The Knoxville Sunsphere

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1 Scientific

The Sunsphere in Knoxville, Tennessee was built as the theme structure for the 1982 World's Fair. The project architect was Bruce B. Thompson of Community Tectonics in Knoxville, Tennessee, and the structural engineers were Socrates A. Ioannides and Jack H. Horner of Stanley D. Lindsey and Associates of Nashville, Tennessee.

1.1 Geometry and Materials

Figure 1: The Knoxville Sunsphere. [1]

The Knoxville Sunsphere is best described by a picture. (Figure 1) It is a hexagonal steel truss structure 266 feet tall. The top 74 feet are shaped into a glass plate covered sphere.

The shaft of this structure consists of 6 double columns. The outer 6 columns are splayed at the bottom to provide greater stability, and end at the base of the sphere. The interior six columns run the entire length of the structure. The two sets of columns are stiffened with K bracing. [2]

The sphere is rather unusual because the outer frame carries a significant portion of the weight. This design technique was sufficiently unusual to warrant the appearance of the Sunsphere on the front page of the Engineering News Record. (Figure 3) There are 30 curved steel columns and 13 horizontal steel hoops that form the spherical structure. These are made of 5 × 3 inch steel tubes. The curved steel columns are joined to the main shaft by a tension ring at the top of the sphere, and a compression ring at the bottom. These rings are "space frames" which are constructed of various sizes of tubes (6 × 6 inch to 14 × 14 inch), selected for their good torsional characteristics. On the interior of the sphere, beams extend from the core shaft to support the weight of the observation and restaurant decks. (Figure 2) [2] The visual aspects of the construction process were tracked quite carefully by the local newspapers. Some of these pictures appear in Figures 4 and 5.

The foundation of the Sunsphere consists of spread footings. This is rather unusual for the Knoxville area, as the ground is primarily limestone, which has a tendency to shift and settle.

Figure 2: A photo showing the construction of the Sunsphere. Note the 30 curved steel columns and 13 horizontal steel hoops that support the loads of the windows, observation decks, and restaurant. [2]

Therefore, most heavy buildings in the area are, "founded on caissons or piles to solid rock." [2] The engineers of the Sunsphere believed that it was stable enough to not need these precautions, and thereby saved between $80,000 and $100,000.

A simple analysis of this structure is possible by looking at the effects of dead loads, live loads, and wind loads on the structure.

1.2 Dead Loads

A close inspection of the dead loads acting on the Sunsphere proved difficult, as the architects of the project no longer have these records, and it was never reported in any of the documents examined. The dead loads are therefore calculated using several approximations.

The glass walls of the sphere are estimated first. The surface area of the sphere that is covered in glass is 16,295 ft^2. A structural study of the John Hancock Tower estimates the weight of partitioning, exterior walls, and permanent equipment as 60 psf. [4] Using these values, the weight of the glass walls of the Sunsphere and other miscellaneous parts can be estimated as 980 kips.

The weight of concrete floors in the structure must also be considered. These can be estimated by assuming that the floors are 8 inches thick, and then using a standard density of concrete of 150 lbs/ft^3. This results in a weight of 100 psf for concrete floors. The area of the floors and resulting dead and live loads are estimated in the following table. Note that the first floor is not included because it rests on the ground. It is therefore not supported by the steel structure.

Floor	Radius (ft)	Area (ft^2)	Dead Load (kips)	Live Load (kips)
8	28	2463	246	123
7	34.7	3776	378	189
6	37	4300	430	215
5	34.7	3776	378	189
4	28	2463	246	123
3	40	5027	503	252
2	47.5	7088	709	354
Total			2890	1445

The remainder of the structure is estimated by first assuming that all remaining members are the standard steel shape W 14 × 61. These beams are 14 inches long between flanges, and weight 61 pounds per foot. Estimates for total feet of steel are estimated from the schematic drawing (Figure 6). The detailed estimate is as follows:

