Apparatus for Removing T5 Bulbs

by

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Submitted to the
MECHANICAL ENGINEERING TECHNOLOGY DEPARTMENT
In Partial Fulfillment of the
Requirements for the
Degree of

Bachelor of Science
in
MECHANICAL ENGINEERING TECHNOLOGY

at the

OMI College of Applied Science
University of Cincinnati
May 2008

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Mechanical Engineering Technology

Certified by _____
Amir Salehpour,
Thesis Advisor

Accepted by _____
Muthar Al-Ubaidi, PhD, Department Head
Mechanical Engineering Technology

ABSTRACT

T5 fluorescent light bulbs are becoming more common in schools, offices, and retail stores. However it is difficult to replace the bulbs because there is no tool available to aid in achieving the proper torque. The maintenance department of the University of Cincinnati requested the design and creation of a tool that would assist in the replacement of the T5 light bulbs around campus. After interviewing Ronald Lambers, Assistant Director Electrical System & Facilities Management Operations, the specific needs of the device were identified and three concepts were considered. These needs include being safety oriented, lightweight, and easy to use. By comparing the three concepts against the needs, it was determined that the cantilever apparatus was preferred. The projected cost was approximately $117. The design phase began on January 7, 2008 and the manufacturing phase began on March 17, 2008. The entire project was tested by June 4 and completed by June 11, 2008.

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PROBLEM STATEMENT AND BACKGROUND

Lights are an essential part of buildings and as technology advances light bulbs are getting smaller and brighter. T5 light bulbs are used in recessed indirect lighting applications. Since they are small however, it can be challenging to apply enough torque to remove the bulb. The University of Cincinnati (UC) Maintenance Department has requested a tool that would be able to apply the necessary torque to remove the bulb more easily.

RESEARCH, TECHNOLOGY AND EXISTING PRODUCTS

A bulb changing tool for T5 florescent light bulbs does not currently exist. From extensive internet research, the only bulb changing tools that could be found were for incandescent and flood lights (Appendix A). These tools are ineffective for removing the T5 bulbs as they are simply designed to unscrew the bulb, while the T5 bulbs require a quarter turn from its tangent plane in order to be removed. The most common of these changers are the 4-pc Bulb Changer Set With Pole, Light Bulb Changer, and Unger Flood Light Changer. (1) (2) (3)

Figure 1 is an indirect T5 light fixture that is located out of sight on top of an awning. The light is reflected up off of the front shield. The researched tools only extend up and are not able to reach fixtures like in figure 1 nor are they able to apply the necessary torque to a T5 bulb as in figure 2. Figure 2 is a direct T5 light fixture that faces down with a cover for dispersing the light.

An interview with Ronald Lambers, Assistant Director of Facilities Management for UC, produced information concerning a tool capable of changing a T5 light bulb. He desires a tool that is versatile and flexible enough to fit into a variety of fixtures. (4) Figures 1 and 2 are examples of the various T5 fixtures throughout the University of Cincinnati campus.

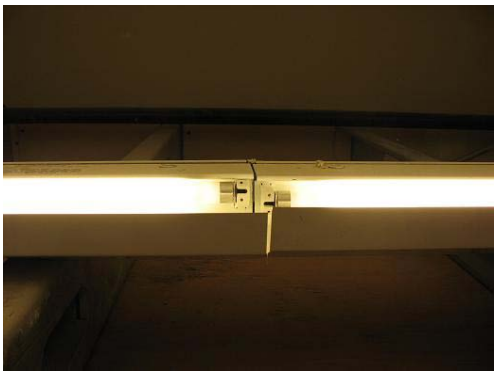


Figure 1 – T5 fixture located in the University Pavilion

Figure 2 – T5 fixture located in the Richard E. Lindner Center

CUSTOMER NEEDS AND IMPORTANCE

A customer survey revealed that the most desired features to be included were durability, ease of operation, adjustability to other bulbs and appearance (Appendix B). The survey was distributed to thirty people who work with fluorescent lighting. These features translated into engineering characteristics and rated. The most important characteristics are the fork design, handle design and material. (Appendix C).

PRODUCT OBJECTIVES

The T5 Bulb Changing Tool will include the following features:

Table 1- List of Features

Feature	Method of Measurement
The apparatus will not shatter the light bulb.	The gripper can be operated 10 times without the bulb breaking
The apparatus can be used by one person.	The tool will be given to 10 people in order to see if they can use the apparatus
The apparatus will not require other tools when removing a light bulb.	The tool will be the only tool needed removing the bulb.
The apparatus will weigh less than five pounds.	The apparatus will be placed on a scale
The apparatus can be used to remove and install T5 bulbs.	The tool will be given to 10 people in order to see if the tool works
The apparatus will be adjustable to other bulb sizes.	The gripper will fit on fluorescent bulbs from T5 to T8
The apparatus can be used for removing bulbs from indirect lighting fixtures.	The apparatus will be tested on a 5 indirect lighting fixtures and 5 direct lighting fixtures
The apparatus can be used in conjunction with a ladder.	The tool will be used to remove a bulb while standing on a ladder.

