HOUSTON ASTRODOME
(Harris County Sport Stadium)
(Harris County Domed Stadium)
8400 Kirby Drive
Houston
Harris County
Texas

HAER TX-108
TX-108

PHOTOGRAPHS

WRITTEN HISTORICAL AND DESCRIPTIVE DATA

HISTORIC AMERICAN ENGINEERING RECORD
National Park Service
U.S. Department of the Interior
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(Harris County Sport Stadium)
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HAER No. TX-108

LOCATION:	8400 Kirby Drive, Houston, Harris County, Texas
DATE OF CONSTRUCTION:	completed in 1964
ARCHITECT:	Lloyd & Morgan; Wilson, Morris, Crain and Anderson
CONTRACTOR:	H.A. Lott, Inc., Houston (Herbert H. Eyster, project manager), general contractor Sam P. Wallace Company, mechanical contractor Fisk Electric, electrical contractor The Prescon Corporation, prestressing contractor
STRUCTURAL ENGINEER:	Walter P. Moore and Associates, Inc.
CONSULTING ENGINEERS:	Praeger-Kavanagh-Waterbury, New York City J.G. Turney, Houston Lockwood, Andrews & Newnam, Inc., Houston I.A. Naman & Associates, Houston, mechanical system Dale S. Cooper & Associates, Houston, mechanical system Dr. G. R. Kiewitt and Mr. Louis O. Bass, Roof Structures, Inc., St. Louis, dome design Bolt, Beranek and Newman, Cambridge, MA, sound system
MATERIALS:	American Bridge Division of U.S. Steel Corporation, fabricated and erected the steel; The Rackle Company, Houston, supplied precast concrete; American Seating Company supplied seating
SIGNIFICANCE:	Originally called the Harris County Domed Stadium, the Astrodome was completed in 1964. Conceived as the home of the Houston Colts and the Houston Oilers, it was termed by many as the Eighth Wonder of the World. It was the first time that a stadium was built for both baseball and football that was totally enclosed and fully air-conditioned. The building covers 9.14 acres of land. Circular in shape, the outer diameter of the Astrodome is 710’ and the clear span of the dome roof is 642’.

HISTORIANS: Adapted from "Astrodome-An Engineering Marvel of the 1960s" by Kenneth E. Zimmerman, Retired, Vice Chairman, and Narendra K. Gosain, Ph.D., P.E., Senior Principal, Executive Director, Structural Diagnostics, Walter P. Moore and Associates, Inc., presented at the Texas Section, American Society of Civil Engineers (ASCE) fall meeting, Houston, Texas, September 29-October 2, 2004.

PROJECT INFORMATION: The Historic American Engineering Record (HAER) is a long-range program to document historically significant engineering and industrial works in the United States. HAER is administered by Heritage Documentation Programs, a division of the National Park Service, U.S. Department of the Interior. Jet Lowe, HAER Photographer, produced the large format photography. Justine Christianson, HAER Historian, prepared the documentation for transmittal to the Library of Congress.

INTRODUCTION

Originally called the Harris County Domed Stadium, the Astrodome was completed in 1964. Conceived as the home of the Houston Colts and the Houston Oilers, it was termed by many as the Eighth Wonder of the World. It was the first time that a stadium was built for both baseball and football that was totally enclosed and fully air-conditioned. The building covers 9.14 acres of land. Circular in shape, the outer diameter of the Astrodome is 710', and the clear span of the dome roof is 642'. Houston's baseball and football teams no longer use the Astrodome. The Astros now play at Minute Maid Park, and the Houston Texans play at Reliant Stadium.

This report provides an overview of the different structural challenges that faced the design team of the Astrodome in the 1960s. Some of the issues that had to be dealt with included the design and construction of the dome structure and the assessment of wind forces on the dome roof, allowance for forces caused by thermal expansion and contraction of the dome structure on the supporting columns, bracing for lateral loads at the seating area, bracing of the 33' tall perimeter concrete retaining walls for lateral earth forces and the foundation design at depths far below the water table elevation.

HOFHEINZ AND THE ASTRODOME

In the 1960s, many businessmen pondered over the possibility of bringing a national baseball team to Houston, Texas. However, the challenges in Houston appeared to be insurmountable, not from the point of view of patronage and fan support for the game, but from the vagaries of the Houston weather coupled with heat, humidity, and mosquitoes that would make either playing or watching ballgames an unpleasant experience. However, one businessman dared to dream about a fully air-conditioned stadium, which had never been done before. This man was Roy M. Hofheinz (1912-1982), a Houston politician and entrepreneur. He had the distinction of being the Harris County judge from 1936 to 1944, and then mayor of Houston from 1953 to 1955. After serving as the Harris County judge, he became known as Judge Roy Hofheinz for the rest of his life.