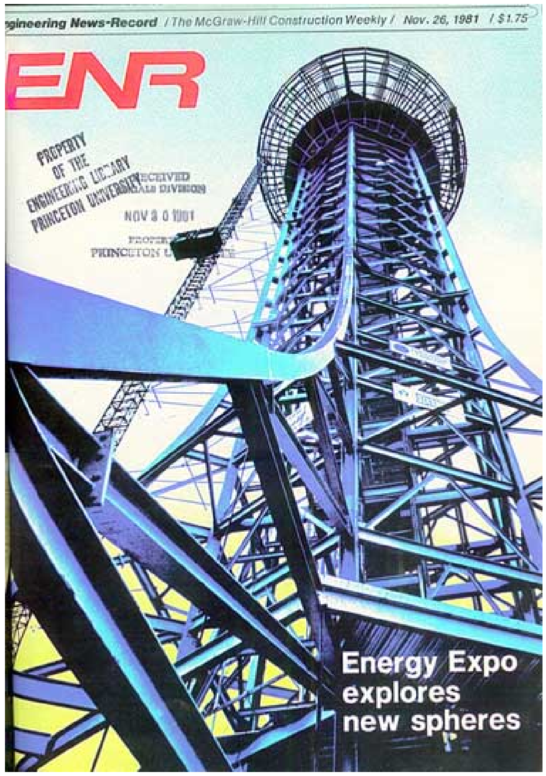

Figure 3: The cover of the Engineering News Record from November 26, 1981, showing the construction of the Sunsphere. [2]

6 interior columns	1596'
6 exterior columns	1200'
23 floors of interior elevator bracing	2944'
5 floors of glass bracing	2040'
18 floors of interior K bracing	2592'
18 floors of exterior column bracing	1722'
Total	12,094'

This results in 740 kips of steel structure, and a total of 4610 kips of dead load.

1.3 Live Loads

The live loads in the structure consist primarily of visitors to the restaurant and observation decks. For an estimate of this value we may use a standard load for office buildings of 50 psf. Indeed, as the Sunsphere is currently used as an office building, this would seem to be appropriate. The square footage of the occupiable space is estimated from the schematic drawing. (Figure 6) Each of the top five floors on the interior of the sphere are considered occupiable, as are the bottom two levels of the tower. Again, the first floor is not considered because it is not supported by the steel structure. A summary of results appears in the table in Section 1.2.

The final estimate is 1445 kips of live load. This estimate is a generous one since the interior of the building is largely occupied by the elevator shafts and stairways. However, it is better to overestimate than underestimate.

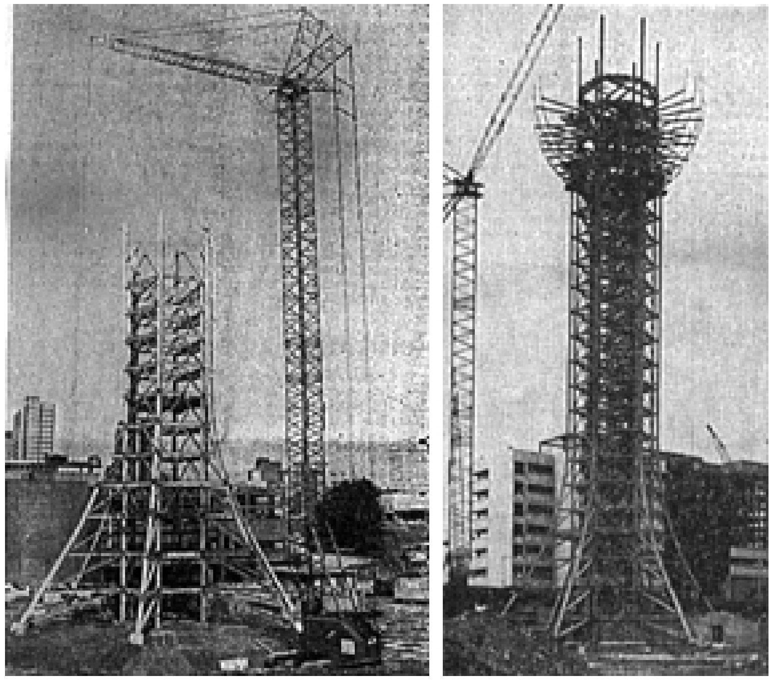

Figure 4: Early construction pictures of the Sunsphere. [3]