The method of measurement will insure that the feature is included in the apparatus.

DESIGN

DESIGN ALTERNATIVE AND SELECTION

The next step in designing this apparatus was to determine what the best design will be. In order to do this, a minimum of three designs were created.

1.1.1 Design Alternative 1: Handle with Forks

The first design, handle with forks, would be a small handle approximately 5 in. by 3in. at the largest point as shown in figure 3. It contained a trigger that would shift the forks. That would turn the forces into a tangential force around the bulb and would rotate the bulb a quarter turn. The bulb would then be released and easily removed. This design would require two tools, one for each end of the bulb.

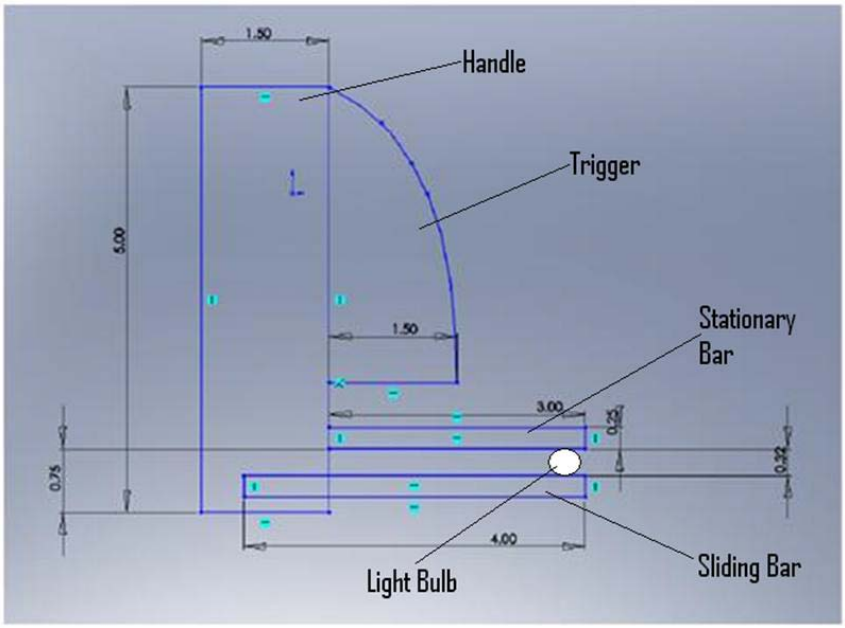


Figure 3 – Handle with Forks

1.1.2 Design Alternative 2: Handle with a Loop

The second design, handle with a loop, would be approximately the same size as the first design. The handle would have a rubber strip that would come out of the top of it as shown in figure 4. This rubber strip would have to be wrapped around the bulb and locked into the handle. The handle could then be rotated around the bulb to loosen and remove the bulb. This design would also require two tools.

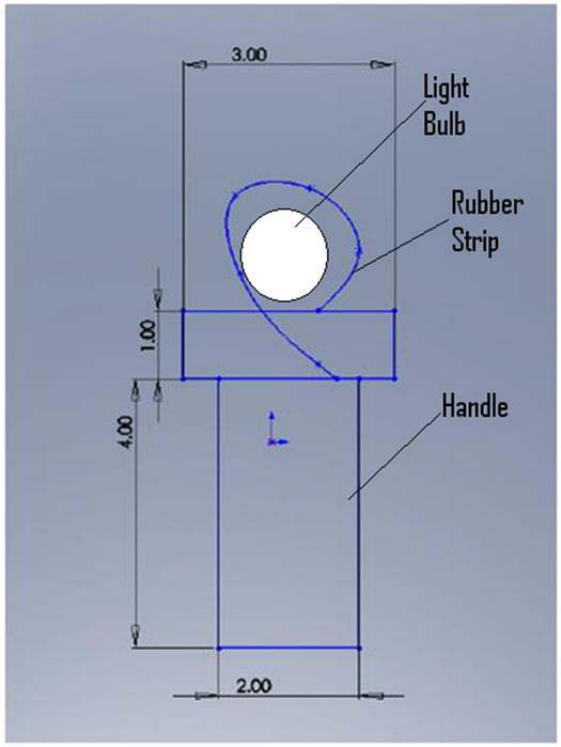


Figure 4 – Handle with a Loop

1.1.3 Design Alternative 3: Cantilever Apparatus

The third design, cantilever apparatus, would utilize multiple components as shown in figure 5. This apparatus would have a handle that is perpendicular to the frame. The arms would reach in opposite directions. At the ends of the arms, a set of rubber coated fingers would be ready to grip the bulb. The fingers would tighten around the bulb by a cantilever system. The cantilever apparatus would only require one tool because it grabs the bulb at both end and applies the torque evenly.