Hofheinz and his business partner, Robert (Bob) E. Smith created the Houston Sports Association with the goal of getting a major league franchise in Houston. In order the build the world's first air-conditioned stadium, the Houston Sports Association needed the Harris County voters to approve a public bond issue planned for February 1961. This was a daunting task considering that Judge Roy Hofheinz and Bob Smith needed the support of African American voters. They decided to elicit help from Mr. Quentin R. Mease, a World War II Air Force veteran and one of Houston's most respected and influential African Americans. Mr. Mease and the other African American leaders agreed to campaign for the bond issue on the condition that the new stadium be opened as an integrated facility. This had become an important issue since it was only in 1960 that various lunch counters in Houston had become integrated. Judge Roy Hofheinz and Bob

Smith both agreed to Quentin Mease's condition, and the bond issue of $42,000,000 was passed to pay for the project.

Once the commitment had been made to build a new air-conditioned stadium, the Houston Sports Association got its major league franchise, the Houston Colt 45's who played in a temporary stadium adjacent to the Astrodome.

DESCRIPTION

The Astrodome is a domed circular concrete and steel framed building with an adequate playing field for both football and baseball. The building covers 9.14 acres (398,138 square feet) of land. The diameter of the domed roof is 642', and the outer diameter of the stadium itself is 710'. The playfield diameter is 516'. Vertically, the stadium has nine levels. One level is the field level and contains principally the exhibition spaces and mechanical and electrical rooms. Level two is devoted to mechanical equipment, dressing rooms, locker rooms, concession areas, offices for athletic teams and moveable stands. Level three holds the administrative offices, local team offices, storage areas, mechanical areas, and ticket booths. Level four functions as the main seating level with concessions in various locations. Level five has box seats, press and television spaces, and concessions. Level six has luxury box suites. Level seven has box and grandstand seats, comprising the second largest seating area. Level eight has the low roof area in the original design that was later converted to more seating in a 1989 expansion project. Level nine has the skybox seating level 107' above the playfield level.

The playfield has an elevation of 33', which is 207' below the level of the dome framing. The dome has a rise of 93'. Generally the level around the perimeter of the stadium (parking area) is at an elevation of 57'. The playfield level is thus 24' below the grade level. A ramp to the field level is provided in centerfield.

For baseball, the distance from home plate along the foul lines is 340', and to dead center, the distance is 405'. For football, the field is regulation size, and the areas normally black for baseball are covered for football. As originally designed before the 1989 expansion, the seating for various events was: baseball, 45,772; football, 52,382; boxing, 66,000; conventions, 55,000.

The stadium is cooled and heated using equipment with approximately 6,000 tons of cooling capacity and circulating approximately 2,000,000 cubic feet of air per minute. Fresh air intake is approximately 200,000 cubic feet per minute. Smoke and hot air are both expelled at the top of the dome.

CONSTRUCTION

The general contract for construction indicated the following quantities were used in construction:

• Earthwork, including excavation and backfill	250,000 cubic yards
• Cast-in-place concrete	40,000 cubic yards
• Reinforcing steel bars	2,500 tons
• Structural steel	
General stadium framing	6,000 tons
Dome structure	3,000 tons
• Pre-stressing tendons	25,000 lineal feet

In terms of 1960s dollars, the structural cost of the stadium was as follows: the stadium cost $5,300,000 and the dome cost $1,500,000.

STRUCTURAL CHALLENGES

Dome Structure

The dome is the most spectacular element of the stadium and has been its biggest attraction for the past forty years. A great deal of thought had to go into the selection of framing and the covering of the dome roof structure, as well as cost, aesthetics, and impact on air conditioning and air flow. There was a keen desire to have a grass field as well. No prototype existed to draw on for guidance from which to learn. Harris County, in consultation with the architects involved, decided that competitive design proposals would be received from interested firms that had experience and expertise in long span roof structures.

