Base for U.S.A. manned spaced rockets

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Base for U.S.A. Manned Space Rockets[1])

(Structures for Assembly and Launching)

Base américaine de fusées spatiales habitées

(Installations de montage et de lancement)

Amerikanische Basis für bemannte Weltraum-Raketen

(Montage- und Start-Anlagen)

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Introduction

The current manned space rocket program of the National Aeronautics and Space Administration (the first phase involving a Moon Landing) makes use of a combination of space-rocket and spacecraft standing 364 ft. high and weighing 3000 tons when ready for take-off. The space rocket itself without fuel weighs 250 tons. Earlier space vehicles were assembled on their launching pads where it sometimes took many weeks before all pre-launch operations and tests could be completed. In 1962 the National Aeronautics and Space Administration (NASA) determined that the moon would be the initial objective and that a more economical and efficient manner of handling the new huge Saturn V space rockets should be used. It was decided:

— to assemble and test the vehicle components indoors in a controlled industrial environment — a huge hangar with a capacity for assembling four space vehicles vertically, the Vehicle Assembly Building (V.A.B.);

— and to transport each launch-ready vehicle in upright position to its pad where after fueling and final pre-launch checks the lift-off would take place.

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[1]) A preview of this report, entitled "An Important Rocket Base in the U.S.A.", was presented at the 7th Congress of I.A.B.S.E. at Rio de Janeiro on 12 August 1964.

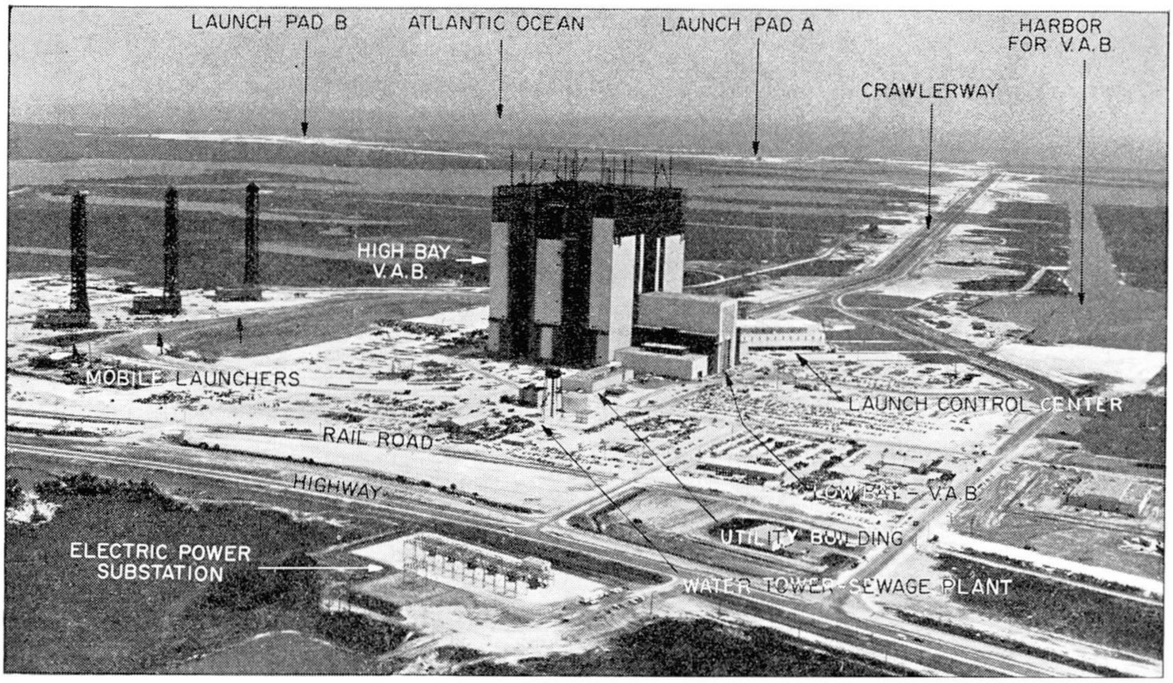


Fig. 1. Air view of entire complex 39.

The pads are separated from the assembly area and nerve center by about 3 miles, the distance required for safety from noise and blast.

Engineering difficulties arose from the beginning because of the immense size and weight of the rocket components and the short period available for the design of the assembly facilities. It was necessary to design the industrial and erection facilities for the rocket components even before the full details of units such as rocket parts, engines, and devices were known.

Three concepts for the transport of the space vehicle from the hangar to the launch pad were considered:

Rolling the vehicle on rails supported by heavy concrete foundations.

Floating it on a barge in a system of canals.

Moving it on a caterpillar-tread transporter, called the crawler-transporter, along a high-capacity dual road with $6^1/_2$ ft. thick flexible pavement, called the crawlerway.

The crawler-transporter concept was adopted because its estimated cost proved to be the lowest. The space vehicle will be erected inside the assembly building (V.A.B.) on a 160 ft. $\times$ 137 ft. launch platform 46 ft. high which also supports the rocket's 380-ft.-high umbilical tower. The entire platform, referred to as a mobile launcher, together with the space vehicle and its computer complex, will be lifted from its place in the V.A.B. by a crawler-transporter and will be moved to the launch pad as one unit. The load, totalling $17^1/_2$ million pounds, including the weight of the crawler-transporter, will be moved against winds up to 46 miles per hr at a speed of 1 mile per hr. Each mobile launcher is the base of an actual launch and is designed for the expected

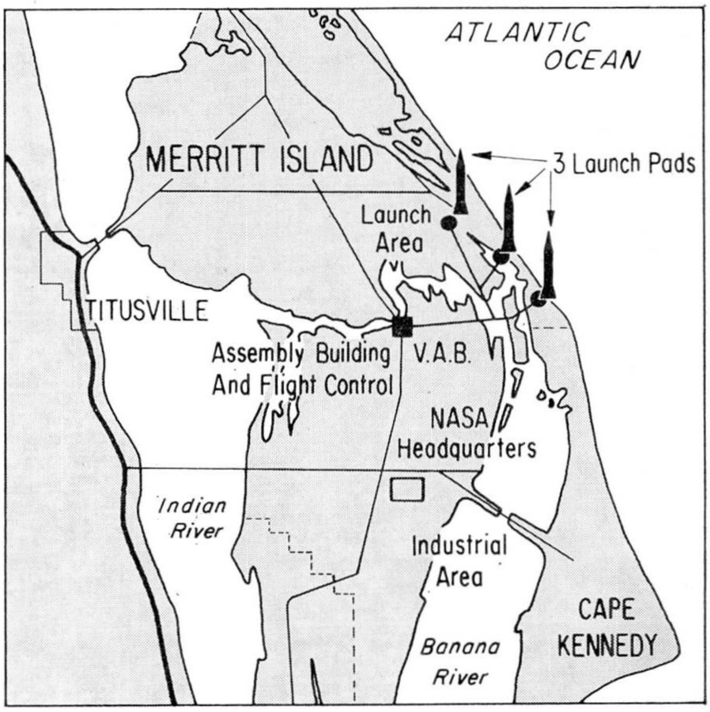


Fig. 2. Location plan.

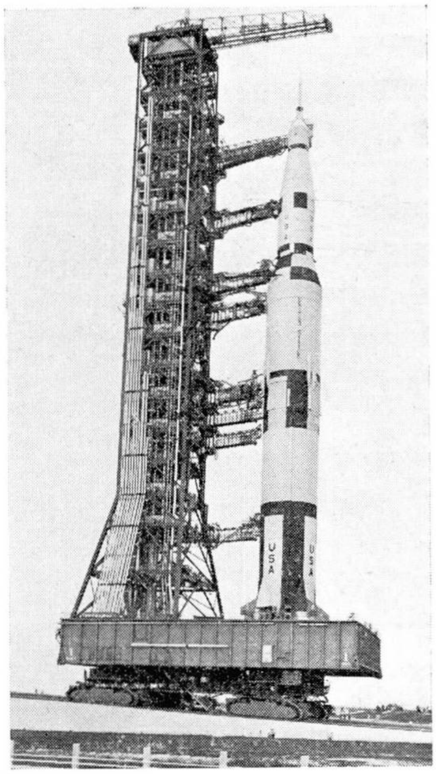


Fig. 3. Mobile launcher with space-vehicle.

temperatures, stresses, and vibrations. The essential tested connections to each space vehicle are never separated from the ground support and the launch control equipment during the assembly, transport and pre-launch stages. The nerve center with its orchestra of instruments for check-out, control, and pre-launch testing is the Launch Control Center, from which the launch operations will be conducted.

The Vehicle Assembly Building at the NASA John F. Kennedy Space Center in Florida is a huge structure. Towering 526 ft. high, its doorways are large enough to admit a 45-story skyscraper. Its volume is the greatest ever enclosed in a single building; it required about 100000 tons of steel and is equipped with two 250-ton capacity cranes of 462-ft. hook height. Foundations required a forest of piles whose total length measures 128 miles.

Fig. 3 shows a mobile launcher with its steel platform on which the first Apollo Saturn V Moon Rocket is mounted. The umbilical tower firmly connected to the platform is shown on the left carrying cabling, propellant fuel, and other services to the vehicle and to the spacecraft through eight umbilical swing-arms. The picture shows the crawler-transporter on the inclined ramp to the pad moving the launcher with the space-vehicle. A balancing device keeps the rocket vertical.