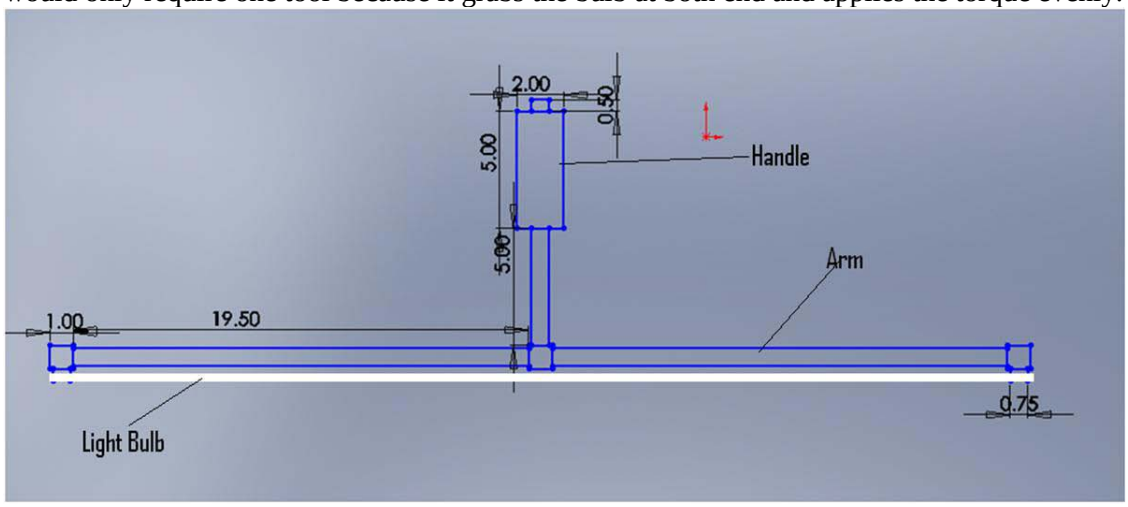


Figure 5 – Cantilever Apparatus

1.1.4 Design Selection

Once the designs were developed, Pugh's concept selection method was used to determine which design is best. The adjustable cantilever apparatus was used as the datum on the first iteration of Pugh's method because it was thought to be better than the other two. On the second iteration, the handle with a loop was used as the datum because it scored higher than the handle with forks. After two iterations, the third design was designated the best design. The cantilever apparatus was proved better than the handle with forks and only slightly better than the handle with a loop (Appendix F).

LOADING CONDITIONS

Through testing on the bulb, the initial loading conditions were found. As shown in figure 6, the method of finding the minimum amount of force required to achieve the necessary torque for releasing the bulb. The calculations determined that it takes 0.6 in.-lbs. of torque for the bulb to be released, and that bulb can withstand 8 in.-lbs. of torque without breaking. Figure 7 shows the testing apparatus for finding the crushing force on the bulb. This method revealed that it would take 85 lbs. of force to break the bulb. Due to lifting requirements according to the Washington State Department of Labor and Industry the apparatus should have a maximum weight limit of five pounds. (Appendix A)