The minimum design criteria for the dome as given in the specifications were as follows:

• Live load	15 PSF
• Sonic boom loading	2 PSF
• Wind load	40 PSF, or load from wind tunnel test using sustained wind velocity of 135 mph with gusts of 165 mph
• Dead load	self weight of structure; 3" thick Tectum deck on bulb tees with plastic skylights

The specifications also required that a 1/8-scale model test be performed in a wind tunnel to verify wind forces on the dome structure. McDonnell Aircraft Corporation in St. Louis, Missouri, conducted the wind tunnel test. Dr. Herbert Beckman, Aerodynamicist, and Dr. Ing, Professor of Mechanical Engineering, Rice University, Houston, Texas, independently evaluated the results of the test. In his report dated September 29, 1961, Dr. Beckman wrote: "During the tests, the model is subjected to a steady air stream while hurricane winds consist of small grain turbulence with a gust diameter of usually not more than 100 or 200 feet. These gusts will result in only partial loading of the building, and as a consequence, are less effective than a steady wind would be. The wind tunnel data can be considered to give "conservative" loads compared with corresponding flow conditions in hurricanes."

Reactions on the dome support columns using the wind tunnel tests were very close to the reactions computed manually by Mr. Louis O. Bass of Roof Structure, Inc. Credit for the design work on the dome roof structure goes to Dr. G.R. Kiewitt and Mr. Louis O. Bass of Roof Structures, Inc.

The lamella dome structure has a diamond shaped pattern on the spherical surface. The arch ribs or ring members are steel trusses having an overall depth of 5'-6". The top and bottom chords vary from WF 16 x 58 to WF 16 x 78. The web members are two angles: 3-1/2" x 3-1/2" x 1/4". The short lamellas between ring members are also steel trusses measuring 5'-6" deep. The top and bottom chords of these trusses vary from WF 14 x 30 to WF 14 x 53. In these trusses also, the web members are two angles: 3-1/2" x 3-1/2" x 1/4". The lamella dome framing is supported on a tension ring that is also a truss 5'-6" deep. The top chord of this highly stressed member is WF 14 x 370, and the bottom chord is WF 14 x 314. Once again, two angles (3-1/2" x 3-1/2" x 1/4") were used as web members in the tension ring. All structural steel used in the lamella dome structure was ASTM A36 steel. Connections between the various elements of the lamella framing were made using ASTM A325 bolts. All welding was done using AWS E7018 electrodes. Full penetration butt weld splices provided continuity in the top and bottom chord members of the tension ring.

The erection of the dome framing required the fabrication and erection of thirty-seven steel towers. The erector placed the dome framing in pie sectors in opposing pairs, there being twelve sectors of 30 degrees each. The erection of the steel presented some problems since at a temperature of 60 degrees Fahrenheit, and with the dead loads applied, the tension ring had to stay vertical. Jacks were placed at the top of the erection towers to make the adjustments as the erection progressed. After the alignment was confirmed and all connections were made, the plan was to remove the jacks in the early days of 1964.

Jacks were gradually retracted over all the towers, and at each lowering, the tension ring alignment and supporting column plumbness was checked. However, the results of the plumbness of the columns varied daily. This obviously was of great concern to not only the engineers with Roof Structures, Inc., and Walter P. Moore, but it also made the County Commissioners very nervous. However, after checking and rechecking the monitoring data carefully and ensuring that there was nothing amiss with the design of the supporting columns, the decision was made to retract the jacks all the way and to set the frame free.

The monitoring work, however, continued in order to verify whether the degree to which the columns were out of plumb stayed constant from day to day. Unfortunately, this number did not stay constant but varied daily. Several days elapsed before Kenneth Zimmerman (the principal author of this paper) figured out that the variation was due to the temperature effects. The columns needed to be checked at the same time on successive days to ensure that there were no variations in temperature. Calculations had been done earlier in the design phase for temperature effects. As such, Zimmerman made the comment, “The old girl was behaving just as predicted!”.

Dome Deflections

There was a great deal of interest in the deflections of the dome under various load conditions. The dead load deflection was calculated to be 1.88”. When the jacks were released and the dome was free from all erection towers, the deflection measured was within .25” of what was predicted. The live load deflection was predicted to be .94”. Considering that the dome was going to be air conditioned, a temperature differential of 70 degrees Fahrenheit was used above or below the base temperature of 60 degrees Fahrenheit for temperature stresses and movements, which was determined to be plus or minus 1.80”. For the design wind load, the horizontal movement was 5.5”. This posed a challenge to both the architects and engineers on the design of the expansion joint at the edge of the dome. The joint needed to be designed for a total movement of 11”. The design team came up with a very elegant solution that is virtually maintenance free to a large extent. The solution consisted of a screen attached to the tension ring that extended beyond a concrete curb on the edge of the stadium roof just below the dome. The screen and curb lap sufficiently so as not to allow rain to blow into the interior, and the curb height was designed to keep rainwater from spilling down the roof edge.