1.4 Wind Loads

The wind loads on the structure are not expected to be very high for this structure. Because it is located in a valley it is sheltered from the worst of the wind. On one windy day after the World's Fair had ended, six passengers were caught in an elevator inside the Sunsphere when it jammed due to deflection of the tower in gusting winds. The airport approximately 10 miles away recorded gusts of 40 mph. Since the tower reacted so poorly to such light loading, it will be assumed here that the designed windload was only 80 mph.

The unusual shape of the Sunsphere makes it subject not only to normal wind forces, but also to aerodynamic forces. The equation for aerodynamic force (drag) on a sphere is:

$$D = \frac{1}{2}\rho V^2 C_d A$$

Where ρ is atmospheric density, V is wind velocity, C_d is the drag coefficient of a sphere, and A is the projected area of the sphere that is exposed to the wind. [5] Assuming atmospheric conditions and a C_d of 0.14, the force acting on the sphere is only 9.8 kips. Because this shape is relatively streamlined, the forces on it are quite small. Doing a similar analysis for the shaft of the structure and assuming an appropriate C_d of 1.2, the forces acting on the shaft are 146.2 kips. The total is 156 kips, or This comes out to .59 kips/ft, only a quarter of the estimate used for the Eiffel Tower in structural studies. [4] However, the Sunsphere is located in a much more sheltered area, and as evidenced by the jammed elevator, was probably not designed for a very high wind load.

1.5 Efficiency

Before evaluating the efficiency of the structure, it is first necessary to determine weather wind loading should be an important consideration in the analysis. If the following equation is true, then wind loads are not generally considered significant to the design.

$$\frac{N_w + N_g}{N_g} \leq \frac{4}{3}$$

Figure 5: Late construction of the Sunsphere. [2]

N_w is stress caused by wind loads and N_g is stress caused by gravity loads. Assuming that the majority of the windloads would be taken by the outer 6 columns while the gravity loads would be divided evenly among all 12 columns, the left side of the equation yields only 1.05.

Knowing that wind loads may be neglected, the efficiency of the structure may now be calculated from the equation:

$$\eta = \frac{f_{act}}{f_{all}}$$

Where f_{act} is the actual stress and f_{all} is the allowable stress. The actual stress is calculated by dividing the gravity loads by the area of steel bearing these loads. A W 14 $\times$ 61 shape has a cross sectional area of 17.9 in^2. Using this knowledge and the fact that there are 12 load bearing columns, the actual stress is found to be 9.40 ksi. Assuming an allowable stress of 20 ksi for steel, the Sunsphere is found to have an efficiency of 47%.