Figure 6 - Torque Testing Apparatus

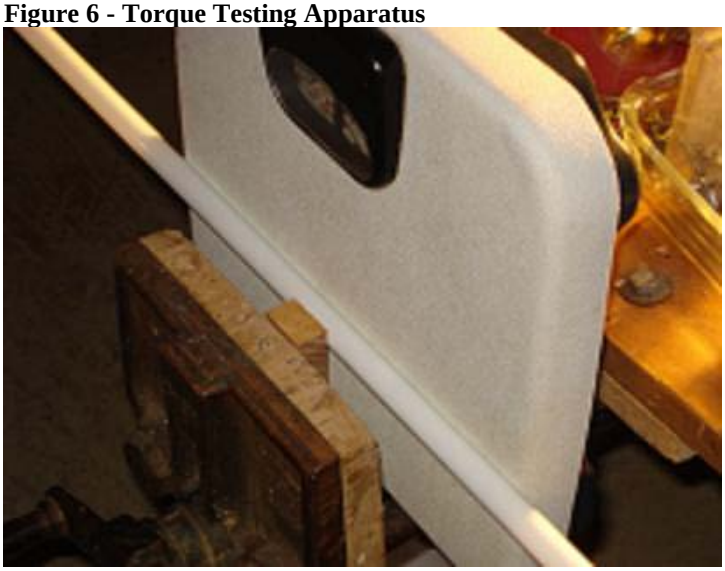


Figure 7 – Force Testing Apparatus

DESIGN ANALYSIS

The requirements for the cantilever apparatus require an analysis of the gripper claw and the arm. Through material analysis, the required diameter and the stress on the arm were calculated. The arm would experience a total stress of 38.22 psi and a deflection of -9.562×10^{-3} in. for a tube with a 1 in. outer diameter and a ¾ in. inner diameter. (Appendix G) PVC piping was chosen for the material because it is lightweight and has a yield strength of 7,500 psi. (Appendix A) After selecting a PVC pipe for the arms, the factor of safety was determined to be 196. This factor of safety was preferred because ¾ in. PVC pipe was readily available, would make the manufacturing process easier, and would insure product reliability.

$$\sigma_x = \frac{M_2 C}{I} = \frac{M_2 \frac{D}{2}}{\frac{\pi}{64}(D^4 - d^4)} = \frac{2.1 * \frac{1}{2}}{\frac{\pi}{64}(1^4 - .75^4)} = 31.29psi$$

$$\tau = \frac{M_1 C}{J} = \frac{T\frac{D}{2}}{\frac{\pi}{32}(D^4 - d^4)} = \frac{.6 * \frac{1}{2}}{\frac{\pi}{32}(1^4 - .75^4)} = 4.47psi$$

$$\sigma_{max} = \frac{1}{2}(\sigma_x + \sigma_y) + \sqrt{(\frac{1}{2}(\sigma_x - \sigma_x))^2 + \tau_{xy}^2}$$

$$= \frac{1}{2}((31.29) + (0)) + \sqrt{(\frac{1}{2}(31.29 - (0)))^2 + (4.47)^2} = 38.22psi$$

$$\delta = \frac{PL^3}{48EI} = -\frac{.1 * 42^3}{48 * 481000\frac{\pi(1^4 - .75^4)}{64}} = -9.562 * 10^{-3}in$$

COMPONENT SELECTION

In order to keep the apparatus light enough to use overhead, PVC, Aluminum 6061, and Steel were selected for the major components. The PVC will be used for the frame. The Aluminum 6061 will be used for the gripper case because it was a lightweight metal that can easily machined and welded. The steel will be used for the gripper claw because it will be able to withstand the forces and can be easily machined. Gasket Rubber will be added to the gripper claw in order to increase friction and to keep the metal from touching the bulb.

FABRICATION AND ASSEMBLY

The apparatus was constructed in two sub-assemblies. The parts that needed to be fabricated were the gripper components therefore it was the first sub-assembly to be constructed. The gripper case was cut to size and had a specified slot milled out of it. The lower claw brace was mounted into place with epoxy. The materials for the claws were cut out of 7/8 in. steel pipe and bar stock. They were fashioned by welding them together and grinding out a slot to reduce interference. The two claws were then pinned together and attached to the assembly. The lower claw was mounted to the casing by epoxy in order to keep it stationary. The upper claw was connected to a 1/16 in. steel cable that ran through copper tubing to the handle.

The second sub-assembly was the PVC frame. The handle of the frame and the arms were glued with PVC cement into a PVC t-section. Hose clamps were used to attach the gripper case to the frame. The activator mechanism was mounted to the handle of the frame and the steel cable from the gripper claws was connected to it. The apparatus was then tested and fine tuned in accordance with the purposed specifications of the device.

PROJECT MANAGEMENT

BUDGET

The project will cost approximately $120 (Appendix D). The objective is to produce a tool to remove T5 bulb at a reasonable cost. This budget includes only the material costs. Table 2 is a preliminary budget for the apparatus:

Table 2 - Budget

Materials	Qty	Forecasted Amount	Actual Amount
PVC Pipe	1	$7.00	$14.00
Steel Claw	2	$60.00	$93.00
Al 6061 End Cap	1	$24.00	$13.00
Spring	1	$10.00	$2.00
Pin	2	$16.00	Donated
Miscellaneous Expenses		$0.00	$16.00
Total		$117.00	$138.00

SCHEDULE

The schedule begins on January 7, 2008 and ends on June 13, 2008 (Appendix E). The schedule maps out the tasks and the due dates. Table 3 show the major benchmark dates:

Table 3- Task Benchmarks

Tasks	Date Due	Completion Date
Proof of Design Agreement	January 17	February 25
Design Freeze	February 21	May 8
Winter Oral Presentation	March 13	March 13
Design Report	March 17	March 17
Final Testing	April 28	June 4
Demonstration to the Advisor	May 1	June 4
Tech Expo	May 22	May 22
Spring Oral Presentation	May 29	May 28
Final Report	June 5	June 11

