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Design of Hands-On Solar Power Exhibit for Children's Science Museum

Chad A. Stott

Christina Carmen

Jayme Berstell

Danny Nease

Jeremy White

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Student Name: Chad Stott

Department: Mechanical and Aerospace Engineering

College: Engineering

Degree: Mechanical Engineering

Advisor Name: Dr. Christina Carmen

Full title of project as it should appear in Graduation Program and on transcript:

DESIGN OF HANDS-ON SOLAR POWER EXHIBIT FOR CHILDREN'S SCIENCE MUSEUM

Abstract (should be included at the beginning of your project as well):

A capstone senior design class in the Mechanical and Aerospace Engineering (MAE) Department at the University of Alabama in Huntsville (UAH) was tasked by Sci-Quest, a hands-on children's science museum in Huntsville, Alabama (AL), to design and build an exhibit that will teach children how solar panels function. The goal of the project was to create an exhibit that is educational, entertaining, and aesthetically pleasing while maintaining safety as the ultimate goal.
This paper reviews the decisions and engineering principles that shaped the final exhibit design. Gearing ratios, power conversions, Computer Aided Design (CAD), calculation of the center of gravity, and Finite Element Analysis (FEA) all were critical when designing the exhibit in order to verify the final product would hold up to the rigors of extended and frequent use for many years.
The final configuration for the exhibit has a crank handle that turns an electric generator to power an overhead light. The light is focused onto a single solar panel which is hooked up to a K'nex® rollercoaster. Mounted adjacent to the light is a cloud mechanism that rotates in conjunction with every turn of the crank handle. As the crank turns, the "cloud" will rotate and periodically interrupt the light and prevent it from shining upon the solar panel. This conveys the principle that solar power can be used as electrical sources but that it also has its drawbacks. The cloud is geared in such a manner that the power will be cut-off during each cycle of the roller coaster car to better display the solar power principles.

Approved by:

Project Advisor: Christina L Carmen (Signature) Date: 11/1/2011

Department Chair: [signature] (Signature) Date: 11/1/11

Honors Program Director: [signature] (Signature) Date: 11-2-11

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DESIGN OF HANDS-ON SOLAR POWER EXHIBIT FOR CHILDREN'S SCIENCE MUSEUM

Chad A. Stott, Christina L. Carmen, Ph.D
Mechanical and Aerospace Engineering (MAE) Department
University of Alabama in Huntsville (UAH)
Huntsville, Alabama, USA

Jayme Berstell
MAE Department
UAH
Huntsville, Alabama, USA

Danny Nease
MAE Department
UAH
Huntsville, Alabama, USA

Jeremy White
MAE Department
UAH
Huntsville, Alabama, USA

ABSTRACT

A capstone senior design class in the Mechanical and Aerospace Engineering (MAE) Department at the University of Alabama in Huntsville (UAH) was tasked by Sci-Quest, a hands-on children's science museum in Huntsville, Alabama (AL), to design and build an exhibit that will teach children how solar panels function. The goal of the project was to create an exhibit that is educational, entertaining, and aesthetically pleasing while maintaining safety as the ultimate goal.

This paper reviews the decisions and engineering principles that shaped the final exhibit design. Gearing ratios, power conversions, Computer Aided Design (CAD), calculation of the center of gravity, and Finite Element Analysis (FEA) all were critical when designing the exhibit in order to verify the final product would hold up to the rigors of extended and frequent use for many years.

The final configuration for the exhibit has a crank handle that turns an electric generator to power an overhead light. The light is focused onto a single solar panel which is hooked up to a K'nex® rollercoaster. Mounted adjacent to the light is a cloud mechanism that rotates in conjunction with every turn of the crank handle. As the crank turns, the "cloud" will rotate and periodically interrupt the light and prevent it from shining upon the solar panel. This conveys the principle that solar power can be used as electrical sources but that it also has its drawbacks. The cloud is geared in such a manner that the power will be cut-off during each cycle of the roller coaster car to better display the solar power principles.