Fig. 4 shows the crawler-transporter, a huge tractor-like vehicle, self-powered and equipped with four twin-track caterpillars. The crawler-trans-

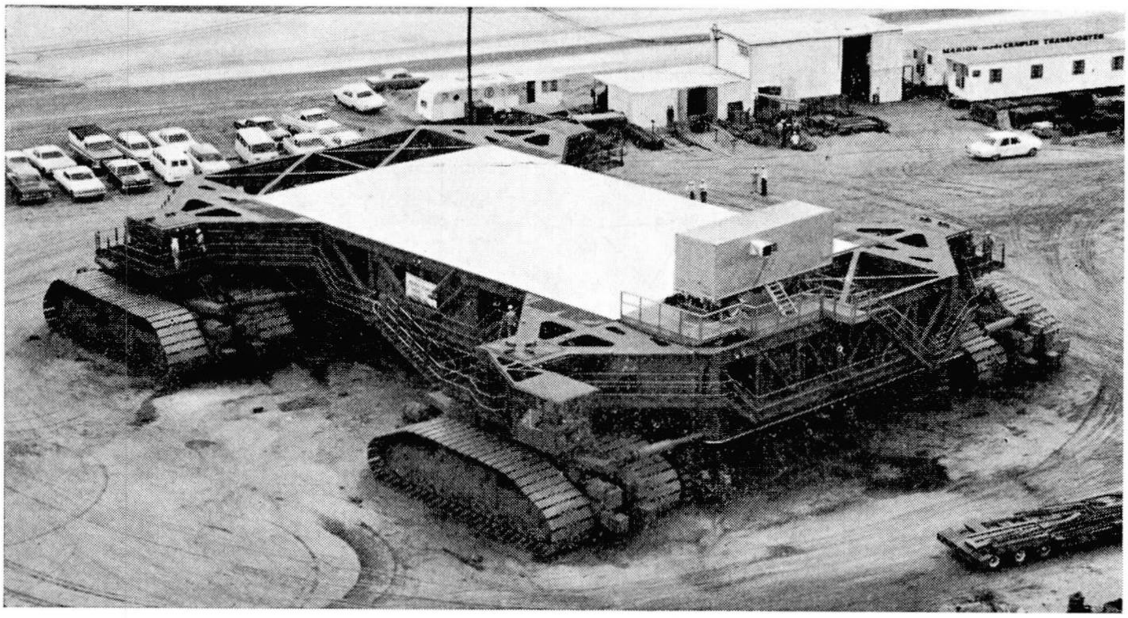


Fig. 4. Crawler-transporter.

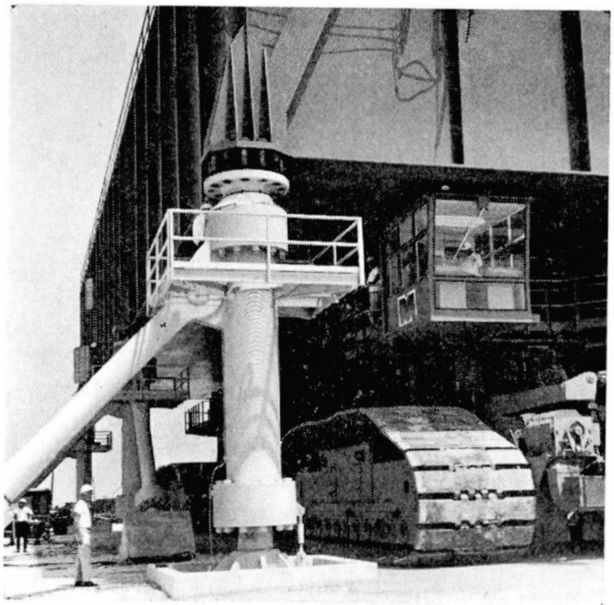


Fig. 5. Crawler (close up).

porter can move under the platform of the mobile launcher to lift the whole platform together with the space-vehicle and spacecraft and its umbilical tower clear of its supports.

Fig. 5 is a close-up of the crawler-transporter, ready to lift the mobile-launcher platform off its supports. In Fig. 6a the mobile launcher with the first Apollo Saturn V Moon Rocket has just moved out of the Vehicle Assembly Building for its trip to the launch pad. In the left foreground is the Launch Control Center, a monolithic concrete structure. The open door, 456 ft. high, of the Assembly Building, is in the background. Moving along the crawlerway, the crawler-transporter rides quietly without vibration, like a big ship. The two

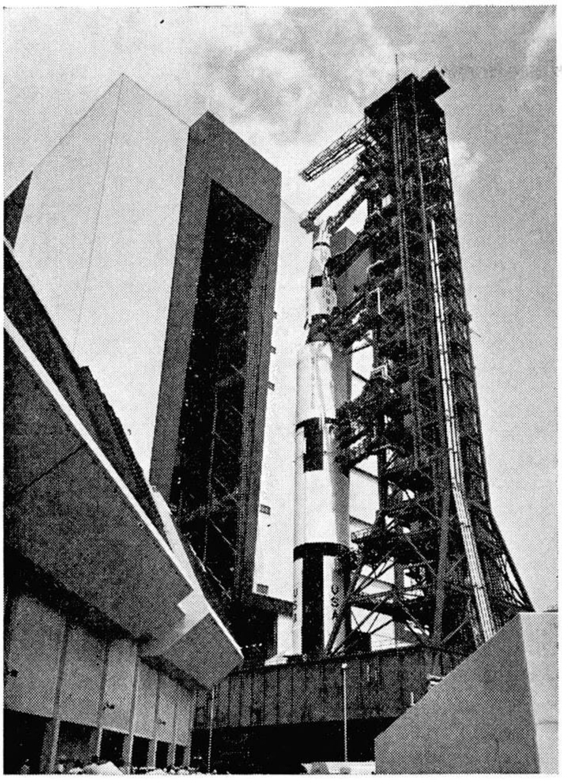


Fig. 6a.

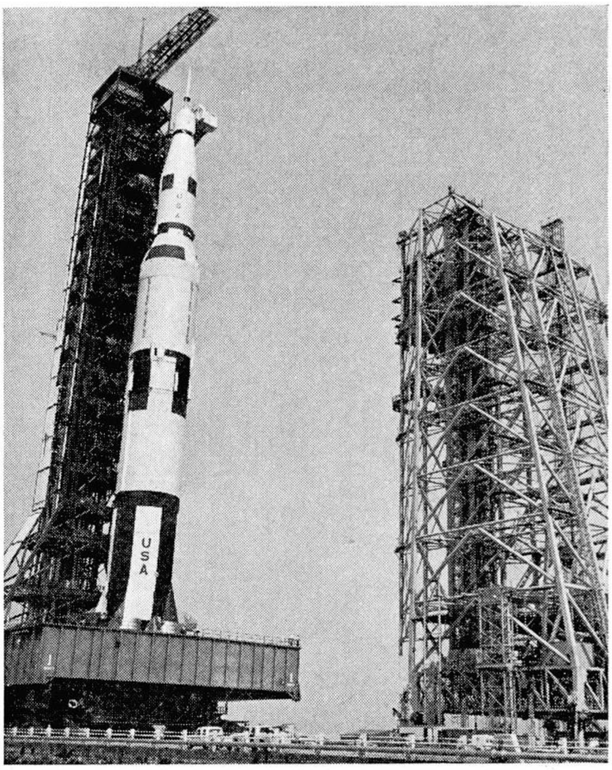


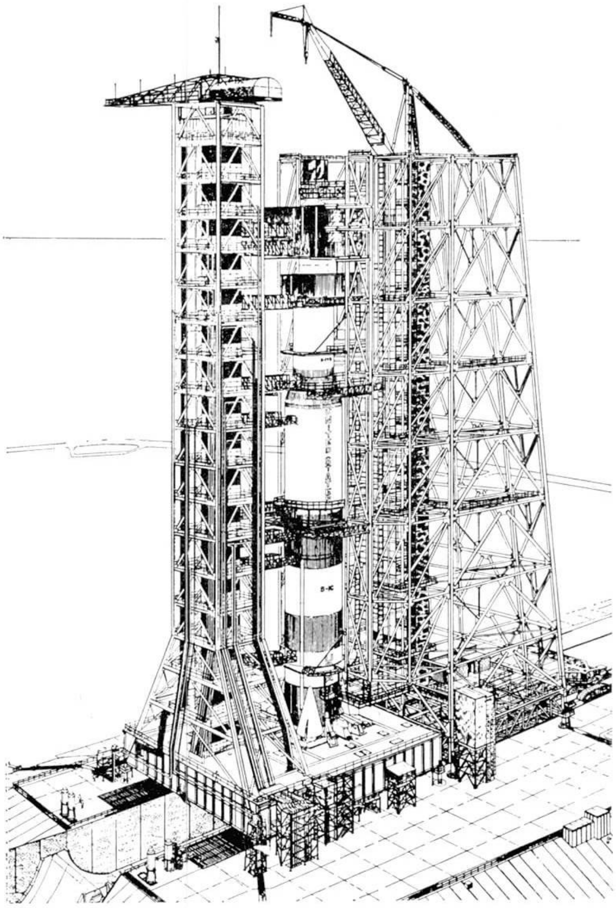
Fig. 6b.

lanes of the crawlerway are each 40-ft. wide and constitute the strongest super-highway ever built.

In Fig. 6b the mobile launcher with the first Apollo Saturn V Moon Rocket is shown in transit on the crawlerway as it passes the 400-ft. high service-tower structure (shown on the right). After the crawler-transporter has deposited the launcher with the rocket on the launch pad it will return and move the service-tower to the launch pad for final servicing of the space-vehicle.

Fig. 7 indicates how the Apollo-Saturn V space-vehicle and launcher assembly will appear at the launch pad, the point of departure for the flight. The crawler-transporter has positioned the skyscraping combination of the mobile-launcher with the rocket (in the center) and its umbilical tower (on the left). Next, the crawler-transporter has carried in and positioned the 400-ft. high service-tower structure shown on the right. This mobile service-structure, which is a skeletal frame work supported on a heavy rectangular base and braced with steelpipe weighs $11^1/_2$ million pounds; it will provide full access to the space-vehicle for final servicing. The support pedestals of the mobile launcher and the service structure are anchored in the concrete and steel structure of the launch pad. Prior to lift-off the crawler-transporter will move under the mobile service structure again, lift it from its supports, and park it at a safe distance.

Fig. 8 shows the mid-1965 construction status of a launch pad with its



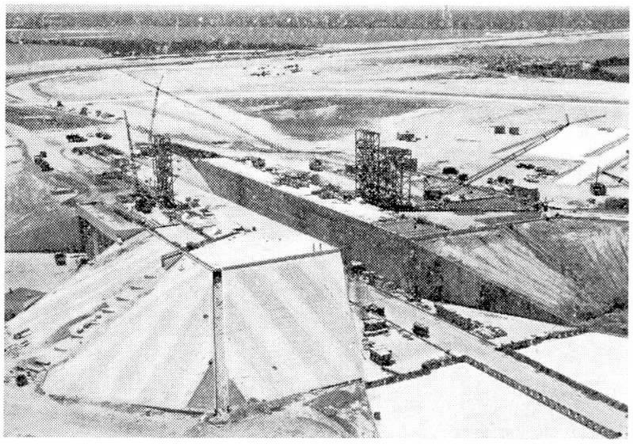


Fig. 8. Launching pad — construction view.