CONCLUSION

The maintenance department of the University of Cincinnati requested the design and creation of a tool that would aid in the replacement of T5 light bulbs. After identifying the specific needs of the device, three designs were considered. The designs were compared using Pugh's concept selection method and the cantilever apparatus was selected as the preferred design. Since the device would be used primarily overhead, the selected components were chosen to minimize the overall weight. The apparatus consisted of two sub-assemblies; the gripper and the frame. The tension on the gripper claws was adjusted to meet the specified requirements of the device. The tool was then tested by the maintenance department with satisfactory results.

The apparatus could be improved for overall functionality, lower net weight, lower cost and improved ergonomic design. The gripper claws could be thinned and constructed of plastics. The steel cables could be run through the interior of the frame. The connection of the activator to the steel cables could be improved. These suggested improvements are based the results of multiple tests and customer response.

REFERENCES

1. 4-Pc. Bulb Changer Set With Pole. *Improvements.* [Online] HSN Improvements, LLC, 1998 - 2007. [Cited: 12 11, 2007.] http://www.improvementscatalog.com/home/improvements/1617-4-pc-bulb-changer-set-pole.html.

2. Find Light Bulb Changer and other Tools & Testers at Aubuchon Harware. *Aubuchon Hardware.*

[Online] Aubuchon Hardware, 2007. [Cited: 11 2007, 12.] http://electrical.hardwarestore.com/15-62-light-bulb-changers/light-bulb-changer-602035.aspx#features.
3. **Target.com.** Unger Flood Light Chnger. *Target.com.* [Online] Target, 2007. [Cited: 11 2007, 12.] http://www.target.com/Unger-Flood-Light-Changer/dp/B000E48IU6/sr=1-6/qid=1199114792/ref=sr_1_6/601-7472173-3726552?ie=UTF8&rh=k%3Alight%20bulb%20tools&page=1.
4. **Lambers, Ronald J.** *Assistant Director Electrical Systems & Facilities Management Operations.* Cincinnati, 12 7, 2007.
5. **Industry, WISHA Services Division: Washington State Department of Labor and Industry.** *Lessons for Lifting and Moving Materials.* Olympia : WISHA Services Division, 2000.
6. **Plastics International**. *PVC (Polyvinyl Chloride).* Edin Prairie: Plastics International, 2007

APPENDIX A: RESEARCH

http://www.improvementscatalog.com/home/improvements/1617-4-pc-bulb-changer-set-pole.html 12/4/2007 4-Pc. Bulb Changer Set With Pole, Improvementscatalog.com

4-Pc. Bulb Changer Set With Pole

4-Pc. Bulb Changer Set With Pole
View larger/Additional Views

4-Pc. Bulb Changer Set With Pole

Safely Change Bulbs "Way Up There"...Even Remove Broken Bulbs!

No more climbing shaky ladders or chairs...just screw the appropriate changer onto the telescoping extension pole. You'll safely install and remove light bulbs (even broken ones) over stairways, on cathedral ceilings, in track lighting, recessed lights...any out-of-the-way fixture, indoors and out.

Set includes spring-operated changers for: **standard incandescent bulbs, floodlights, broken bulbs,** and a suction cup holder for **recessed and track lighting.** The spring changers have latex rubber pads and metal flex holders for a secure grip. Four-section, steel **telescoping pole extends from 4' to 16' long,** and locks in place at any length. For more versatility, the pole's threaded tip also accepts standard threaded attachments.

(1)

Features Derived

- Rubber to protect bulb

Light Bulb Changer  http://electrical.hardwarestore.com/15-62-light-bulb-changers/light-bulb-changer-602035.aspx#features. 12/11/07, Find Light Bulb Changer and other Tools & Testers, Aubuchon Harware. For use with flood, standard incandescent, recessed and track lighting bulbs. Change bulbs safely, quickly and easily. Includes 11' telescoping extension pole. This Light Bulb Changer is one of many top quality items in our Light Bulb Changers department. Aubuchon Item # **602035** Light Bulb Changer This item is available ONLINE ONLY. • Bayco Model # LBC-600SDL • A-LINE, FLOODLIGHT & RECESSED/TRACK LIGHTING • Unit: each • Unit Weight: 3.1300 lbs • UPC Code: 017398450065 (2)	No Features Derived