INTRODUCTION

The hands-on learning center, Sci-Quest, was interested in procuring a new exhibit to teach children about the use of solar panels. A solar energy display would teach children about green technologies and possibly interest children to be involved with green energy technologies later in life. An ideal exhibit would not only be educational, but would be fun to use, and be able to hold a child's attention for as long as possible. To generate the most interest from the display, the exhibit should relate solar panels to a real life situation such that the children understand the role solar power could play in everyday life. The exhibit should also provide auditory, visual, and kinesthetic learning opportunities so that children with different learning styles could remember the exhibit after visiting the learning center. The exhibit should be safe, include descriptive signage, and be able to provide the best educational experience possible.

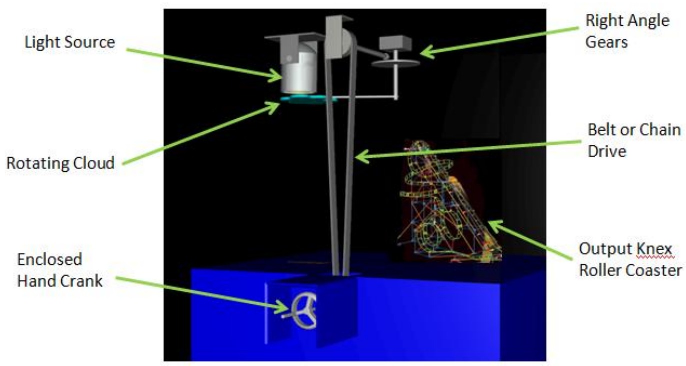

Figure 1. System Layout

The exhibit was designed by creating several concepts, then deciding which one would be the most beneficial and entertaining to the children. This was accomplished via the use of a decision matrix, which is an evaluation tool from the NASA Systems Engineering Handbook [1]. In this project, the best design was one in which a hand crank was used to power a light source which would power a ferris wheel via a solar panel. Once the best option was selected, the design was changed from a ferris wheel to a roller coaster to provide better attraction and entertainment. A cloud mechanism was then added to the design to simulate a real-world problem when using solar panels, as shown in Figure 1.

DESIGN PROJECT REQUIREMENTS

SciQuest allowed the UAH design students to ultimately decide on how the exhibit would work and facilitate the children's attention and learning, but they did have a few requirements so that all children may enjoy the exhibit fairly and safely.

First and most important is that safety from every aspect takes precedence. The various methods that the children can hurt themselves must be taken into consideration. This is further discussed and analyzed in the "Safety of Exhibit" section of the present paper.

Other design requirements require the exhibit to be durable and withstand long periods of use since the museum is open 6 to 9 hours every day. The handle was analyzed using FEA to make sure it can withstand a small child hanging from it.

The exhibit must also be able to be moved anywhere within the museum as the staff deems necessary but not easily moved by museum patrons. Visitors must not be able to move the exhibit after it has been positioned within the facility. Casters will be placed at the bottom of the exhibit so that staff may unlock the casters before moving the exhibit. These casters will be mounted in such a way as to minimize their visibility and be only accessible to unlock after a lockable entry is accessed. This lockable door will also protect the internals of the exhibit and allow the staff access when necessary. The internal components must also be able to remain intact during movement between areas of the museum.

The height was not limited by museum staff but the preferable footprint had to be no more than five feet long and five feet wide. Maintenance should be relatively easy with supplied blueprints and technical specifications provided at the time of completion.

The last two criteria that had to be met are that guests visiting the museum should not easily take apart the exhibit and the American Disabilities Act [2] must be followed so all children will be able to all enjoy the museum equally. It was suggested that hexagonal bolts be used as fasteners in order to counteract any unwanted disassembly. All controls and necessary viewing angles must be accessible from no more than a height of thirty-six inches to accommodate individuals in wheelchairs.

