected for each of these structures. Of primary concern was crew safety and the damage that could result from a direct hit. In addition to the possibility of superficial damage, Apollo ground support equipment is characterized by sophisticated electronic equipment that would be subjected to peak loads surpassing their design limitations. Finally, protection was needed for the Apollo/Saturn V which, on the launch pad, fueled, and ready for launch, represents the explosive potential of one million pounds of TNT.

Concurrent Design

A second set of design problems were introduced by the very nature of the Apollo program. With a 1970 deadline for landing our astronauts on the moon, there was little time for planning activities in terms of optimum sequencing. In order to maintain schedules many projects had to be accomplished simultaneously that would more desirably have been scheduled step by step. In short, the problem faced was one of concurrent design.

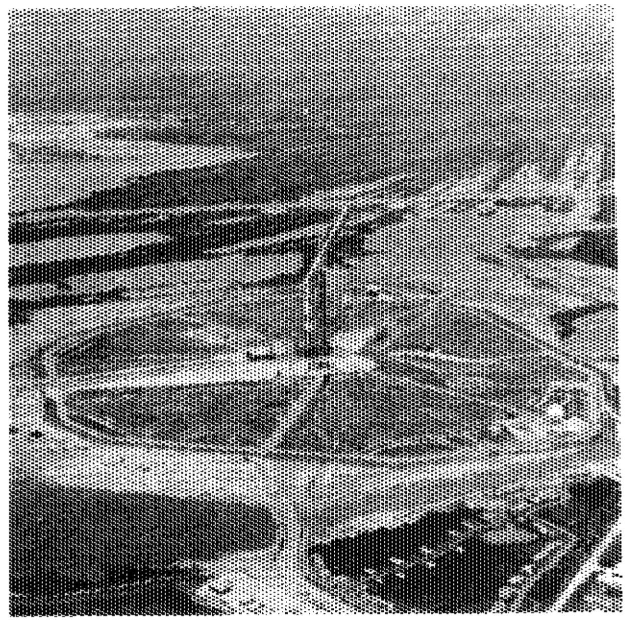
The Mobile Service Structure interfaces with virtually every major element at Launch Complex 39. And yet, to hold to the Apollo schedule, design engineers working on the Mobile Service Structure had to anticipate features of the Mobile Launcher, the Transporter, and even the launch vehicle itself, which had not yet been finalized.

Mobile Service Structure

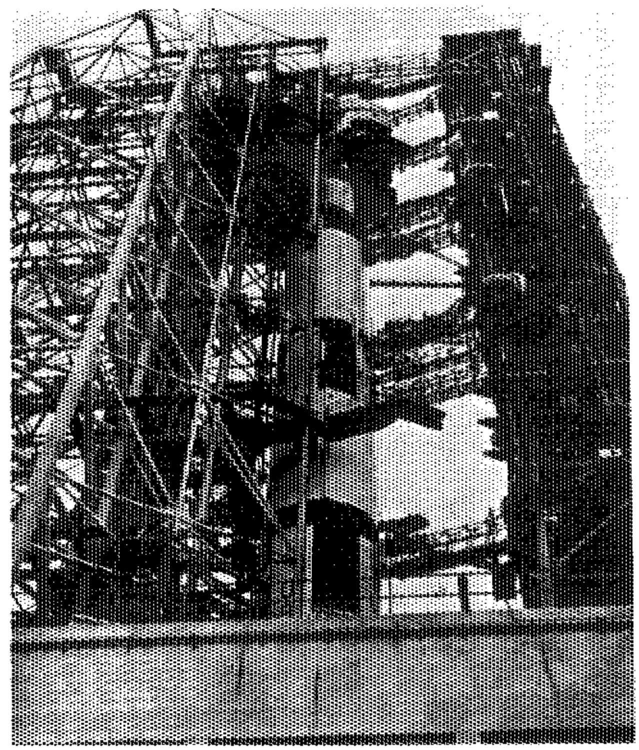
These were all factors that applied universally throughout Launch Complex 39. They controlled decisions made on virtually every aspect of design and construction for the nation's spaceport. To these factors were added the specific qualifications of each item of ground support equipment. Again, the Mobile Service Structure serves as a good example.

Work Platforms

The Mobile Service Structure provides 360-degree personnel access for the full 354-foot height of the Apollo space vehicle, including the Command Module, Service Module and the Lunar Module. It also serves for the check-out of systems, adjustments to components, installation of certain pyrotechnic devices and the servicing of other operational systems necessary for final launch preparations. All of these functions are carried out by personnel working on five work platforms, and as



Launch Pad A during facilities checkout of the 500-F version of the Apollo/Saturn V.



The Mobile Service Structure is positioned at Pad A with work platforms encompassing the launch vehicle.

such, the entire Mobile Service Structure exists for one reason - to support platforms and their related activities.