Unger Flood Light Changer

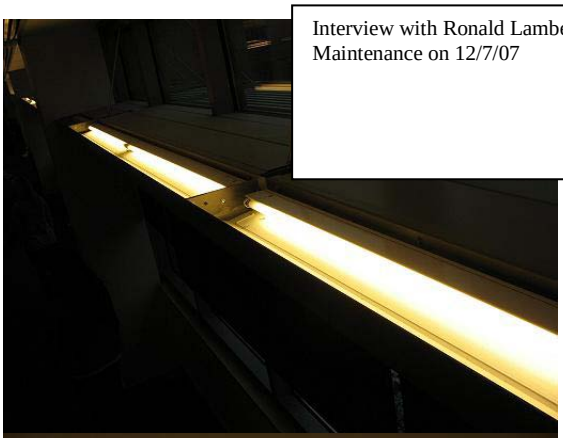
No Features Derived

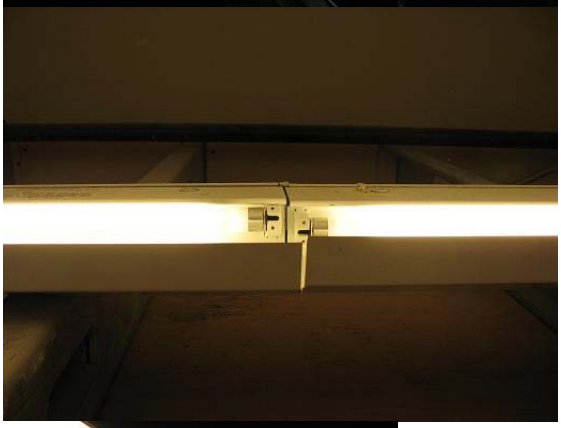
http://www.target.com/Unger-Flood-Light-Changer/dp/B000E48IU6/sr=1-6/qid=1199114792/ref=sr_1_6/601-7472173-3726552?ie=UTF8&rh=k%3Alight%20bulb%20tools&page=1. 12/11/07, Unger Flood Light Chnger, Target.com

• Easily reach and change recessed floodlights and light bulbs
• Insulated design protects your fingers
• Made for use with 300-watt bulbs and larger
• Designed to attach to the Unger 3-Stage Telepole (sold separately)
• 8.5L"

(3)

Interview with Ronald Lambers from UC Maintenance on 12/7/07



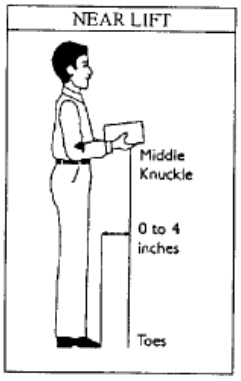


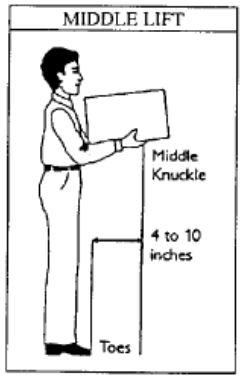
A tool is needed to change the T5 light bulbs. It needs to attach to the bulb and apply enough torque to twist the bulb in order to change the bulb.

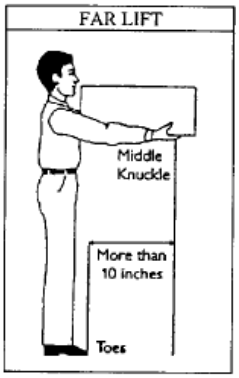
(4)

Features Derived

- Works with multiple fixtures
- Fits in the hand
- Squeeze activation







NEAR LIFT	
DANGER ZONE	More than 51 lbs 5 points*
CAUTION ZONE	17 to 51 lbs 3 points
SAFE ZONE	Less than 17 lbs 0 points

MIDDLE LIFT	
DANGER ZONE	More than 35 lbs 6 points
CAUTION ZONE	12 to 35 lbs 3 points
SAFE ZONE	Less than 12 lbs 0 points

FAR LIFT	
DANGER ZONE	More than 28 lbs 6 points
CAUTION ZONE	10 to 28 lbs 3 points
SAFE ZONE	Less than 10 lbs 0 points

(5)

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PVC conforms to ASTM D-1784-95 Class 12454-B (Formerly Type I Grade 1) and is manufactured without the use of plasticizers or fillers. It can be used in self-supporting construction up to 140° F (depending on chemistry). It exhibits excellent fire ratings (UL-94V-0) and has a flame spread under 20 per ASTM-E-84.

- Strength – PVC combines tensile strength and stiffness for the toughest applications.
- Chemical Resistance – PVC is resistant to most acids and alkali solutions.
- Workability – PVC can be machined, cut, welded and glued for fabrication versatility.
- Low Cost – PVC is an economical choice for fabricating equipment, tanks, pumps etc.
- Consistency – PVC is extruded through most of the available gauges for dimensional consistency.
- Flammability – PVC is self-extinguishing.