SAFETY OF EXHIBIT

Since the primary users of the museum's exhibit are children, the upmost importance was given to keeping the users of this exhibit protected from any perceivable accident that may be avoided. The team decided to round all corners and edges of the exhibit and also to create a design with no gaps around moving parts. The only moving part that the children have access to is the crank shaft handle. In order to prevent hair and small fingers from intermingling with the shaft, the team decided to build a shroud around the gap between the handle and the rest of the exhibit. Additionally, wood surfaces not only will be rounded, but also sanded and painted to reduce the chance of splinters.

All electrical components, circuitry, wiring, and small moving parts are to remain inaccessible to users. The center of gravity needed to be low enough that the input to the exhibit will not tip the exhibit over along with unexpected forces. Sandbags or other weights can also be placed in the bottom to give provide a satisfactory factor of safety. The plexiglass used will be three-eighths of an inch thick to prevent shattering but still be economical enough for the project to remain within budget. Also, a foam or rubber covering will be applied to the handle so people will be protected from any accidental bump.

The safety of the final design was quantified by using a military risk assessment as described in MIL-STD-882, Revision D [3]. Tables 1 and 2 define the terms used for the consequence and frequency of safety hazards of a system. Table 3 assigns a score for every combination of the frequency and consequence of any safety hazard. Table 4 designates the results into four groups of various risk acceptability and is the only table from Revision B [4] of the same standard. The reason the team used this table from a previous revision is because criterion for the risk assessment is categorized in Revision D to what level of personnel are required to sign off on the risk. Without this hierarchy, the team decided to stick with the layout as presented in Revision B for better clarity in this application. Higher point values are most desirable while the lowest point values are assigned as "unacceptable."

Table 1. Frequency of Hazard Occurance Terms

Description*	Level	Specific Individual Item	Fleet or Inventory**
Frequent	A	Likely to occur often in the life of an item, with a probability of occurrence greater than 10^{-1} in that life.	Continuously experienced.
Probable	B	Will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life.	Will occur frequently.
Occasional	C	Likely to occur some time in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.	Will occur several times.
Remote	D	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.	Unlikely to occur, but possible.

Table 2. Consequence of Hazard Occurance Terms

Description	Category	Environmental, Safety, and Health Result Criteria
Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1M, or irreversible severe environmental damage that violates law or regulation.
Critical	II	Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200K but less than $1M, or reversible environmental damage causing a violation of law or regulation.
Marginal	III	Could result in injury or occupational illness resulting in one or more lost work days(s), loss exceeding $10K but less than $200K, or mitigatible environmental damage without violation of law or regulation where restoration activities can be accomplished.
Negligible	IV	Could result in injury or illness not resulting in a lost work day, loss exceeding $2K but less than $10K, or minimal environmental damage not violating law or regulation.

Table 3. Hazard-Assessment Matrix

SEVERITY PROBABILITY	Catastrophic	Critical	Marginal	Negligible
Frequent	1	3	7	13
Probable	2	5	9	16
Occasional	4	6	11	18
Remote	8	10	14	19
Improbable	12	15	17	20

Table 4. Criterion for Risk Index

Hazard-risk index	Criterion
1--5	Unacceptable
6--9	Undesirable
10--17	Acceptable with review
18--20	Acceptable without review

Table 5. Results of Military Risk Assessment

Hazard	Frequency Level	Consequence Level	Hazard Index #	Criterion
Hand Slippage on hand crank	Occasional	Negligible	18	Acceptable without Review
Eye damage from staring at light	Occasional	Negligible	18	Acceptable without Review
Hair getting caught in crank	Improbable	Marginal	17	Acceptable with review
Injury resulting from sharp edges of mechanical components	Remote	Marginal	14	Acceptable with review
Tipping of display	improbable	Critical	15	Acceptable with review

Table 5 shows how the military risk assessment was applied to the final design of the solar panel exhibit. Five hazards were evaluated and assigned frequency and consequence levels. Points were assigned according to the Hazard-Assessment Matrix and the necessary criterion noted. Tipping of the display, injury resulting from sharp edges of mechanical components, and hair getting caught in the crank all received noted risk as "acceptable with review." This means these factors must be guarded against within the design or, at a minimum, with warning labels applied to the hardware. Hand slippage on the hand crank and eye damage from staring at the light received noted risk as "acceptable without review," meaning these hazards have been properly addressed.