Design of the work platforms involved a number of considerations. The two lower platforms were to be vertically self-propelled to service all levels of the launch vehicle. The top three platforms, fixed platforms had to be capable of being repositioned to allow for possible future vehicle configurations. Each platform had to be designed so it could be opened while the Mobile Service

Structure was being positioned at the launch pad, yet, when closed, adequate clearance must be maintained for deflection of the vehicle and the structure due to wind and weather conditions. In the final analysis, the lower four work platforms were designed using the clamshell concept while the top platform uses the vice-jaw method.

A definite clearance band or spectrum of tolerances was developed to assure mating of the tower structure, work platforms, vehicle booster and all projections in the launch area. It was decided that the Mobile Service Structure would be set down within $\pm$ 6 inches of the fixed support column centers and it had to arrive at the launch pad within 6 inches of the design elevation.

Weight was another limitation. Based on the capabilities of the Transporter, the total weight allowed for the Mobile Service Structure, including all permanently mounted equipment, was limited to 12 million pounds. In addition to this basic weight value was the specification that not more than 4 million pounds could be directed to any of the four pickup points under any loading condition.

In reviewing basic design criteria it is necessary to talk about each factor, separately. But the design and construction of the Mobile Service Structure posed a series of interlocking problems with the solution to one problem depending on the solution of another.

For example, while at the parking stand, the Mobile Service Structure will rest on pedestals located at the outer four corners. During transit, the Transporter will carry the Mobile Service Structure by a second set of pickup points located on 90-foot center lines. The resulting stress reversals are such that the Mobile Service Structure actually required designing a piece of ground support equipment that must meet two sets of circumstances. It required two structures in one.

Personnel Access

There is one additional design criterion to define, mostly because it was unique in itself - personnel access. The requirements for matching certain specific points on the Mobile Launcher with points at the launch pad, indicated that the lowest basic working level (the base deck of the tower) would be 47 feet above the roadway.

This meant devising an elevator which could be lowered to the ground and operated as a normal elevator, and then be raised into the structure for clearance when the Mobile Service Structure was in transit. This "elevator within an elevator" made it possible to carry men from the ground level up to the working deck. Once on the Mobile Service Structure, high rise elevators would carry them to the work platforms and fixed lower landings.

These then, are some of the major factors that confronted the design engineers as they first tried to imagine the proper configuration for the Mobile Service Structure.

Structural Configuration

Design engineers developed a general tower configuration that consisted of eight tower sections, each approximately 44 feet high. The result was four parallel upright trusses approximately 355 feet high resting on a 22-foot deep base truss complex 130 feet square. Two lateral trusses were formed by the addition of bracing members across the front and rear planes of the tower. The resulting tower and base structure consisted of 1458 members connected at 416 joints. It was from the forward plane of this assembly that the work platforms were cantilevered.

During the preliminary design stages all trusses which proved to be determinate were solved by graphical methods and all trusses statically indeterminate were solved by the method described by C. C. Maugh. The most complicated indeterminate trusses, the front and rear planes, required 48 simultaneous equations for solution. These equations were written and programmed into a 1620 computer and required 3-1/2 hours of solution using the Gauss-Seidel iteration procedure. Based on the results of these solutions the preliminary member sizes were chosen.

The results of these preliminary calculations confirmed early doubts. As the 1620 computer published results, it became increasingly clear that a structure of this size, having to meet the demands of mobility, total weight, weight distribution, and the other factors earlier outlined, had to be analyzed as a single unit, a space frame, if we were to obtain an accurate accounting of the forces and stresses within each member. The magnitude of this analysis surpassed any known method of manual calculation.

The final structural analysis was obtained by modifying the relatively new space frame computer program "FRAN." Input data for this program amounted to determining x, y, and z coordinates for each of 416 joints and the various properties of each of the 1458 members. All properties such as section modulus, moment of inertia, area, radius of gyration, etc., were recorded on data cards and fed into the computer. An additional set of cards was prepared stating dead loads, live loads, and wind loading conditions.

After much discussion, a total of 15 combined loading conditions were programmed into the computer. These included winds normal to each plane, diagonal winds, and various loadings that could result from possible malfunctions of the Transporter or other operational hazards. The resulting drag factor would have a direct bearing on the capability to hold maximum weight distribution to each pickup point at less than 4 million pounds. The resulting computer solution gave a drag factor of 0.9, surprisingly close to 1.3 that would be normal were the Mobile Service Structure a closed-in structure.

Construction

The actual construction of the Mobile Service Structure presented a series of challenges in which project engineers sought to find simple solutions to complex problems.

Some method of weighing the Mobile Structure was necessary to provide constant monitoring of both total weight and weight distribution during construction. A unique system of load cells was designed with one placed on each of the fixed support columns upon which the Mobile Service Structure was assembled. These load cells were also used to determine the reactions caused by wind forces on the structure. The resulting information will help to fill the presently existing void for data describing wind forces on large open structures.