Property	ASTM Test Method	Units	PVC
Physical			
Density	D 792	g/cc	1.42
Water Absorption	D 570	%	0.06
Cell Class	1784		12454-B
Rockwell Hardness	D 785	R Scale	115
Shore Durometer	D 2240	D	89
Mechanical			
Tensile Modulus	D 638	psi	411,000
Yield Strength	D 638	psi	7,500
Flexural Modulus	D 790	psi	491,000
Yield Strength	D 790	psi	12,800
Izod Impact	D 256	ft-lb/in	1.0
Thermal			
Vicate Softening Point	D 1525	°F	181
Heat Deflection Temperature	D 648	°F	179
Linear Coefficient of Expansion		in/in/°F	3.2 x 10^-5
Flammability	D 635	—	Self-Extinguishing
Flammability	UL 94	—	V-0
Flame Spread	E 84	—	15
Electrical			
Volume Resistivity	D 257	ohm/cm	5.4 x 10^15
Dielectric Constant	D 150	60 Hz	3.19
Dissipation Factor	D 150	60 Hz	0.0096
Loss Index	D 150	60 Hz	0.030
Dielectric Strength	D 149	V/mil	544
Chemical			
Chemical Resistance	D 1784	—	Class B

NOTE: The information contained herein are typical values intended for reference and comparison purposes only. They should NOT be used as a basis for design specifications or quality control. Contact us for manufacturers' complete material property datasheets. All values at 73°F (23°C) unless otherwise noted.

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APPENDIX B: CUSTOMER SURVEY RESULTS

APPENDIX C: CUSTOMER QUALITY DEVELOPMENT

	material	squeeze activation	rubber to protect bulb	handle design	fork design	Customer importance	Sales points	Improvement (Absolute weight) ratio	Relative weight
Operation									
1. easy to operate		9	3			4	1.5	6.0	0.28
Features									
2. duability	9			3	3	4.5	1.4	6.3	0.30
3. size				9	3	3.5	1.0	3.5	0.17
4. adjustable					9	3	1.3	3.9	0.18
5. appearance	3			9	9	1.5	1.0	1.5	0.07
Absolute Importance	2.9	2.55	0.85	3.01	3.68	12.98		21.2	1.00
Relative importance	0.22	0.20	0.07	0.23	0.28				

APPENDIX D: PROOF OF DESIGN

Prood of Design

Apparatus for Removing T5 Bulbs from Lighting Fixtures

Justin Eyre

University of Cincinnati

College of Applied Science

This tool design will meet the project objective listed in the proposal. Each of these objectives will be addressed in the design process. Listed below are the observable objectives for the design.

Observable Objectives

- The apparatus will not shatter bulb.
- The apparatus can be used by one person.
- The apparatus will not require other tool when removing a bulb.
- The apparatus will weigh five pounds.
- The apparatus can be used to remove and install T5 bulbs.
- The apparatus will adjustable to other bulb sizes.
- The apparatus can be used for removing bulbs from indirect lighting fixtures.
- The apparatus can be used in conjunction with a ladder.

Justin Eyre: _____ Date: 2/25/08

Amir Salehpour: _____ Date: 2/25/08

APPENDIX E: SCHEDULE

T5 Bulb Changing Tool Project Schedule																						
Week	Winter Quarter Week Number											Spring Quarter Week Number										
	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11
Dates	Jan. 7 - 11	Jan. 14 - 18	Jan. 21 - 25	Jan. 28 - Feb 1	Feb. 4 - 8	Feb. 11 - 15	Feb. 18 - 22	Feb. 23 - 29	Mar. 3 - 7	Mar. 10 - 14	Mar. 17 - 21	Mar. 21 - Apr. 4	Apr. 7 - 11	Apr. 14 - 18	Apr. 21 - 25	Apr. 28 - May 2	May 5 - 9	May 12 - 16	May 19 - 23	May 26 - 30	Jun. 2 - 6	Jun. 9 - 13
Task																						
Weighted Objective Method																						
Proof of Design Statement																						
Proof of Design Agreement		17																				
Design Handle																						
Design Rotation Device																						
Construct Drawings																						
Design Freeze							21															
Work on Oral Presentation																						
Give Oral Presentation										13												
Work on Design Report																						
Design Report Due											17											
Bill of Materials																						
Purchase Materials																						
Construct Tool																						
Test Tool																						
Modifications (if Necessary)																						
Retest Tool																						
Modifications (if Necessary)																						
Final Testing																						
Demonstrate to Advisor																1						
Prepare for Tech Expo																						
Tech Expo																			22			
Work on Oral Presentation																						
Give Oral Presentation																				29		
Work on Final Report																						
Present Final Report																						9