MARKET SURVEY

With no previous experience in the field of science museum exhibits, a market survey was perceived as the best manner in which to determine what the target age group finds interesting. Children 2 – 18 years old were asked about their favorite toys. With this information, the output device could be selected that would best hold a child's interest.

The toys mentioned by the children in the survey were split into two groups. For the final design to function properly, the output device has to be powered by electricity and also be within budget.

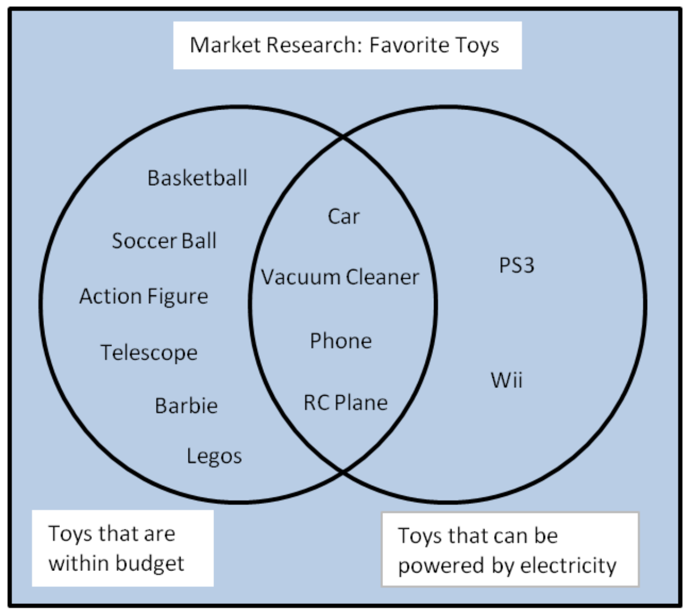

Figure 2. Market Survey - Favorite Toys

Figure 2 illustrates that the only toys that are powered by electricity and within budget are a solar-powered car traveling on a track, a vacuum cleaner, cell phone, and remote-controlled aircraft. The vacuum cleaner and cell phone were dismissed since neither easily involved the participant. The car was selected because of the contained nature of a track for more reliability. Over time, the decision was made to use a roller coaster toy since the car is integral to the track.

ELECTRIC POWER SUPPLY

The roller coaster output device operates using two AA batteries so the total needed power output would have to equal that same amount. In order for the participant to realize one of the potential drawbacks of solar power, no capacitors could be used in the circuitry of the exhibit so that the car on the tracks will stop in order to demonstrate the lack of energy from the solar panel that will be blocked by the cloud mechanism.

The AA batteries are rated at 1.5 volts each but deliver considerable less during actual discharge. The two batteries for the K'nex© rollercoaster are in series and require about 2200 milliampere-hours in order to run. Figure 3 is a chart that Duracell® provides regarding the performance of their batteries [5]; the output wattage required to run the roller coaster comes out to be 50 milliwatts, or 0.05 watts of power.