Fig. 7. Crawler and launcher and serviec tower on the launch pad.

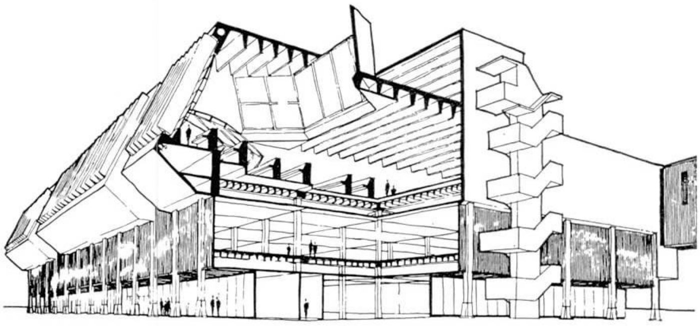


Fig. 9. Launch Control Center — (cross sectional drawing).

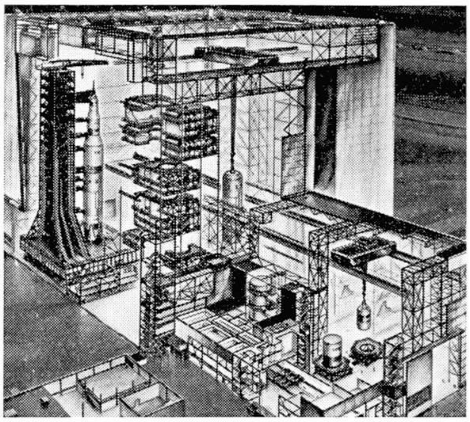


Fig. 10. Rendering of V.A.B., showing NASA operations.

facilities for propellant storage, wide flame channel, and concrete slabs faced with fire resistant materials to withstand the flames of the five rocket engines under full power. The crawlerway is in the background. Each of the two launch pads covers an area of almost a quarter of a square mile. The subsurface material (particularly a layer of clay) under the entire pad area was consolidated prior to construction by preloading for four months with a surcharge of sand piled 80 ft. high. This pad contains 120 000 cu. yd. of concrete.

The assembly and launch facilities for Saturn V at the John F. Kennedy

Space Center, described in this report, are known as Complex 39 of the John F. Kennedy Space Center. The American manned moon landing program is known as Project Apollo.

Fig. 9 shows the Launch Control Center, a 4-story monolithic reinforced concrete building, 378 ft. × 181 ft., which makes extensive use of precast and prestressed elements. Each of four fire-control rooms, 80 ft. × 120 ft., corresponds to one of the large assembly bays of the V.A.B. as well as to one of the launch pads. The glass front which faces the launch pads is equipped with adjustable sun visors of aluminum. Thus, a launch can be viewed from the Control Center directly as well as on its batteries of television screens. The Center is connected with the V.A.B. by an enclosed bridge (see also Fig. 24).

The Vehicle Assembly Building

Conditions surrounding the design of the assembly and launch facilities were unusual. The mightiest building ever erected, the V.A.B. was designed within less than one year, on the basis of mere concepts, and the work kept on schedule in spite of frequent changes in the requirements. Planning for facilities was done years in advance for a spacecraft which is only now in the development stage. Lack of time was a constant problem in every phase of the project and considerably increased the difficulties of management coordination.

As rocket stages arrive from fabrication centers by barge or plane they will be loaded onto special carriers and transported to the Vehicle Assembly Building (V.A.B.), entering it at the low-bay end. After testing the components, the rocket stages will be moved to the high-bay area, and from its transfer aisle to one of the four huge assembly bays for final vertical assembly and mating. Four space rockets can be assembled in the V.A.B. at one time. All pre-flight testing and vertical assembly of the vehicle and the spacecraft on its mobile launcher will be accomplished within the V.A.B., except for adding fuel, explosive hardware, and payload. Each space-vehicle mounted on its mobile launcher will leave the building through one of the large assembly-bay doors.

Among the factors influencing the choice of layout and structure for the V.A.B. were: 1. stiffness against wind loads, 2. adaptability to changes, 3. ease of connection with future extensions (planning included provisions for a 50 percent increase in assembly capacity to accommodate six space vehicles), and 4. above all, adequate working room for the operations expected to take place within the building and an efficient arrangement of it.

Many alternates were considered before final selections were made of layout, materials, and systems for the structural framing, floors, doors, walls, and foundations. In a number of instances, the use of the conventional and standard systems was found advantageous as compared with the use of more sophisticated systems. Conventional solutions resulted in shorter fabrication time, and often proved to be more adaptable to criteria changes. They offered less difficulty in meeting requirements for more space and for future extensions. Finally, conventional solutions in some situations were judged to be less vulnerable to hurricanes during the construction period.

As an example, the alternate concepts considered for the large assembly bay doors included:

1. Immense self-contained tower-shaped doors of truss and shell configuration to be moved like the mobile launcher; and
2. overhead-type doors of multiple folded plates of metal or plastic; and
3. horizontal-swing or bascule-type doors.

Shell-type door leaves lost much of their apparent advantage when reversal of wind pressure was considered. They took too much space when stacked, and their wind-load distribution produced undesirable concentration of reactions which would have required extra beams, guides and rollers for distribution to the V.A.B. structure. Consequently, it was decided to design the doors of simple standard components, without glamour but with maximum reliability. Similarly, choices between other alternate systems were influenced by a desire to increase reliability and to have a built-in safety reserve, rather than to achieve bold or elegant solutions not fully proven for construction within compressed time schedules and overtime working conditions.

The shape chosen for the V.A.B. is not the most advantageous from the standpoint of minimizing the wind pressures, but it is economical and good from the standpoint of wind deflections which had to be restricted to prevent damage to the space vehicle. The structure, as finally adopted, is stiff against wind, with stresses due to temperature changes held to an acceptable magnitude. In concept, the assembly building consists of a three-dimensional system of steel trusses and horizontal diaphragms of composite steel beam and lightweight reinforced-concrete construction. Its shape was selected to accommodate the many operational requirements and space limitations. The low-bay portion of the V.A.B. measures 442 ft. $\times$ 275 ft. and is 211 ft. high; the high-bay portion measures 518 ft. $\times$ 442 ft. and is 526 ft. high.

Fig. 10 illustrates the operational problems, how rocket components of a Saturn V are handled by various lifting devices and assembled on its mobile launcher platform. The low bay is in the foreground.

Fig. 11 shows how the "platforms" which provided access to the early rockets now have become multi-storied, movable shops which can envelop the space rocket at any desired level and, when no longer needed, can be retracted on cantilever supports into the surrounding V.A.B. framing like big drawers. The elevators of the V.A.B. can be stopped at all regular floors and at any shop level.

Each of the large assembly bays is closed by doors, 456 ft. high, 152 ft. wide at the bottom, and 76 ft. wide in the upper portions. They are composed

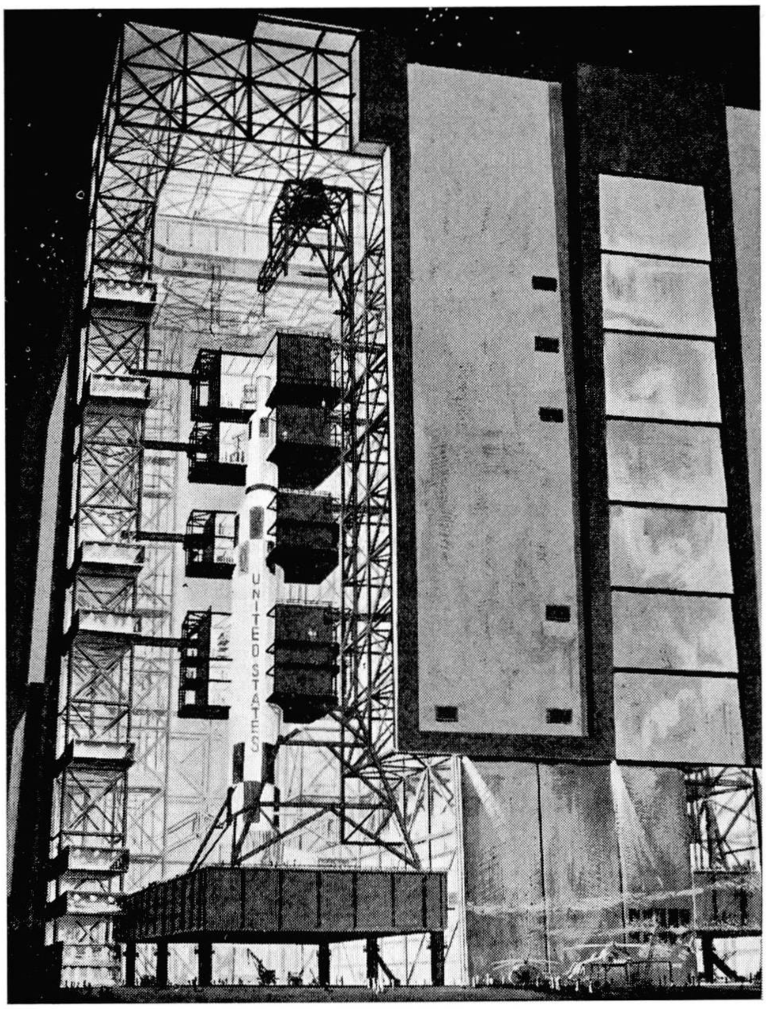


Fig. 11. Rendering of V.A.B., exterior view showing rocket inside V.A.B.