Not a Structure

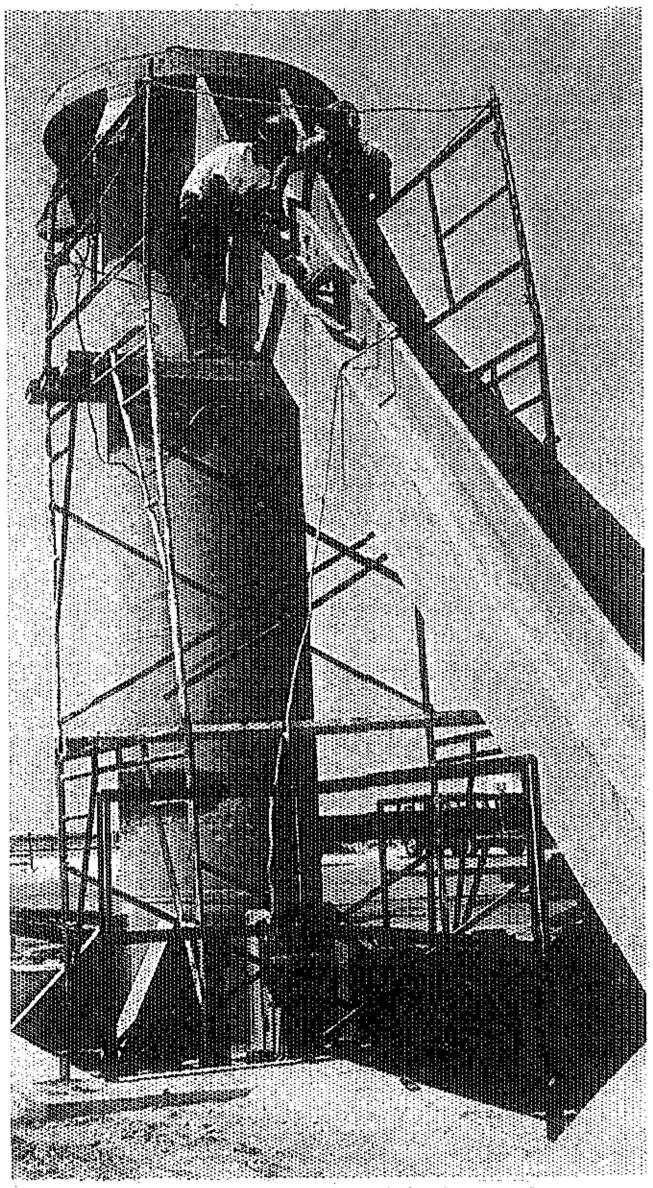
It was also during construction of the Mobile Service Structure that the term structure became looked upon as a misnomer. As earlier stated, the purpose of the entire structure is to support the tower's relocatable work platforms. These five platforms range in weight from 50,000 to 250,000 pounds. They are mounted on gear-tooth racks that run the full height of the platform support structure. The two moving platforms are powered by electric motors driving gears that move the platforms vertically at a travel rate of 10 feet per minute. In addition, the fixed platforms are locked onto the racks but can be repositioned with a system of cables and sheaves using one of the self-propelled platforms as motive power. In reality then, the Mobile Service Structure is not a huge portable structure -- it is a nine-and-one-half-million pound portable elevator shaft.

It is in viewing the Mobile Service Structure as an elevator shaft that one of the more interesting problem areas arise. As previously stated, the combined weight of the five work platforms is 945,000 pounds. These platforms could not be added to the structure until the basic tower assembly had been completed. Adding this much weight after tower completion was known to result in a calculated spring back of the forward plane. This spring back had to be built into the design concept with additional tolerances provided to assure a sufficiently true forward plane that would allow free vertical travel for each of the work platforms.

To accomplish this the construction team was allowed a tolerance of $\pm$ one inch for any hundred feet on the forward vertical plane and $\pm$ one inch for the total height. Maintaining this tolerance was further complicated by the necessity of the built-in chamber to allow for the spring back. This chamber was four inches distributed equally along the entire height of the forward wall.

In the final analysis the forward plane of the Mobile Service Structure was 1-1/2 inches out of alignment when completed, half an inch too much. To overcome this defect several gusset plates were reworked and the columns placed in tolerance for alignment.

It would be difficult to limit the volume of pertinent data on the design and construction of the Mobile Service Structure. The task was major and its completion represents an example of team effort typical of the space program. NASA's agent for supervising the design and construction of the Mobile Service Structure was the Canaveral District of the U.S. Army Corp of Engineers. The actual design and engineering were provided by the Rust Engineering Co. Construction was accomplished under a prime contract awarded to the joint venture of Morrison-Knudsen-Perini-Hardeman. These, however, are only the major responsibility areas. It would be difficult to itemize the total participation required to complete the Mobile Service Structure.