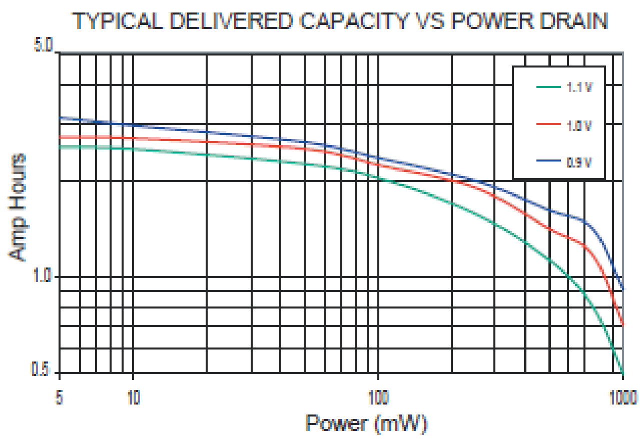

Figure 3. Provided Data from Duracell [5]

The selected solar panels are rated at an output of 0.45 watts of maximum power output so more than enough power should be generated from the light source.

Experimenting with different light sources demonstrated that both incandescent and Light Emitting Diode (LED) lights will produce power from the solar panels. LED lights were selected since they require less power to light and last longer. It is also interesting to note that red LED lights that were tested will decrease the power output from the solar panels in case ambient light sources produced too much electricity in the system.

The electric generator that powers the light source also had to be accounted for. Since the solar panels cannot pick up all the light from the lights overhead, there will be considerable energy loss from the lights to the panels, at least much more than the loss from all other areas of energy transfer. The output energy from the generator will be maximized with gear ratios based on experimentation and test runs in order to ensure that the light has enough power to run with modest input from the child. Resistors will be in place per the results of the tests so that the system does not overheat and cause a greater chance of failure or worst-case scenario, a fire.

The other factor that goes into converting enough light into energy is the amount of lumens that the light source can produce. Direct sun light averages a lux of 100,000 lumen per square meter. The area of the solar panel is 0.0406 square meters. This amounts to a needed output of 4060 lumen from our light source. Even with a shield around the light source, not all the light will be directly on the solar panel but this serves as the bare minimum to get enough energy for the system to work.

CENTER OF GRAVITY CALCULATION

It is apparent that an exhibit must not be top-heavy so it stays in position and is sturdy. There is the potential that if the exhibit is too heavy, it may hinder the movement of the exhibit by the museum staff. The ideal center of gravity would be below the thirty-six inch mark since that is the maximum height of the input forces from the museum visitors.

The height of the center of gravity for the basic structure of the exhibit was determined to be over twenty-eight inches, less than eight inches below the needed thirty-six inch limit. Since this was calculated without considering any of the internal parts the value is bound to raise the center of gravity to near the threshold of tipping under worst-case scenario conditions. A lower center of gravity is preferred rather than risk any danger to the user, bystanders, exhibits in the vicinity, and the building itself.

The simple solution is to place removable objects with substantial weight in the bottom of the exhibit so the center of gravity is lowered to make it more stable. This also works well for the staff that is in charge of moving the exhibit since the added weight can be removed and replaced after it is in the desired position in the museum. The bottom of the exhibit where these weights will be placed will have the same access as the casters, meaning it will be behind a locked door that only the staff will have access to.

Table 6. Center of Gravity Calculation

Calculation of total weight

	Density (lb/ft^3)	Volume (ft^3)	Weight (lbf)	Total Weight (lbf)	
Particle Board Top	38	0.667	25.33	1x	25.33
Plexiglass Sides	73.7	0.093	6.85	4x	27.4
2X4 Posts	30	0.109	3.28	4x	13.1
2x4 Frame	30	0.109	3.28	8x	26.2
Particle Board Siding	38	0.625	23.75	4x	95.0
2x4 Base	30	0.109	3.28	8x	26.2
Particle Board Bottom/Top	38	0.833	31.65	2x	63.3
Total Weight (lbf)	276.53				

Calculation of Center of Gravity

	Ȳ (in.)	Weight (lbf)	y (lbf*in.)
Particle Board Top	71.75	25.33	1817.43
Plexiglass Siding	54.00	6.85	369.90
2x4 Post	54.00	3.28	177.12
Particle Board Top	36.31	31.65	1149.21
2x4 Frame	18.00	2*(3.28)	118.08
Particle Board Siding	18.00	23.75	427.50
2x4 Base	0.75	4*(3.28)	9.84
Particle Board Bottom	0.31	31.65	9.89
Total		142.19	4078.97
Center of Gravity (in.)		28.69	