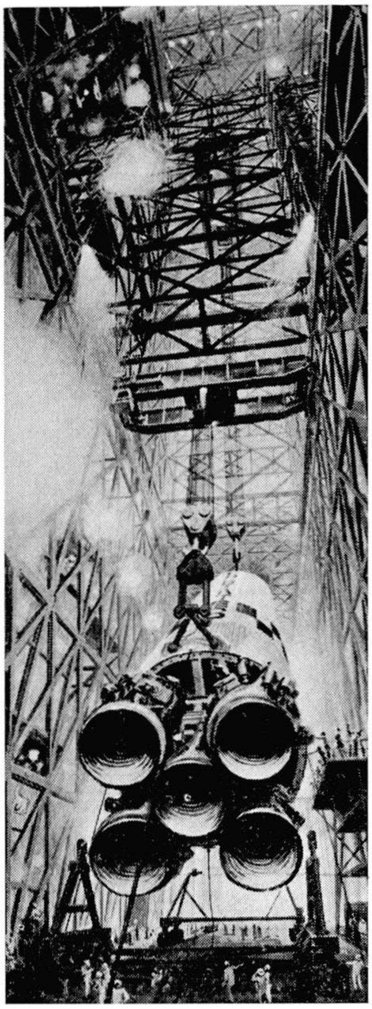


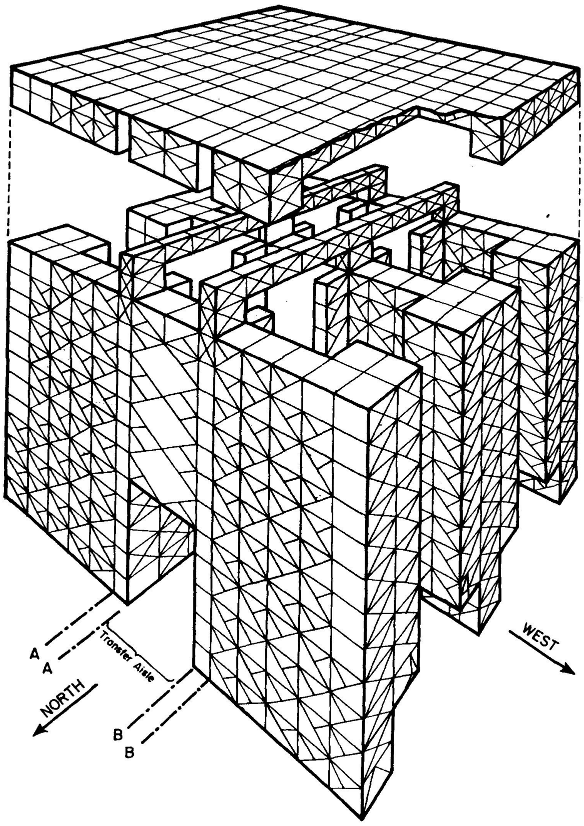
Fig. 12. Transfer aisle of V.A.B. (rendering).

of aluminum-sheathed leaves (shown on the right), weighing between 32 and 73 tons. The largest leaves are 114 ft. $\times$ 38 ft. Bottom leaves slide horizontally while leaves above them lift vertically into a pocket above the doorway. The doors are designed to open in less than sixty minutes.

In Fig. 12, a view taken within the transfer aisle of the V.A.B., two cranes are shown handling the assembled first stage of the Saturn V space vehicle with its five rocket engines which will develop a total thrust of $7^1/_2$ million pounds.

Space Trusses Carry Wind Loads

The truss system of the high bay was laid out in multiples of 38 ft. both vertically and horizontally. Trusses are parallel to three mutually perpendicular planes. Configuration of trusses along vertical sections was varied from panel to panel to conform to clearance requirements of the arms of the umbilical tower, the cranes, and the movable shops when retracted. As the stiffness



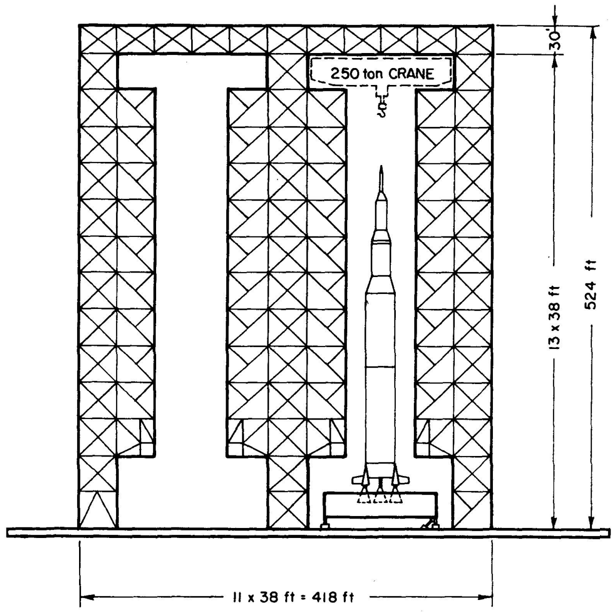


Fig. 14. North-South Section through Assembly Chambers of V.A.B.

Fig. 13. Isometric view of structure of V.A.B.

of the trusses varies, so does their participation in the transfer of lateral forces. The following is a simplified explanation of the wind carrying action of the V.A.B. structure.

The structure (Fig. 13) derives the major part of its stiffness from the roof slab and truss diaphragm below roof level, from the exterior diaphragms along north and south walls, from the truss "double-bents" A-A and B-B along the transfer aisle (north-south direction), and from east-west bents between assembly bays. Fig. 13 is a diagrammatic view of these main truss systems with all secondary trusses and door framing removed for clarity. Fig. 13 is oriented to show the north and west directions, the center lines of bents A-A and B-B, and gives an indication of the plan layout of the high bay. It shows the transfer aisle separating the four assembly chambers — two on the east of it and two on the west —, and the outline of trusses along the north and west walls. The truss frames in the north-south direction are connected with the east-west trusses for combined space action. All of these trusses are of varying characteristics and behavior.

As the loads from a north wind impinge upon the structure through its north and south walls and are distributed through the truss diaphragm of the roof, it becomes apparent that the wind thrusts are distributed in proportion to the stiffness of north-south bents. Compatibility of deflections establishes that bents A-A and B-B, being the stiffest, each take 32 percent of the north wind, whereas the north-south framing shown in Fig. 14 takes only 5 percent of the north wind. Similarly it can be shown that winds in the east-west direction are carried primarily by the framing between assembly chambers and the truss bents along north and south walls. Winds in other directions may be considered resolved into north-south and east-west components.

When the horizontal section of the High Bay in Fig. 13 is considered as that of a gigantic box, it can be visualized that the "double-bent trusses" along the north wall and along the south wall are the flanges of this giant box section and that the "double-bent trusses" A-A and B-B are the webs. In other words, not only do the trusses in north-south direction (webs) take the north wind, but the trusses in other direction (flanges) contribute to the carrying action as well.

Fig. 15 is an east-west section through the assembly chambers, Fig. 16 a north-south section along the transfer aisle showing bents of type A-A or B-B.

Wind forces will have a governing influence. Operations in the structure can continue safely with winds up to 63 miles per hour (about 100 km per h.), including gusts, measured at 30 ft. above ground level, with sidesway not to exceed 4 in. at the level of the uppermost movable shops. If winds exceed this velocity, assembly work will stop, space vehicles will not be transported, doors will be closed and movable shops will be retracted so that space vehicles will not be damaged by deflections of the building. The structure is capable of taking hurricane winds of 125 miles per hour, including gusts, at the 30 ft. level and of 195 miles per hour (above 300 km per h.) at roof level.

To determine the actual forces due to high winds on the structure, a study was made of the available literature of tests, meteorological data, design experience and measurements of pressure on high structures and in connec-

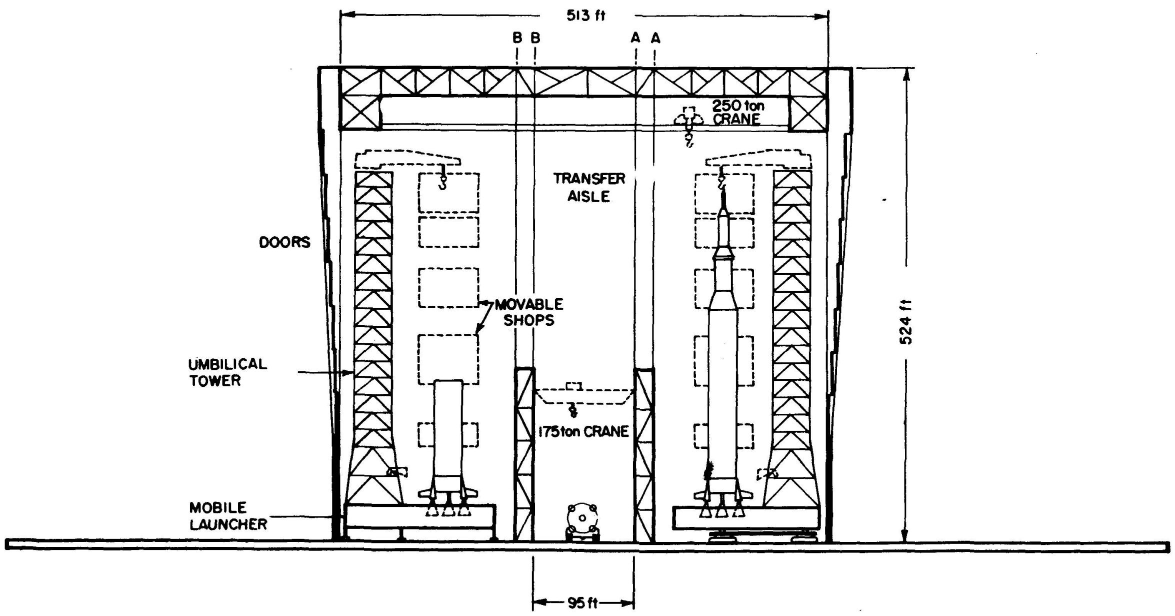


Fig. 15. East-West Section through Assembly Chambers.