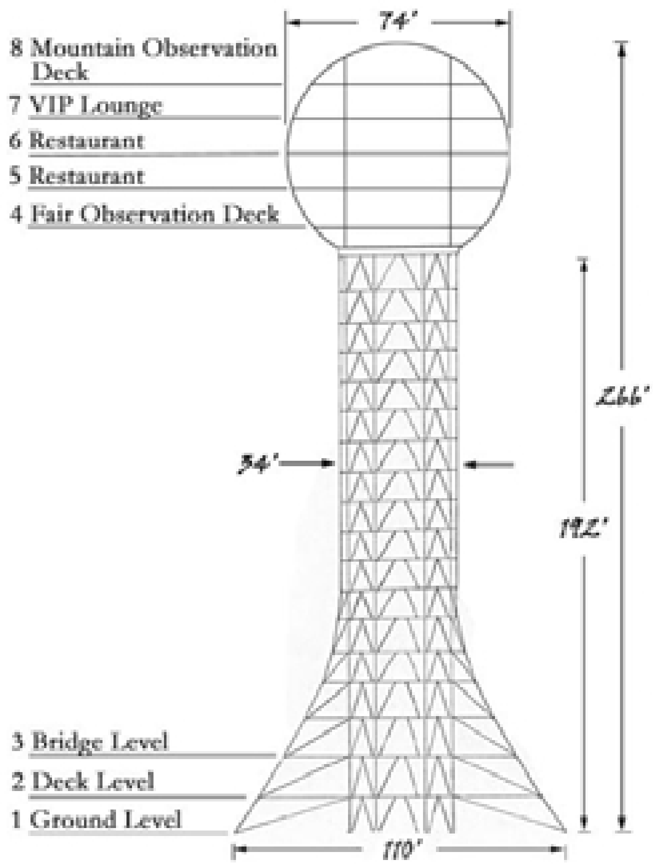

Figure 6: A schematic drawing of the Sunsphere.

2 Social

The Sunsphere was designed as a necessary “Theme Structure” for the 1982 World’s Fair. The Sunsphere was to be Knoxville, Tennessee’s Eiffel Tower, or Space Needle. Because the theme of the 1982 fair was to be “Energy Turns the World,” the Theme Structure for the fair was to be a “Monument to the Sun, the source of all energy.” [6] The architecture firm chosen for the design was Community Tectonics. The president of this company at the time was William Denton and the founder was Hubert Bebb, a man who had experience designing structures for several World’s Fairs. The original design for the Sunsphere was to be a large glass sphere on a concrete platform. The sphere would be about a hundred feet off the ground, have gold tinted windows, and would have a diameter for 86.5 feet to symbolize the 865,000 mile diameter of the sun. This idea had several problems however. The first was that because the structure was to be built in a valley, the structure would be partially hidden by surrounding buildings and would therefore not have a very dramatic bearing over the fair site. Also, the estimated cost of this design was too high to be allowable. The architecture firm knew that it could reduce the price while raising the height if the pedestal for the sphere could be made of steel alone. However, Knoxville building codes forbade construction in steel for the purposes of reducing fire hazards. The World’s Fair Committee appealed to the city council to make an exception to this rule and the city ruled in their favor.

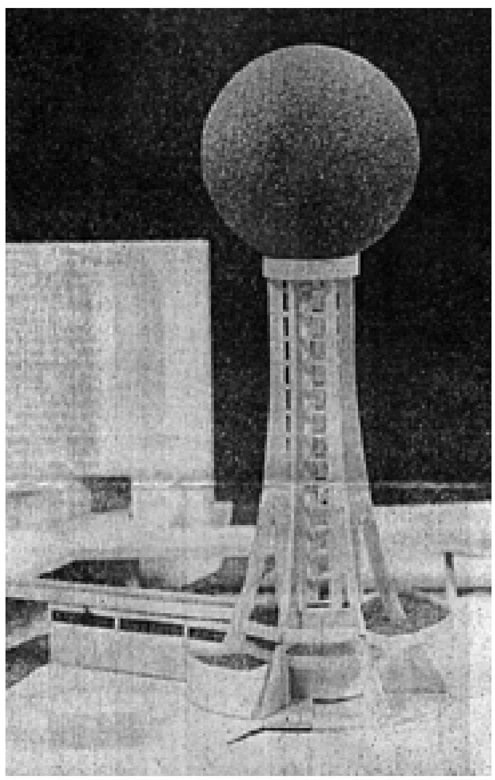

Figure 7: An early architect’s model of the Sunsphere [7]

The second design of the Sunsphere consisted of a 192-foot steel truss-work tower with a 74-foot diameter gold-tinted globe on top. (Figure 7) This design was purposely made small compared to other World’s Fair theme structure predecessors. Not only was it more economical, but it also addressed a concern of visitors to World’s Fairs such as those in Seattle and San Antonio. At these sites the theme structures were so tall that it was difficult to see the actual fair site from inside the structure. The final construction cost of the structure was $4 million dollars. Construction was begun by Rentenbach Engineering Corporation on January 23, 1981 and the topping off ceremonies were conducted August 24, 1981. When it was completed, the Sunsphere became the first spherical building in the United States. The exterior of the sphere was constructed of 360 windows coated with 24-carat gold dust. This gives the Sunsphere its reflective golden color and while still allowing visitors to see out the windows. Furthermore, the windows conserve energy by reducing air conditioning costs for the interior. [8] Unfortunately, each of these windows cost $1,000. The observation decks and restaurant on the interior of the sphere could be reached via three glass elevators. The observation decks were located on the top and bottom floors to provide excellent views of both the fair site and the surrounding Knoxville and Smoky Mountain areas. The second and third floors contained a restaurant with seats for 260 diners, and the fourth floor contained the kitchen for the restaurant and a VIP dining room with seats for 38 diners. A fast food concession stand was operated at the base of the Sunsphere for the duration of the World's Fair. [7]