APPENDIX F: PUGH'S CONCEPT SELECTION

First Iteration

	Adjustable Cantilever Apparatus	Handle With Forks	Handle With A Loop
Size	DATUM	+	+
Ease of Operation		-	-
Appearance		-	-
Adjustable to other bulbs		S	S
Durability		-	+
Ease of Maintenance		-	+
Cost to Manufacture		-	-
∑+		1	3
∑-		5	3
∑S		1	1

Second Iteration

	Handle With A Loop	Handle With Forks	Adjustable Cantilever Apparatus
Size	DATUM	S	-
Ease of Operation		+	+
Appearance		+	+
Adjustable to other bulbs		S	S
Durability		-	+
Ease of Maintenance		-	-
Cost to Manufacture		-	+
∑+		2	4
∑-		3	2
∑S		2	1

APPENDIX G: CALCULATIONS

$M_1 = T = 0.6\ in - lbs$
$M_2 = 0.1lbs * 21in = 2.1in - lbs$

With a 1in diameter

$$\sigma_x = \frac{M_2 C}{I} = \frac{M_2 \frac{d}{2}}{\frac{\pi}{64} d^4} = \frac{64 M_2}{2\pi d^3} = \frac{64(2.1)}{2\pi(1)^3} = 21.4psi$$

$$\tau = \frac{M_1 C}{J} = \frac{T \frac{d}{2}}{\frac{\pi}{32} d^4} = \frac{32T}{2\pi d^3} = \frac{32(.6)}{2\pi(1)^3} = 3.06psi$$

$$\sigma_{max} = \frac{1}{2}(\sigma_x + \sigma_y) + \sqrt{(\frac{1}{2}(\sigma_x - \sigma_x))^2 + \tau_{xy}^2} = \frac{1}{2}((21.4) + (0)) + \sqrt{(\frac{1}{2}(21.4 - (0)))^2 + (3.06)^2}$$
$$= 21.83\ psi$$

With a ½ in diameter

$$\sigma_x = \frac{M_2 C}{I} = \frac{M_2 \frac{d}{2}}{\frac{\pi}{64} d^4} = \frac{64 M_2}{2\pi d^3} = \frac{64(2.1)}{2\pi(1.5)^3} = 1711.23psi$$

$$\tau = \frac{M_1 C}{J} = \frac{T \frac{d}{2}}{\frac{\pi}{32} d^4} = \frac{32T}{2\pi d^3} = \frac{32(.6)}{2\pi(.5)^3} = 24.45psi$$

$$\sigma_{max} = \frac{1}{2}(\sigma_x + \sigma_y) + \sqrt{(\frac{1}{2}(\sigma_x - \sigma_x))^2 + \tau_{xy}^2}$$
$$= \frac{1}{2}((1711.23) + (0)) + \sqrt{(\frac{1}{2}(171.23 - (0)))^2 + (24.45)^2} = 1711.58\ psi$$

With a ¼ in diameter

$$\sigma_x = \frac{M_2 C}{I} = \frac{M_2 \frac{d}{2}}{\frac{\pi}{64} d^4} = \frac{64 M_2}{2\pi d^3} = \frac{64(2.1)}{2\pi(.25)^3} = 13685.87psi$$

$$\tau = \frac{M_1 C}{J} = \frac{T \frac{d}{2}}{\frac{\pi}{32} d^4} = \frac{32T}{2\pi d^3} = \frac{32(.6)}{2\pi(.25)^3} = 195.57psi$$

$$\sigma_{max} = \frac{1}{2}(\sigma_x + \sigma_y) + \sqrt{(\frac{1}{2}(\sigma_x - \sigma_x))^2 + \tau_{xy}^2}$$
$$= \frac{1}{2}((13685.87) + (0)) + \sqrt{(\frac{1}{2}(13685.87 - (0)))^2 + (195.57)^2} = 13692.66\ psi$$

Flexural Strength for 1 in outer diameter and ¾ in inner diameter

$$\delta = \frac{PL^3}{48EI} = -\frac{.1 * 42^3}{48 * 481000 \frac{\pi(1^4 - .75^4)}{64}} = -9.562 * 10^{-3} in$$

With a ½ in outer diameter and a ¼ in inner diameter

$$\delta = \frac{PL^3}{48EI} = -\frac{.1 * 42^3}{48 * 481000 \frac{\pi(.5^4 - .25^4)}{64}} = -.1115 in$$

With a ¼ in outer diameter and a 1/8 in inner diameter

$$\delta = \frac{PL^3}{48EI} = -\frac{.1 * 42^3}{48 * 481000 \frac{\pi(.25^4 - .125^4)}{64}} = -1.785 in$$

APPENDIX H: DRAWINGS