Columns Supporting Dome

Steel columns, WF 12 x 65, located at every 5 degrees around the perimeter of the dome support the dome structure. These columns had to be designed to permit the movement of the dome structure towards or away from the centroid while not allowing movement from the tangential shear forces resulting from lateral wind loading. This was accomplished by using a “knuckled” column design conceived of by Kenneth Zimmerman. The knuckled columns have 4” diameter high strength steel pins at each end of the column. The lower bearing of the pin is welded to its plate support, and the top side is free to rotate in a close-fitted plate with milled surface. Anchorage is provided at the top against uplift with U-bolts.

Lateral Wind Loads

The lateral wind loads were resisted by X-braced bents extending the stadium to the foundation. However, in certain areas, it was not feasible to provide an X-braced system, so moment frames were used instead. Since there are several expansion joints around the perimeter of the dome structure, each isolated sector had to have its own system of lateral load resistance frames.

People Generated Sway Loads

The rhythmic movement of people in some events was known to cause sway loads in arenas and stadiums. The code required that the stadium be designed for 12 pounds per lineal foot of seating normal to the seats and 24 pounds per lineal foot of seating parallel to the seating. These sway loads were considered additive to the wind lateral forces, and the same system of X-braced frames and rigid frames were used for such forces as well.

Codes Used in Design
All concrete elements were designed using the working stress method in accordance with ACI 381-56. Ultimate strength design was given consideration but not used due to lack of complete code coverage at that time. Maximum concrete strength of 3,000 PSI was used in the project. Extensive use was made of lightweight concrete for all elements above ground. The slab on grade and basement walls were cast in normal weight concrete. The structural steel design was in accordance with AISC 1959, Fifth Edition. Grade of steel used for both the bowl structure and dome structure conformed to ASTM A36.

Foundation Design
The foundation design for the Astrodome turned out to be astonishingly simple. The design was based on the geotechnical recommendations of National Soils Services, Inc., of Houston. Because of the sandy characteristics of the underlying strata, the differential settlements were negligible. Interestingly, 50 percent of the footings were founded on predominately pure sand located approximately 5' below the playfield level. It was only in the 10' deep combined footings at the expansion joints where some wet conditions were encountered. This was remarkable given that the original water table was at an elevation of 44', the playfield elevation was at 33', and the bottom of the deepest excavation was at an elevation of 25'. The water table was lowered by the use of a well point system designed by Lockwood, Andrews & Newnam, Inc. ahead of the general construction work.

Perimeter Retaining Walls
For about 60 percent of the perimeter, the retaining wall extends from the first level to the fourth level for a height of 33'. The other 40 percent of the perimeter wall extended from the first to the third level for a height of 25'. Three concepts were developed to design the walls: 1) a counterfort system; 2) wall braced to interior column footings by diagonal struts, and horizontal struts between footings; 3) tie-backs using pre-stressing strands to dead-man anchors around the perimeter of the dome structure. Cost comparisons of the three schemes indicated that the system using tie-backs and dead-man anchors was most economical.

In order to reduce the lateral earth pressure against the retaining walls, a drained sand backfill was used. The geotechnical engineer completed the lateral equivalent fluid pressure to be 30 PCF.

All walls were designed to span horizontally, with tie-backs placed at 2.5 degrees around the perimeter. Two levels of tie-backs were provided such that the positive wall moments and the negative wall moments were approximately equal. The lower tie-back was placed close to the footing, and the second tie-back was placed close to the mid-height of the wall.

Strands used were .25" in diameter. The distance from the wall to the dead-man anchors was approximately 80'. Since the strands needed to be buried in the soil, there was a serious concern about the possibility of corrosion over the years, and the resulting loss in cross section of the strands. As a result, a decision was made to use the cathodic protection system to protect the strands from the corrosive effects of the soil. This cathodic protection is still operational as of this date.

CONCLUSION
At the time the Astrodome was completed, the United States had entered into the space age with the NASA facility located in Houston. The prefix "Astro" not only became popular but also synonymous with gigantic. Judge Roy Hofheinz renamed the Houston Colt 45's to the Astros, and the Harris County Domed Stadium became known as the Astrodome. The dream of Judy Roy Hofheinz had become a reality, and he branded the Astrodome the "Eighth Wonder of the World."

ANNOTATED BIBLIOGRAPHY

The following is a preliminary list of articles relating to the design and construction of the Astrodome and is in no way comprehensive. Compiled by Justine Christianson, HAER Historian, 2005.

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________. "Houston Astrodome—Power Plant and Mechanical Services Design." *ASHRAE Journal, Official Publication of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.* 8, no. 6 (June 1966): 90-91.
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Construction details of dome.

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