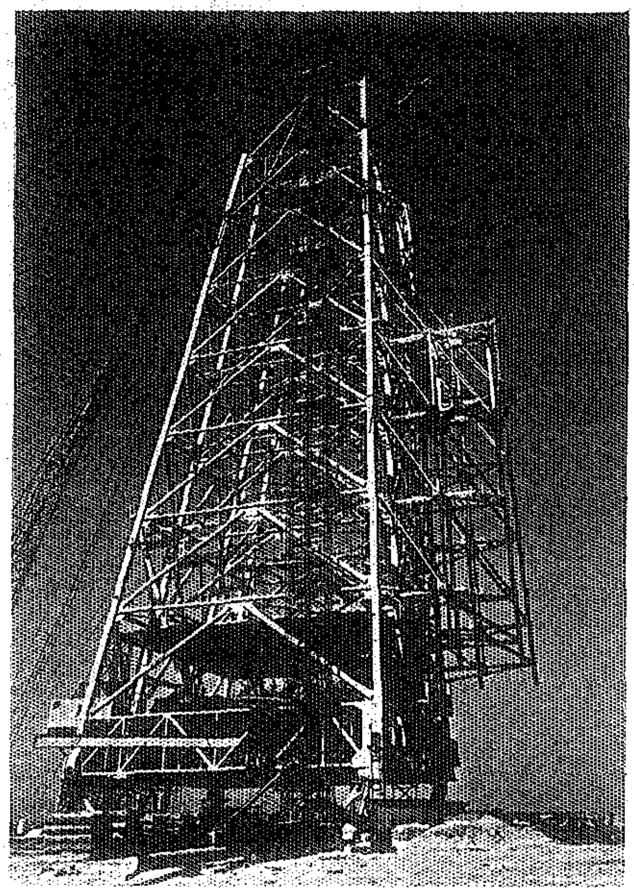


Four support columns hold the Mobile Service Structure while at the parking stand

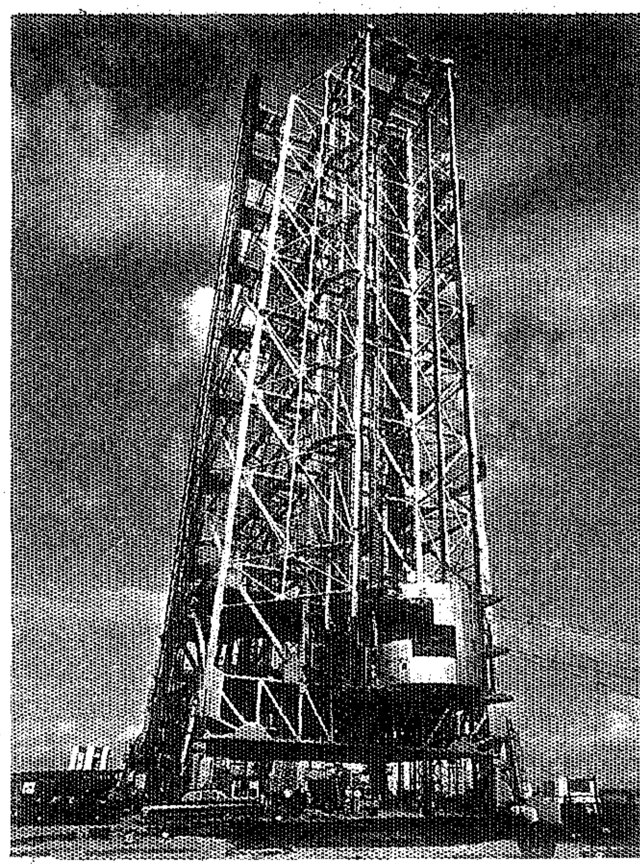
Conclusion

As interesting as a detailed study of the Mobile Service Structure might be, it only serves as one example of an entire new family of ground support equipment. What is needed now is a complete in-depth study to collect and document the magnitude of this accomplishment by ground support engineers.

Even after such a study, the true magnitude of the challenges faced, can be fully realized only by those members of the NASA/contractor team that faced these problems as a day to day way of life. This idea was summarized by a Senior Design Engineer who worked on the design of the Mobile Service Structure. His final report on this project concluded, "In closing, I would like to say that the engineering and design of the Mobile Service Structure was truly a team effort; all the engineers, designers and draftsmen deserve recognition for their participation in this unusual project and I am certain the problems, frustrations and at times the despair we all felt made better engineers of all of us."



A four-inch chamber was built in to allow for spring-back caused by 950,000 pound work platforms.



A final adjustment of half an inch was required to bring structure's front plane into tolerance.