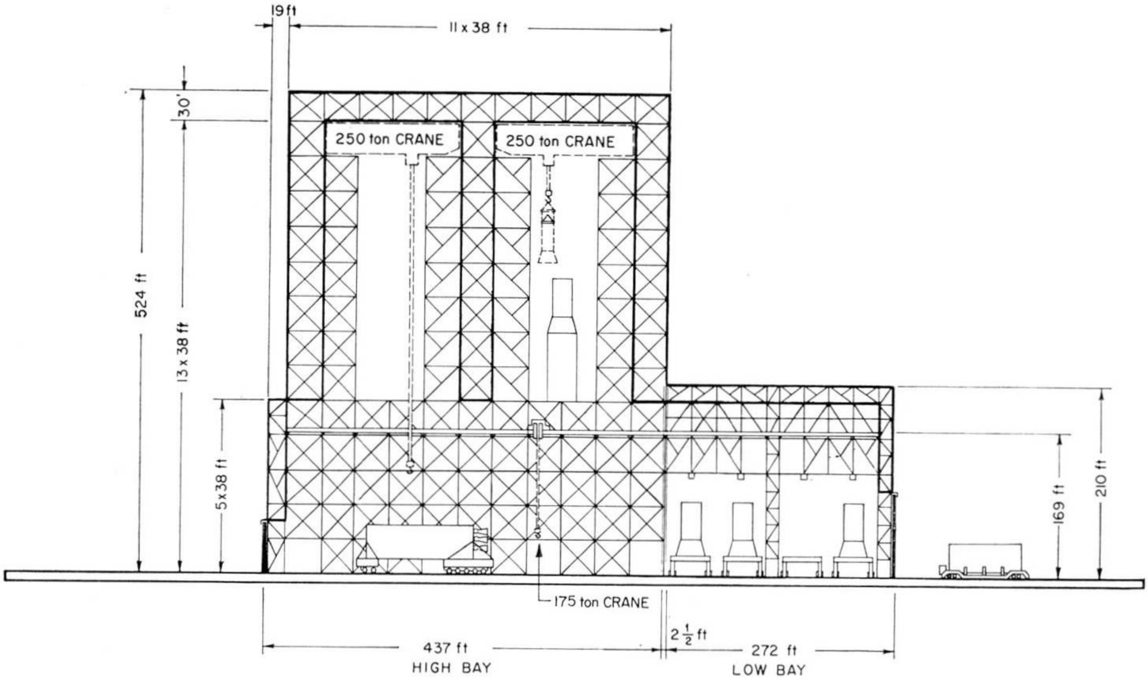
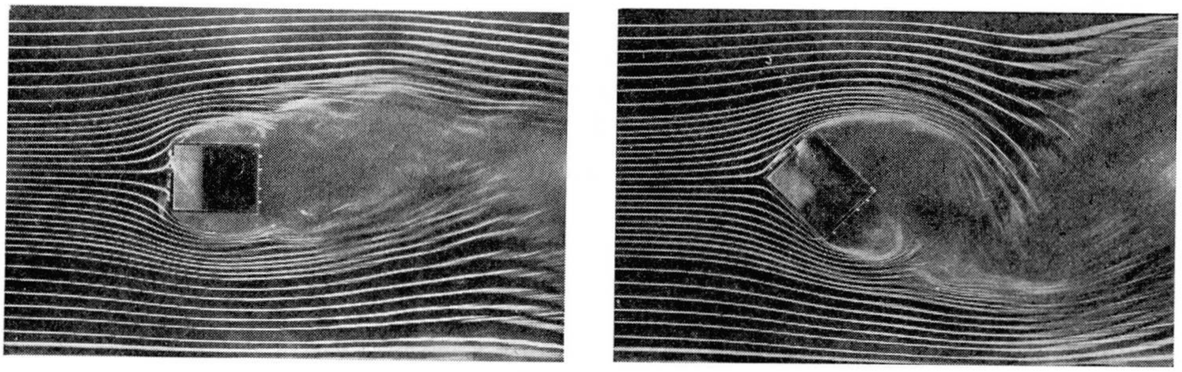


Fig. 16. North-South Section along transfer aisle of V.A.B.



a b

Fig. 17. Smoke tunnel test.

tion with recent hurricanes. Further, wind-tunnel tests were conducted on scale models of the V.A.B. as a check on design assumptions. A two-dimensional smoke tunnel test (Fig. 17) gave a rough indication of the wind flow around the building. The design assumptions and the test results were found to be in satisfactory agreement.

Wind velocity and pressure curves developed for various winds with respect to various heights of the structure are charted in Figs. 18 and 19. External pressure coefficients used for the design of the structure under winds of different directions are shown in Fig. 20. The coefficients of internal pressure ranged between positive and negative values. The gust factor c_g, x, an exponent defining variation with height z, and v_{30}, the basic wind speed at a height of 30 ft. above the ground (see Fig. 18), are influenced by the type of storm, the

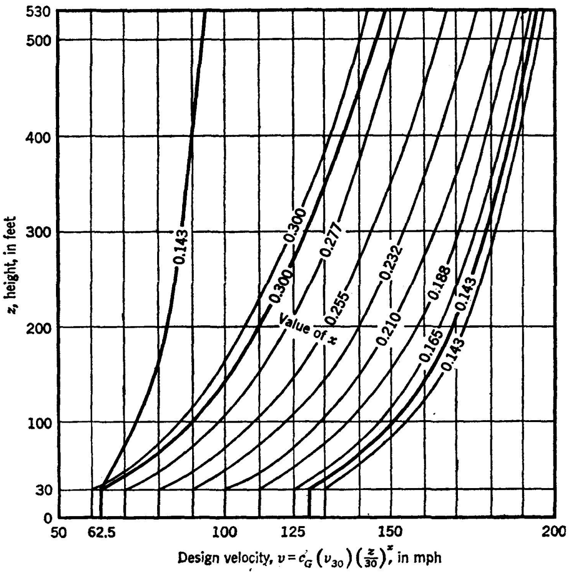


Fig. 18. Wind velocity as a function of height.

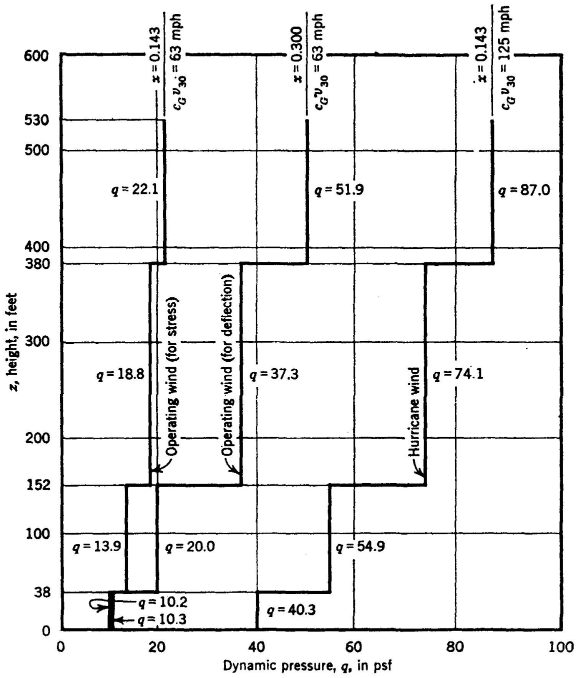


Fig. 19. Wind pressure as a function of height.

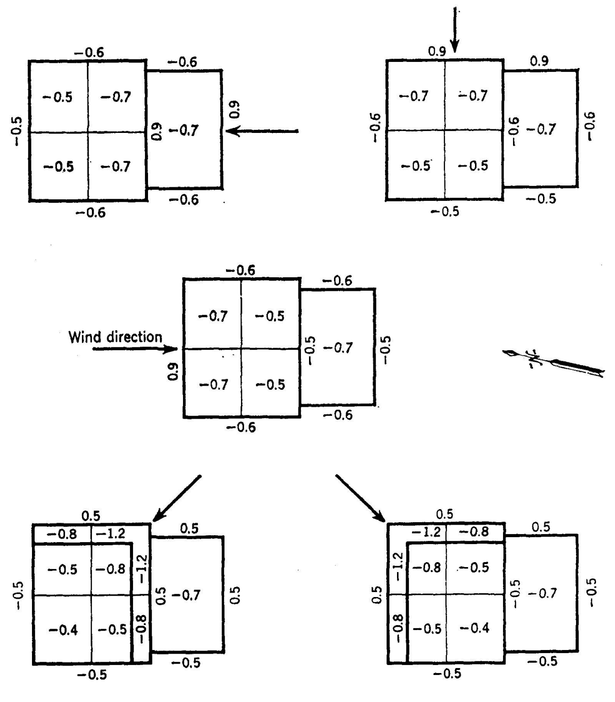


Fig. 20. External pressure coefficients.

terrain in the wind path, and the geometry of the building. It will take gusts of 10 or more seconds duration to envelop the V.A.B. structure. Accordingly, a gust factor of 1.1, independent of the height z, was considered conservative. A storm arriving in Florida from the sea has a steep velocity profile, compatible with pressure gradient, curvature of the wind path, roughness of water surface, and other factors affecting air movements. A storm arriving after some travel over land will have its wind profile modified by increased turbulence. The exponent $x = {}^1/_7$ was chosen for the profiles of maximum design velocity. A much more severe law ($x = 0.300$) of "wind velocity as function of height" was used for the determination of deflections due to a maximum operating wind than for the determination of stresses due to the basic wind.

Maximum positive wind pressure for the once-in-a-100 year hurricane becomes 40 psf. at the 30 ft. level and about 90 psf. (suction 105 psf.) at roof level (metric equivalents: 195, 440, and 510 kg per m^2). Higher pressures can be tolerated when members or connections reach the plastic range and a redistribution of stresses permits the statically indeterminate system to carry its loads in a different fashion.

Space Frame Statically Highly Indeterminate

The High Bay of the V.A.B. is statically highly indeterminate (2840 times) and therefore has many ways to carry the loads. It is composed of relatively small members. Alterations are not difficult to make and no single member is so vital that it cannot be omitted at a reasonable cost, if later required due to changing criteria. Reserve strength, resulting from high redundancy, is important in a structure which, due to operational modifications, might not be loaded as originally intended.

The framing of the space-truss system of the High Bay is of A-36 structural steel (36,000 psi yield point). Horizontal diaphragms are at the roof level and wherever floors are required. These consist of slabs of semi-lightweight concrete in composite action with structural steel floor beam sections. Concrete floors carry horizontal forces by diaphragm action to the steel beams and at the same time provide composite action for gravity bending. The basic space-truss system has 2440 joints and 12400 members. Deflections due to wind had to be minimized to prevent damage to the space vehicle, and consequently, strains had to be kept low. Clearance requirements resulted in rather high slenderness ratios for the columns. For these reasons the use of high-strength steel would not have offered advantages.