During the World's Fair the Sunsphere was very popular. It saw an average of 60,000 visitors a day from May 1 through October 31 of 1982. Visitors were charged two dollars to ride to the observation decks, and it was believed that these charges would eventually pay for the structure. The Sunsphere was owned privately, and its owners estimated that 80% of the construction costs would be recovered in the first five years, and the remaining costs would be accounted for over the next 30 years. [8] Unfortunately, after the fair ended the Sunsphere ceased to be a popular place for visitors. The restaurant in the sphere was forced to close in March of 1984 because it was losing tremendous amounts of money. [9] Without any income being produced by the Sunsphere, the private owners were unable to pay their loans and when the bank threatened to foreclose in 1986, the Sunsphere and its surrounding land was appraised at only $800,000. [10] Through a long series of financial crises and several possession transfers, the Sunsphere eventually came to be owned by the City of Knoxville. The bottom floor of the sphere has been opened several times as an observation deck, but it only averaged 30 visitors a day, and was therefore unprofitable. The Sunsphere has also been used as housing for construction workers doing renovations on the structure, a reception hall for weddings, and most recently, the offices of the Knoxville Convention and Tourist Bureau.

Figure 8: The Knoxville Sunsphere and the Seattle Space Needle. The Space Needle is actually more than twice the size of the Sunsphere. [11] [12]

To better understand the costs involved in this structure, it is useful to make a comparison to a similar structure, the Seattle Space Needle. (Figure 8) The Space Needle was built for the 1962 World's Fair. It is a total of 604 feet tall and has a maximum diameter at the top of 138 feet. The top of the Space Needle contains stores, revolving restaurants, a lounge, and an outdoor observation deck. The Space Needle is also a steel structure, and it cost 4.5 million dollars to construct. [13] To compare this to the Knoxville Sunsphere, the scale is first adjusted. Scaling by height, the Space Needle would have cost 1.98 million dollars if it were the height of the Sunsphere. However, it was constructed in 1961 instead of 1981. Adjusting for this, the price of the Space Needle would be 8.26 million dollars. Compared to the 4 million-dollar price of the Sunsphere, the Space Needle seems very expensive. However, the comparison is not completely fair. The Space Needle continues to be a popular place to visit and dine, and therefore continues to provide revenue to its owners. It has been voted by local magazines and newspapers to be the most romantic place to dine or to propose marriage in the Northwest. One of its two restaurants has been chosen as one of the top 25 independent restaurants in the country.

In comparison, the Knoxville Sunsphere's restaurant got very poor reviews during the World's Fair, closed in 1984, and no restaurant or other industry has been willing to occupy the space. Some critics have suggested that the reason is because the interior of the Sunsphere offers so little space. (The Space Needle has approximately 10,000 ft^2 of restaurant space, whereas the Sunsphere only has 6000 ft^2) If a restaurant were to be successful it would have no room to spread out. Also, in 1986 the Sunsphere cost $3 per square foot per day just to pay utilities. [10] This would seem to suggest that the increased price of the Space Needle was justified because the added space allowed more flexibility in its use.