FINITE ELEMENT ANALYSIS

The exhibit must be durable enough to withstand the rigorous use primarily from children. The chance that improper use of the end product will occur is high since the environment includes children that are free to explore on their own and try the exhibits as they see fit. Every conceivable use of the exhibit must be taken into consideration. Therefore, the exhibit must be able to withstand various situations.

The worst case, as far as stress on the structure, that can be measured by FEA, is if a child hangs from the outermost edge of the crank handle. The crankshaft will either be directly connected to the electric generator or only a few gears so it will not have much resistance to turns; therefore, the stress will not be high enough to warrant immediate fracture.

Taking into account that the handle will be thirty-four inches from the ground, only smaller children will be able to hang their full body weight from the outer edge of the crank shaft handle. As a practical assumption, the weight of the child was assumed to be fifty pounds with the load pointing directly toward the ground. Figure 4 provides the results of the FEA performed on a crank shaft handle made from ASTM A36 steel.

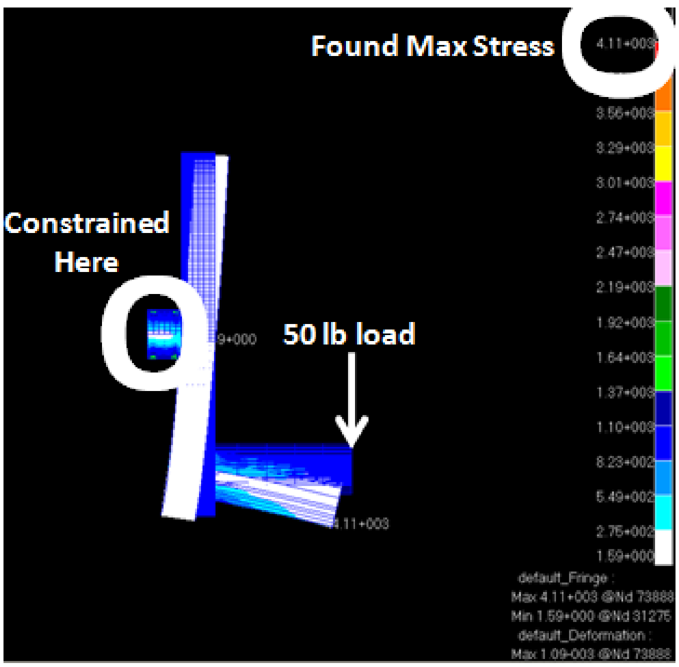

Figure 4. Results of Finite Element Analysis of Crank Shaft Handle (side view)

The handle is shown from a side view with the crank shaft being constrained on the left side of the picture and the 50 pounds being loaded on the handle shown on the right. The diameter of the crank shaft and the handle are 1/2 of an inch with the face of the handle being 1/3 of an inch thick. Deformation in Figure 4 is exaggerated by the software used in order to better visualize which way the object being tested is under tension and compression at different points.

The maximum stress is located on the top of the crank shaft and is noted as 4,110 pounds per square inch (psi). The maximum yield strength of ASTM A36 steel is listed as 36,000 psi so this setup has a factor of safety of 8.76. The factor of safety may be higher than needed but it does allow a heavier load to be safely applied.

GEAR RATIO OF CLOUD MECHANISM

The cloud mechanism is directly connected to the turning motion of the crank shaft by way of a chain and sprocket. That will turn a beveled gear translating the motion of the vertical gear to motion in a horizontal gear. This will then gear down to desired output gear ratio so that the cloud will pass over the solar panel at the same time that the roller coaster is travelling up the first hill of the rollercoaster. The car is chain-driven up the first hill of the roller coaster; the only part of the toy that is powered. To better demonstrate the loss of power from the solar panel as the cloud passes overhead, the car should stop at some point while still on the powered chain-driven track on the first hill.