Towers and framing were designed for floor loads, including the possibility of future floors, at 33 levels, that is at the third points of each 38-ft. vertical module. At several stages of the design, changes required adding floor area. This increased the vertical load, and therefore the ratio of gravity load to lateral load was increased. As a result, uplift forces decreased, and the designers found it less and less difficult to meet wind-deflection requirements. Presently the finished floor area is 1 200 000 sq. ft. Vertical loads include the loads of movable equipment and large doors with their counterweights, the loads of

250-ton and 175-ton capacity cranes, and of smaller cranes and monorails. The dead load of the heaviest crane is 500 tons; one-half of the largest retractable shop weighs 180 tons. Five movable shops are provided in each assembly bay. Because of the eccentricity of crane reactions and other large live loads, columns are subject to substantial bending moments.

The space truss system carries the loads three-dimensionally, but for ease in computation, the analysis was reduced to sets of one-plane problems satisfying geometrical compatibility conditions (compatibility of deformations) among them. After these conditions were achieved, the results for those members common to more than one system were combined. Even so, the determination of forces required the solution of sets of equations with 350 redundants. In view of the strict time schedule to be met, it was considered wise to rely on manual-calculation methods for the preliminary and basic designs used for the sizing of members before making the more precise design calculations. Computers were used initially as a help in solving equations. Subsequently, as confidence increased in the adequacy of assumptions and results, the designers progressively increased their reliance on electronic computations for the solution of forces in truss bents by an iteration method, and for matrix solutions in obtaining forces in planar trusses. A three-dimensional space-frame check by electronic computer increased the designers' confidence in the deflection values previously obtained by combining deflections obtained from analyses of north-south and of east-west planes. This method gave results for five loading conditions in terms of deflected coordinates and member forces of the basic structural system. Finally, a comprehensive computer program enabled the designers to obtain maximum forces in structural members for 88 loading combinations based on 49 basic loading conditions. Throughout the calculations the designers never relied on a single approach, but always used independent checks to avoid being caught in weeks of delay occasioned by errors arising from the use of computers. Actually, only a few weeks were needed for search and correction of discrepancies.

In the design of the structure, columns were assumed restrained at ground floor level, and the effect of deformations of the foundations was considered. Temperature stresses for the V.A.B. were separately analyzed, and these secondary influences were added to the maximum stresses calculated from other loading conditions.

Materials of Construction

Maximum use was made of rolled structural sections. Some of the columns have rolled *H* section cores heavier than any fabricated before. These are 14 inch wide-flange profiles weighing 734 lb. per ft. (1100 kg per m). With plates welded to the cores, the columns are of box section about 2 ft. square

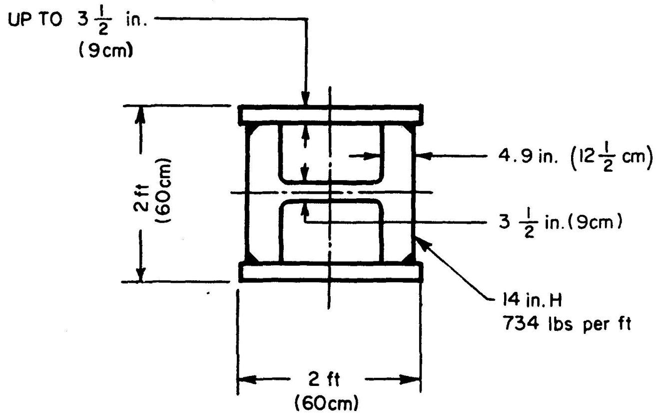


Fig. 21. Section of welded column.

and weigh up to 1305 lb. per ft. (1950 kg per m), see Fig. 21. Typical girders are 30 inch and 33 inch deep, typical floor beams are 18 inch wide-flange sections. Columns and tower units are braced in three planes, usually by diagonal members, 14 inch wide-flange sections. Connecting the many structural members which meet at panel points in all three planes required ingenuity in detailing to minimize secondary stresses which develop because of eccentricities caused by space limitations. Structural members were shop-welded and field-connected with more than one million high-strength bolts.

More than one million sq. ft. of insulated, vinyl-coated, aluminum panels enclose the V.A.B. structure; these wall panels have $1^1/_2$ in. of glass fiber sandwiched between a fluted aluminum outer skin and a galvanized steel inner lining; they were bolted to horizontal steel girts spanning between the columns.

The low-bay structure consists of a series of braced east-west frames tied together by north-south vertical trusses and at floor and roof levels by concrete diaphragms. Beam and girder framing is conventional. Ground floor concrete slab is 12 in. thick in the high bay and transfer aisle, and 10 in. thick in other areas. Composite slabs are 4 in. thick.

Figs. 22 to 25 show Complex 39 in various stages of completion. Fig. 22 pictures the low-bay and the launch control center in the foreground. Mobile launchers are shown being assembled in their erection area in the background where support pedestals anchor each launcher to pile foundations for stability during high winds. A later photograph of the project looking east, Fig. 23, shows the crawlerway, with the Atlantic Ocean in the background. The steel contractor's derricks and the temporary wind bracing across door openings can be seen. In the foreground of Fig. 24, a mid-1965 view, is the launch control center. The V.A.B. is on the right. Fig. 25a is a later view of the complex prior to the erection of the V.A.B. doors. Halves of retractable shops are being assembled in the foreground. Fig. 25b shows the V.A.B. doors in place.

The John F. Kennedy Space Center is located in a low-lying area, originally swampy, underlain by sand and compacted shells and a 40-ft. clay strata.

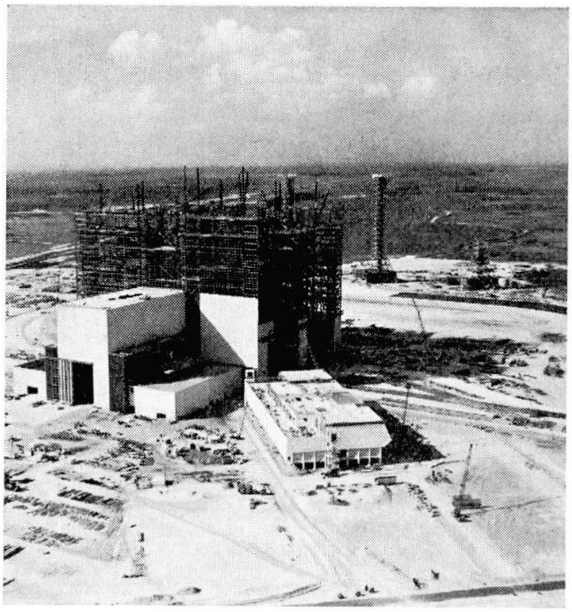


Fig. 22. Air view of V.A.B., towards Northwest with launchers.

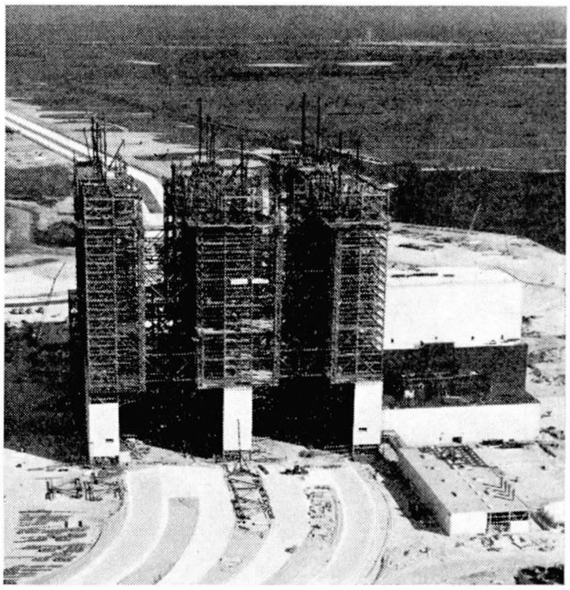


Fig. 23. Air view of V.A.B. towards East.

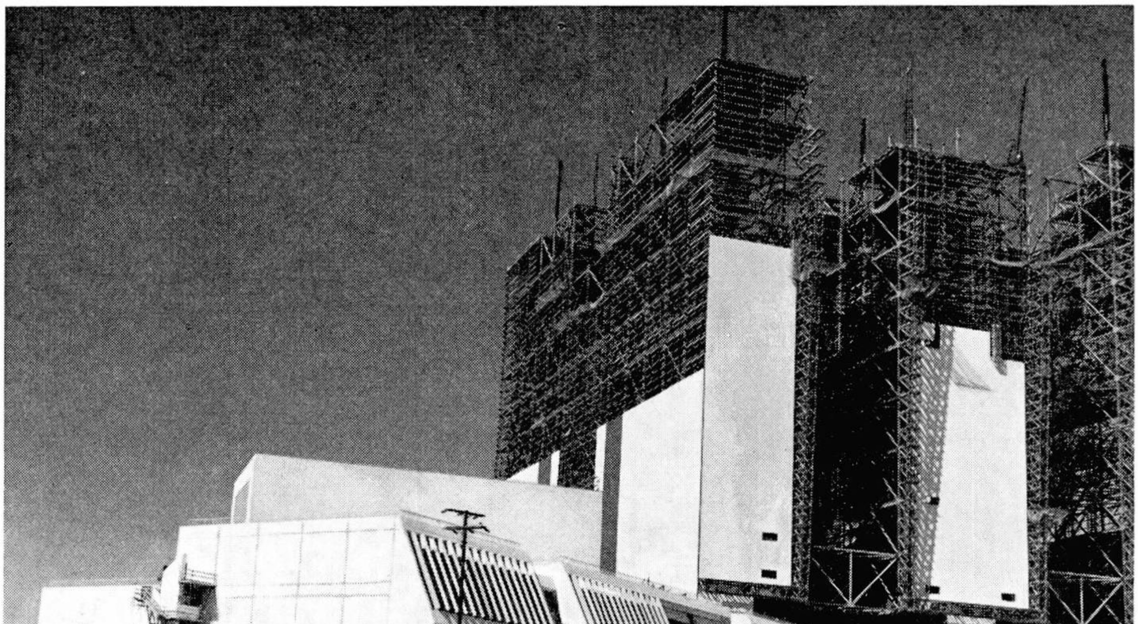
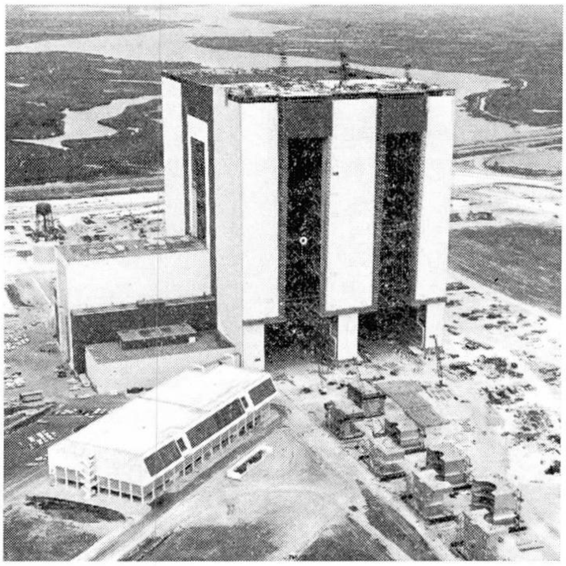
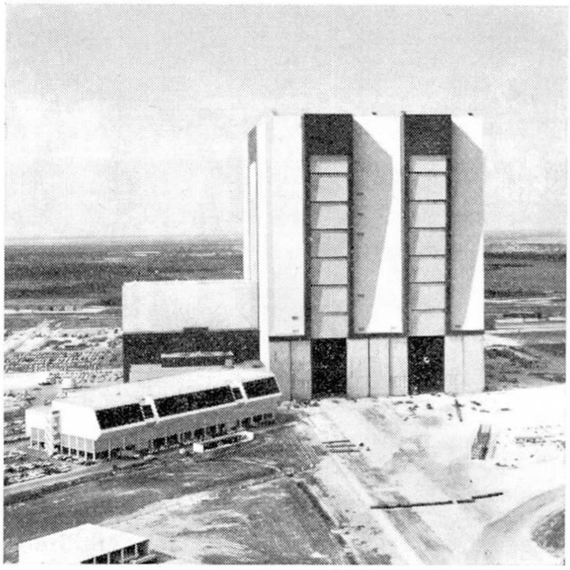