3 Symbolic

Figure 9: The current appearance of the World's Fair grounds near the Sunsphere

As the Sunsphere was originally built it was a beautiful and appropriate structure to serve as a monument to the sun. The base is splayed and the structure is hexagonal in shape to give a strong appearance of stability. Originally there were only three glass elevators on the interior of the structure. This design left a great deal of open space in the pedestal, so the truss appeared to be very light when viewed from the exterior. Furthermore, the space underneath the pedestal was left open except for a single concession stand. This open space helped to provide a park-like atmosphere that was congruent with the carefully planned fair grounds surrounding the structure. (Figure 9) The sphere itself is quite lovely from the exterior. When it is hit by the sun it sparkles brightly and provides a beautiful and appropriate monument to the sun. The lower observation deck on the interior of the sphere is not large but provides an excellent view of the fair grounds. The higher levels where the restaurant was located during the fair was reported by visitors to be an enchanting place to dine in spite of the fact that the food was overpriced and not especially tasty.

The only possible criticism of the structure as it was originally constructed might be that it is not as prominent a structure in the city as it should have been. It was built in a valley very close to an elevated bridge that splits the fair grounds. These two features often make the structure very difficult to see. (Figure 10) There are many parts of downtown Knoxville from which it is impossible to see the Sunsphere because it is behind a hill. In contrast, it is possible to see the Seattle Space Needle from almost any point in the city. Also, when a visitor to the fair grounds looks at the structure the chances are that the bottom portion will be obscured by the bridge, making it appear even shorter than it is. To make the most advantage of this structure it should have been built at least partway up a hill without any other structures immediately obscuring the view.

In spite of the difficulty seeing this structure at times, it is still a very important feature of the Knoxville area. Because of its unusual shape, the Sunsphere is immediately recognizable in a drawing of the skyline. (Figure 11) Without this structure in the city, Knoxville would have a completely unrecognizable profile. Furthermore, the existence of the Sunsphere is often the only thing people

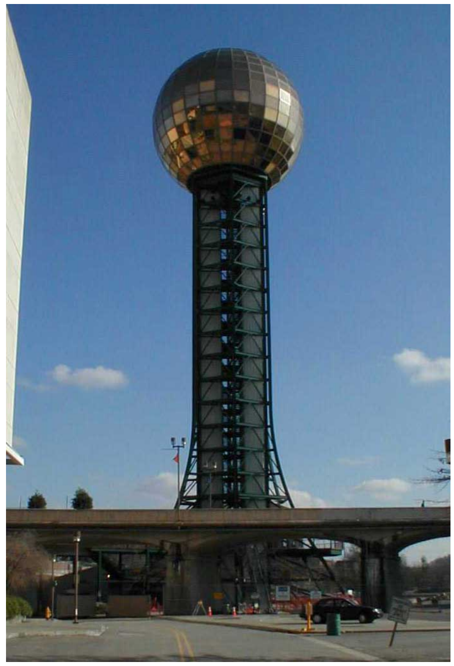

Figure 10: The view of the bottom section of the Sunsphere is blocked by a pedestrian bridge.

Figure 11: Two graphics of the Knoxville skyline. The left picture is the logo for the Knoxville Tourism Alliance, and the right picture is the logo for the Sunsphere City section of the Knoxville Metro Pulse. [14] [15]

know about Knoxville.[1] In older generations this is because of memories of the prominence of the structure in the 1982 World's Fair. In younger generations it seems too often to be because they have watched the Simpson's television show in which Bart visits Knoxville and accidentally knocks over the Sunsphere. (Figure 12)

Recent changes to the Sunsphere have, unfortunately, not been beneficial to the appearance of the structure. The original design of the pedestal left the glass elevators open to the elements where they corroded. When the Convention and Tourist Bureau moved into the structure they did a great deal of remodeling. This included filling in the structure underneath the pedestal with a reception area. Also, the elevator shafts were enclosed by a material that appears to be vinyl siding. Shrouding the area of the elevators shafts, however necessary, reduces the light appearance of the structure. (Figure 13) Also, the construction underneath the pedestal eliminates the park-like atmosphere that formerly existed. Furthermore, since the end of the World's Fair, the grounds of the site have gradually deteriorated to the point where they now appear to be little more than a burial ground for disintegrating concrete. (Figure 14) Without the lovely grounds underneath or the pleasure of

[1] It is this fact that led the city to put the Tourist's Bureau in the top of the sphere.