The time it takes the car to travel up the first hill and the speed that it takes the average individual in the target age range is needed in order to determine what gear ratio will be needed so that the cloud may interrupt the light at the right time.

The car was found to be on the chain-driven track for thirteen seconds. Also, the speed of the average tested child was roughly three revolutions per second on a similar sized crank with little resistance.

$$(13\ s) * \left(3\frac{rev}{s}\right) = 39\ crank\ revolutions$$

It is determined that a total of thirty-nine crank revolutions by the child is required while the car is on the chain-driven track. Therefore, 39:1 is the smallest gear ratio that will achieve the desired result. A larger gear ratio of 32:1 was chosen just in case the cloud narrowly misses the timeframe allotted or the child turns the crank at a slower pace than accounted for.

VERIFICATION TESTS

This project has many uncertainties as far as how the system will interact with itself and its surroundings- including both ambient light from the museum and the people that will be using the finished product. Thorough testing is needed to verify that the system works as designed under the various circumstances that may occur while in permanent use.

Since the exhibit may be moved to different areas of the museum as the staff sees fit, all outside factors need to be accounted for. There is no need for an outlet so it will not limit the number of locations the exhibit may be placed. Because of this, the ambient light from different areas of the museum may play a role in the way the exhibit works. The different areas of the museum were tested for the amount of electricity generated by the ambient light sources by measuring the height at which the solar panel will sit in the exhibit and measuring the voltage that was generated. The minimum was 0.2 volts generated in the section for exhibits that features light as part of the exhibit. The maximum was 2.37 volts directly under a light mounted on a low ceiling toward the front of the museum. The overall average voltage obtained from any single area of the museum was about 1.05 volts. Testing will of course have to verify these results on the full-scale mockup of the exhibit, but the top of the exhibit is likely to eliminate most of the effects of the ambient light sources, but it is still a source of uncertainty until the product is fully tested.

Since the roller coaster is assembled using hundreds of small pieces, the structural integrity was in question especially when in transit between areas of the museum. The roller coaster has since been assembled and it appears the structure will in fact hold together during any and all transit that must take place. The roller coaster was picked up and shaken with no pieces breaking free or even working themselves loose. For added durability all pieces will be glued to each other and the structure as a whole will be fastened to the main structure of the exhibit. It will then continue to be tested to make sure the roller coaster still works as designed with the added stiffness the glue provides and also to make sure none of the glue has interfered with the movement of the car on the track. The design team will ensure that the car will not jump off the track, as this would cause the staff to constantly have to unlock the access door of the exhibit in order to replace the car on the track.

As stated earlier, LED lights create electricity in the solar panel as well as incandescent light bulbs. The advantages of the LED are that they have a longer lifetime which will lessen the burden on the museum maintenance staff, and they create more light per input watt than a conventional incandescent light bulb [6]. Further tests will be performed to verify the best LED or if another type can be used more efficiently.

CONCLUSION

The final design of the exhibit to be displayed within SciQuest in Huntsville, AL and is an all-inclusive system involving the transfer of energy between mechanical and electrical and back to mechanical in a manner that will allow children to learn how solar panels function. The cloud mechanism allows the children to learn about some of the drawbacks of the technology as it currently stands. A great deal of attention when designing this project was focused on the safety of the children and all other participants in the museum and allowing all children to enjoy the product equally. Fabrication of the final product will be completed by November of 2011. Numerous hours of testing will follow the completion of the exhibit to ensure safety and durability. Also, signs will be mounted around the outside of the exhibit in order to explain the product to the children, or so their parents may explain to them more fully what is happening in order to increase interest of alternate methods of energy to the younger generation.

ACKNOWLEDGMENTS

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