Fig. 24. Close-up of Launch Control Center and V.A.B., towards Northwest.



a



b

Fig. 25. Air view of V.A.B., towards Northwest; movable shops stored in yard.

A 2-ft. layer of hard lime rock lies at a depth of 115 ft.; stiff clay silts are below this layer; bedrock is found at a depth of 160 ft. The designers carried out a boring and pile-testing program which resulted in the decision to support the V.A.B. on open-end steel pipe piles, and to construct the Launch Control Center on a concrete mat foundation. Piles are of 16 inch diameter, $^3/_8$ inch wall thickness, each having a capacity of 100 tons static downward load and 47 tons of uplift. A 33 percent increase is permissible in downward load under wind. The V.A.B. is supported on 4225 piles. The piles, cathodically protected, are topped with 10 ft. deep concrete caps. Columns transfer loads to the footings through welded steel-plate assemblies. Foundation concrete used low-heat cement. Maximum pile cap load was 3500 tons.

Construction Features

Foundation work and fabrication of structural steel, under separate contracts, preceded other work. The piles, in 120-ft. sections, were driven with vibratory hammers down to the upper lime-rock layer (115 ft. deep). An additional 60-ft. length was then spliced to each pile and driving was resumed with a heavy steam hammer to puncture the upper rock-layer and penetrate to bearing on bedrock. Fig. 26 shows the forest of piles and some of the equipment used.

Structural steel for the 45000 members in the V.A.B. was rolled at three mills and fabricated in eight different shops in order to meet the tight time schedule. Members were identified by piece marks air-hammered with a die into the surface of the metal. Because of concern over lamination in the steel, the larger rolled sections were inspected at the mill by ultrasonic methods. Heavy partial-penetration welds required careful inspection at the fabricating shops, including magnetic particle examination of 10 percent of the length of any welds, and radiographic inspection where considered important, but rejection rate was low. An attempt was made to detect and correct defects at the site of fabrication, thus minimizing the cost and delays of replacement. Some of the welds which did not meet requirements were field-repaired. A protective coating on the steel, a zinc-rich paint, guarantees freedom from corrosion for the life of the building.

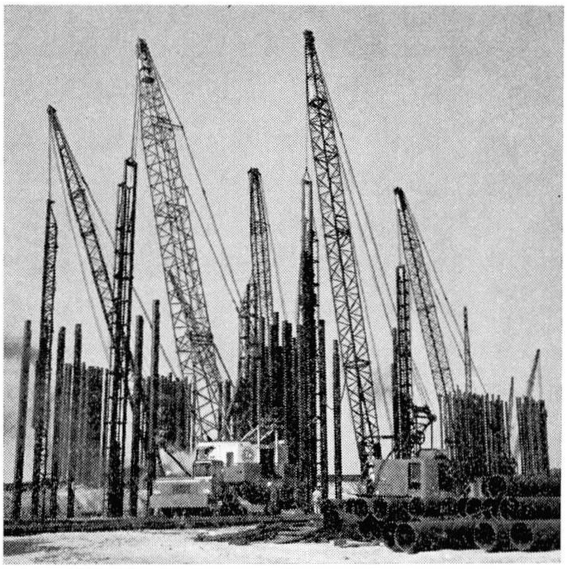


Fig. 26. Forest of piles.

Piles required 21 500 tons of steel and 60 000 tons of steel were procured under an advance procurement contract to permit early mill ordering, fabrication, and erection of the basic V.A.B. framing. The major contract for the general construction of the V.A.B. included 15 000 additional tons of structural steel and more than 2000 tons of reinforcing bars. The total weight of steel used in the V.A.B., therefore, was about 100 000 tons[2]). 400 tons of shop-weld alone were deposited during fabrication! Foundations and ground floor required 30 000 cu. yd. of concrete; and 15 000 cu. yd. more were placed in the structure above ground level.

The structural steel framing of the low-bay portion was erected first, using six 150-ton crawler cranes. These cranes, equipped with 230-ft. booms and 50-ft. jibs, then set the steel for the high-bay portion up to the 210-ft. level. Next, the steel contractor installed twelve guy derricks on top of this incomplete framework to continue erection. Steel and other large construction units

[2]) Steel tonnage for launch-pads, service tower, mobile launchers and other facilities not included herein.

were hoisted by these derricks which were equipped with 100-ft. masts and 90-ft. booms. Two of the derricks teamed up to erect the bridges of the 250-ton cranes. In addition, stiff-leg derricks were employed to set wind bracing beyond the reach of the guyed derricks, and to place the guides for the massive doors.

Check on geometry during erection was maintained by frequent surveys. Generally, the steel erection resembled bridge work more than that of the conventional high-rise building. This impression was strengthened by the appearance of the welded gusset plates connecting the diagonals to the columns.

The contractor had to supplement the permanent bracing of the space framework with large-scale temporary bracing, particularly across door openings. To tighten the million high-strength bolts, which range up to $1^1/_2$ in. diameter, required the largest size of air-operated impact wrenches. In tight spaces where girders and diagonals connect to the columns, the men used universal sockets on the wrenches. Steel surfaces at bolted connections were sandblasted to insure good metal-to-metal contact, positive friction and minimum electrical resistance. Steel studs, usually of $^3/_4$ in. diameter, were field-welded to the top of floor beams to provide positive shear connection to the concrete slab. To exclude paint and to insure clean surfaces where welding was to be done, the contractor protected the steel surfaces with tape.

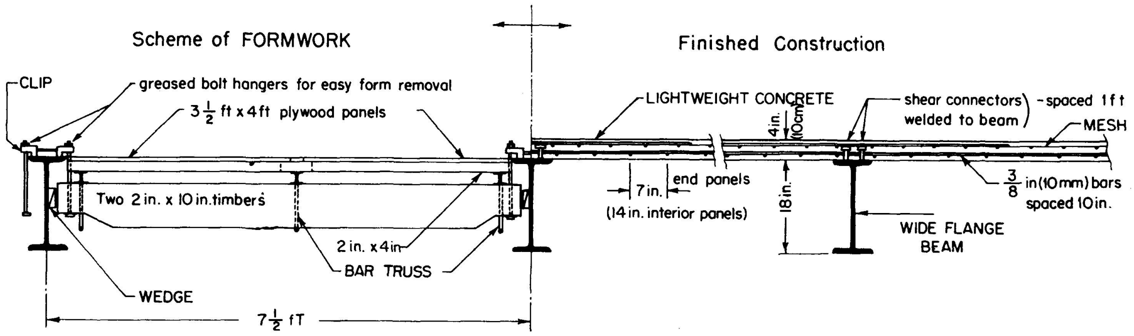


Fig. 27. Section through typical slab of V.A.B., showing form work.

Formwork for concrete floor slabs was suspended from the floor beams, as shown in Fig. 27. Also shown are details of the composite construction and the reinforced lightweight-concrete slabs which are important elements in transferring wind shear through the space framework. A maximum of 7500 sq. ft. of slab concrete was placed in one day. The concrete mix included both a water-reducing retarder and an air-entraining agent. Specified weight of the concrete was 115 lb. per cu. ft. (specific gravity 1.8), and the 28-day cylinder compressive strength 3500 psi. A tensile splitting strength of 330 psi assured reliability in the transfer of shear forces.

Materials and men arrived at construction levels by six elevators located in the asembly bays. However, the sandwich-type, metal wall panels, each $19^1/_2$ ft. $\times$ 5 ft., were lifted by overhead hoists along the outside face of the

V.A.B. to their correct level. They were then rolled sideways into position and fastened by men working from a 4-level cage travelling horizontally and suspended from a temporary rail above the working area. Special translucent plastic panels, which admit natural light to the transfer aisle, enclose the curtain wall above the low-bay roof. Where crane booms did not have adequate reach, a method of lifting the translucent panels through the interior of the building and then lowering them with the use of roof-mounted power hoists was considered but rejected as involving excessive handling. Instead, a helicopter proved to be the fastest and most economical method for erection.