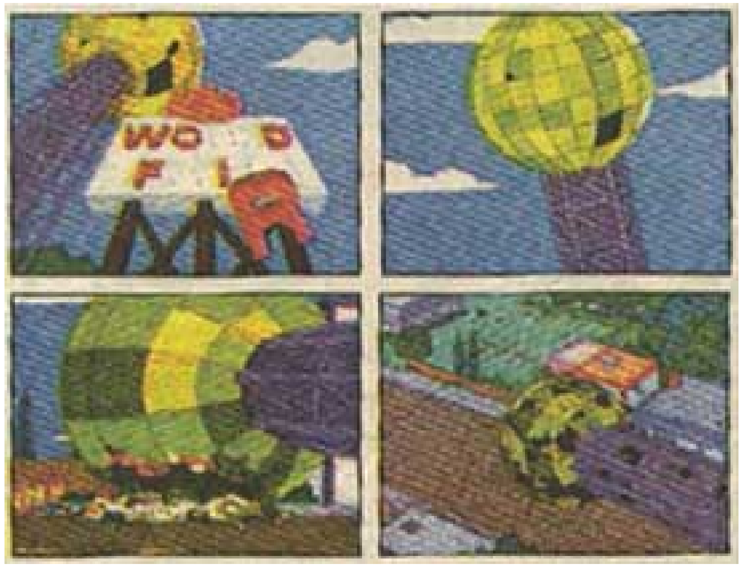

Figure 12: Frames from an episode of the Simpsons, in which Bart visits Knoxville and knocks over the Sunsphere. [1]

the glass elevator ride, the cramped observation deck (Figure 15) might make a visitor wonder if this structure was really worth what it cost to build. To be fair, the observation deck is not open to the public and the pictures that appear in this paper are the result of the photographer sneaking into the structure. It is obvious from the interior, however, why the deck is not open. The windows don't appear to have been cleaned in many years and so all of Knoxville looks as if it was covered in a thick coat of smog. The displays around the deck pointing out the sights of Knoxville are no less than 10 years old, and the carpeting is probably the original. On the whole, the structure would appear to be appropriate for the signature piece of what the *Wall Street Journal* called a "scruffy little city."

It is expected that the upcoming modifications to the area will be an improvement. The nearby Knoxville Convention Center is constructing a second building on a corner of the fair grounds and is demolishing several of the older buildings on the site. After this is completed the Center plans to do extensive landscaping of the fair grounds to restore some of the former beauty to the area. Local newspapers report, as they have since 1984, that several restaurant owners are considering leasing several floors on the interior of the Sunsphere. Considering the additional people the Convention Center will attract, a restaurant could be a successful venture.

Regardless of the details of the appearance of the structure, Knoxville residents are likely to continue taking pride in the Sunsphere for its past and the recognition it brings to the city. The World's Fair site continues to be a centerpiece of Knoxville because of the concerts held in the outdoor amphitheater during the summer, the Fourth of July and Labor Day celebrations, and the many summer festivals held on the grounds. The structure has been beneficial to the city and hopefully, will continue to beautify the area.

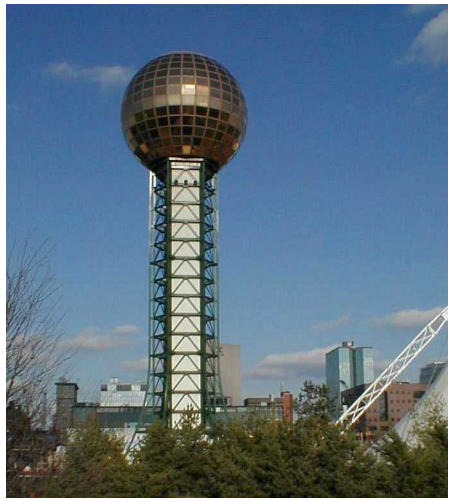

Figure 13: The interior of the Sunsphere has been enclosed to protect the elevators. This picture shows how that reduces the light appearance of the structure.

Figure 14: The formerly park-like atmosphere underneath the Sunsphere is now part of a demolition area.

Figure 15: The fourth floor observation deck with a scale factor.

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