Figs. 28 to 33 show construction progress and a variety of details. Fig. 28

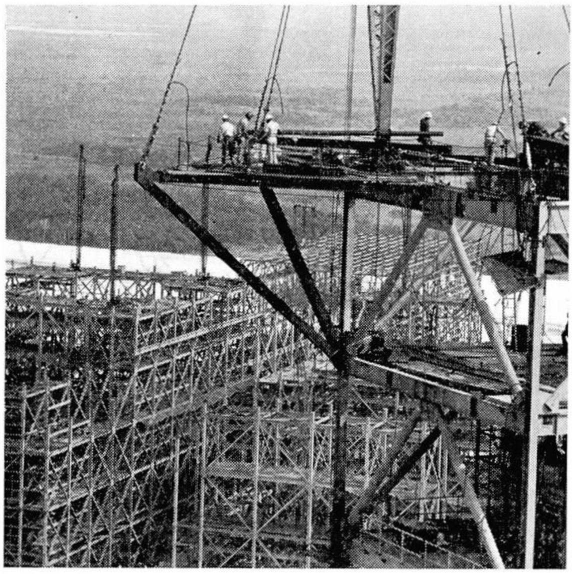


Fig. 28. View of V.A.B. from movable launcher.

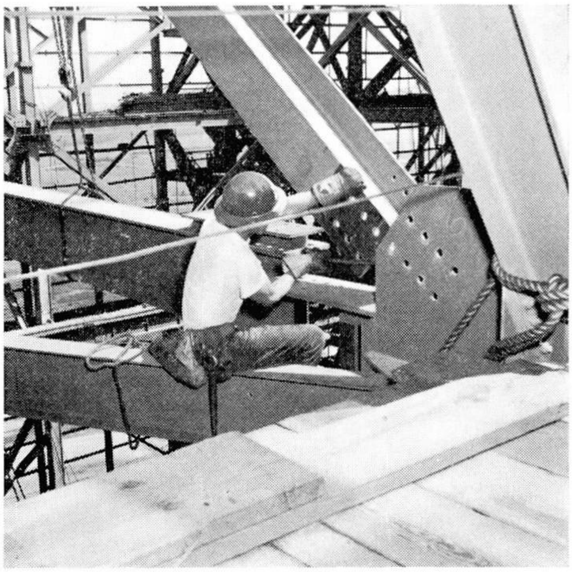


Fig. 29.

Fig. 30.

Fig. 31.

Details of steel erection.

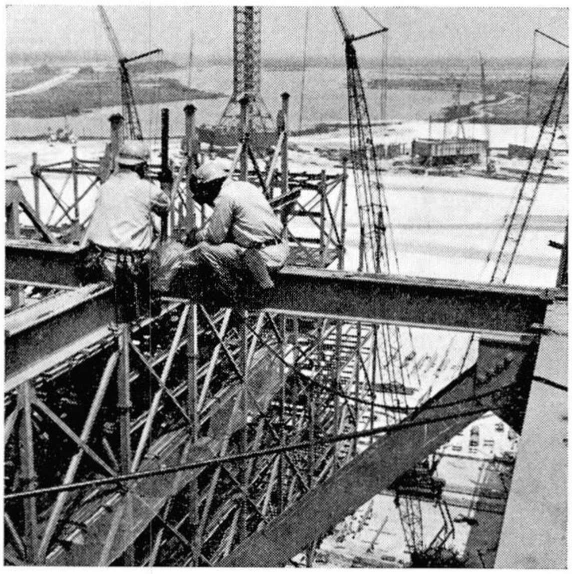


Fig. 32. Welding of shear connectors on top of beams.

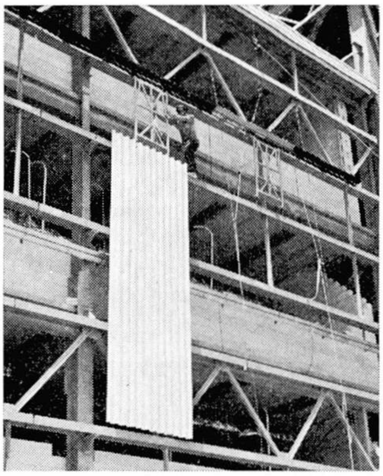


Fig. 33. Erection of wall panel.

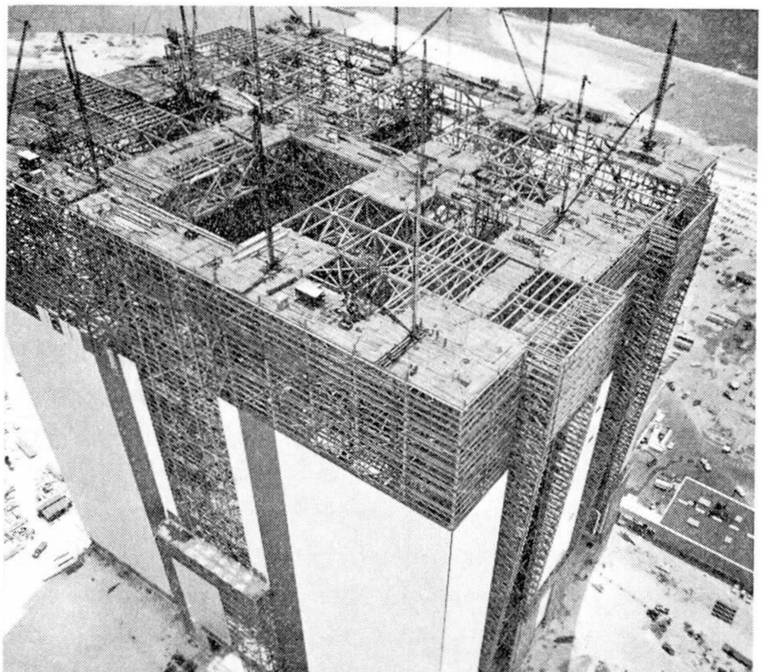


Fig. 34. Top view of V.A.B.

is a view taken from the top of a mobile launcher toward the V.A.B. Note the pipe-bracing in the foreground. In Figs. 29, 30, and 31, showing details of steel erection, note the large gusset plates and the column splices. In Fig. 32, workers on the steel of the V.A.B. are welding shear connectors (studs) to top of beams to insure composite action between floor beams and the concrete floor slab. In Fig. 33, an insulated curtain-wall panel is shown travelling along a horizontal rail to its final erection position. Fig. 34 is a helicopter-view looking down onto the V.A.B. to show the arrangement of derricks on the roof.

The highest point of the V.A.B., an elevator penthouse, is 550 ft. (168 m) above ground level. The dimensions of the building are unprecedented, enclosing a volume of 129 million cu. ft. With possible future extensions, the volume will be 178 million cu. ft.

The designers produced 2700 drawings within less than one year. Total number of shop detail drawings for the project was about 20000, of which 6000 were required for the structural steel alone.

Acknowledgments

The design and construction of the assembly and launching facilities for Apollo Saturn V, here reported, has been most fascinating for all, but particularly for the engineers. The work is a step toward the fulfillment of a dream — the dream of starting mankind on its voyage into space. The Moon is the celestial body closest to the earth and therefore logically the first "station stop" on our travels. While progress in space flight is now only where man was aeronautically 60 years ago, it is gratifying to know that our civil engineering technology is well advanced for the support of space travel. In the steady advancement of this important work, the Bridge and Structural Engineer has had and will have an important role.

The work described herein is nearing completion under the direction of the U.S. Army Corps of Engineers, Canaveral District (Col. W. L. Starnes, District Engineer, J. L. Harvey, Chief of the Engineering Division, and D. E. Eppert, Chief of the Construction Division), which serves as NASA's design and construction agency. For the work at the NASA John F. Kennedy Space Center, Dr. Kurt H. Debus is Director, and Col. A. H. Bagnulo and R. P. Dodd are in charge of facilities engineering.

A combine of contractors, Morrison-Knudsen Co. Inc., the Perini Corp., and Paul Hardeman Inc. carried out the major portion of the construction. The American Bridge Division of the U.S. Steel Corporation had the contract for the fabrication and erection of the structural steel.

The design of the Vehicle Assembly Building, Launch Control Center and surrounding facilities, utilities, and supporting installations was performed by Urbahn Roberts Seelye and Moran (URSAM), a joint venture of four firms:

1. Max Urbahn — Architecture and Planning.
2. Roberts and Schaefer Company — Structural Engineering.
3. Seelye Stevenson Value & Knecht — Mechanical and Electrical Engineering.
4. Mueser Rutledge Wentworth & Johnston (formerly: Moran Proctor Mueser and Rutledge) — Harbor Dock and Foundation Design.

Harvey F. Pierce, Eric C. Molke, A. Amirikian, and Howard Simpson were among URSAM's consultants.

The writer of this report represented Roberts and Schaefer on URSAM's executive committee and was in charge of structural design, and of structural consultation during construction[3]).

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Summary

Assembly and launching facilities for giant space rockets of the Saturn V type are described as they near completion in Florida (U.S.A.). These installations are expected to make flight tests for manned space flight possible by summer 1968. This report includes a description of the design and the con-

[3]) The project described in this report received the American Society of Civil Engineers' Outstanding Civil Engineering Achievement Award for 1966.

struction of the Vehicle Assembly Building structure, a huge space-truss system of steel and horizontal diaphragms of composite structural steel and lightweight concrete construction. Volumetrically, the building is the largest on record, 526 ft. high, with 4 door openings, 456 ft. high.

Résumé

On décrit les installations de montage et de lancement pour fusées spatiales géantes du type Saturn V qui sont actuellement en voie d'achèvement en Floride (U.S.A.). Ces installations doivent permettre l'exécution, au cours de l'été 1968, des essais en vol de capsules spatiales habitées. Dans cette contribution, on trouve décrits le calcul et la construction de la halle de montage, qui est un immense treillis tri-dimensionnel métallique avec des voiles horizontaux mixtes acier et béton léger. Le volume de ce bâtiment constitue un record avec ses 160 m de hauteur; il possède 4 portes d'une hauteur de 138 m.

Zusammenfassung

Der Verfasser beschreibt die Montage und Startanlagen für bemannte Weltraum-Groß-Raketen vom Typ Saturn V, die in Florida (U.S.A.) der Fertigstellung nahen und den Beginn von Versuchsflügen für bemannte Weltraumfahrten ungefähr im Sommer 1968 ermöglichen sollen. Der Bericht enthält eine Beschreibung von Entwurf und Bau des Montage-Bauwerkes, eines Raumsystems von Stahlfachwerken und horizontalen Scheiben in Verbundkonstruktion: Stahl und Leichtbeton. Die Montagehalle, ein Gebäude von größten Raum-Dimensionen, ist 160 Meter hoch und hat 4 Toröffnungen von 138 Meter Höhe.

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